INVESTIGATION OF THE STRUCTURAL CHARACTERISTICS OF LIME-CEMENT CONCRETE

BY

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CERTIFICATION

This is to certify that this work "Investigation of the structural characteristics of lime-cement concrete" was carried out by I, Awodiji Chioma Temitope Gloria (Reg. No. 20124771948), in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy (Ph.D) in Civil Engineering (Structures), of the Federal University of Technology, Owerri.

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DEDICATION

I dedicate this work to my lovely family; Olayinka, Oladayo, Mobolaji, Oluwatobi and Oluwafumilayo.

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ABSTRACT

This work investigated the structural characteristics of lime cement concrete using 30 selected mix ratios. The properties studied include, compressive strength, flexural strength, splitting tensile strength, shear strength, poisson ratio, modulus of elasticity, and modulus of rigidity. A total of 360 concrete cube specimen, 360 concrete prototype beam specimen, and 360 concrete cylinder specimen were cast and cured in open water tanks. 3 specimen were cast for each mix proportion. They were then tested in compression, flexure, and splitting tension respectively at 7 days, 14 days, 21 days, and 28 days. Load values obtained from these test were used to determine the other structural properties of the concrete. Materials used in concrete production were the portland cement (PC), hydrated lime (HL), river sand, granite chippings, and water. The highest value of compressive strength recorded from experimental works at 28 days of curing was 30.83N/mm^2. This occurred at a water-cement (w/c) ratio of 0.562, having a percentage replacement of PC with hydrated lime of 18.75%. Highest values of flexural strength, splitting tensile strength, shear strength, poisson ratio, modulus of elasticity and modulus of rigidity recorded at 28 days of curing were 5.03N/mm^2, 3.725N/mm^2, 1.257N/mm^2, 0.216, 30.708 x 10^3 N/mm^2 and 13.386 x 10^3 N/mm^2 respectively. Lowest values recorded for compressive strength, flexural strength, split tensile strength, shear strength, poisson ratio, modulus of elasticity and modulus of rigidity recorded at 28 days of curing were 15.12N/mm^2, 2.28N/mm^2, 2.00N/mm^2, 0.569N/mm^2, 0.105, 20.264 x 10^{3}N/mm^2 and 8.803 x 10^{3}N/mm^2 respectively. A total of 120 data set were generated experimentally for each property studied. 114 sample data of each property were used to teach the artificial neural networks (ANNs) how to accurately predict the structural properties of the lime cement concrete. The remaining 6 sets of data were left out and used to test how well the networks were predicting after being trained. 7 ANN models were created using the neural network toolbox in the Matlab R2014a software. The feed forward back propagation neural network with "trainlm" training function and the mean square error (mse) performance functions were adopted. The end results of the back propagation neural networks were 6-20-1 (6 inputs, 20 neurons in the hidden layer, and 1 output). Maximum percentage error for all networks were generally below 11% while the maximum correlation coefficients were close to 1. The student's t-test was used to further test the adequacy of the neural network models. The calculated T values for the compressive strength, flexural strength, split tensile strength, shear strength, poisson ratio, modulus of elasticity, and modulus of rigidity neural networks were 1.437, 0.1598, 0.4607, 1.4642, -1.0555, 0.4631, and 1.7069 respectively. They were all less than the 2.065 which is the allowable T value from the statistical table. Therefore, the null hypothesis (H_o) was accepted i.e. there is no significant difference between the neural network models and the experimental results. For lime cement concrete to be used as a structural concrete, PC replacement with hydrated lime must not be up to 30%. Optimum percentage replacement was recorded at 18.75%. Partial replacement of portland cement with hydrated lime was observed to improve the workability of the fresh concrete but reduced the strength of the hardened concrete. The relationship between the structural properties of the lime cement concrete with respect to water cement ratio, showed that the magnitude of each property of concrete increased as water cement ratio increased until the optimum water cement ratios were reached. With the use of the developed ANN models, mix design procedures for lime cement concrete can be carried out with lesser time, and energy requirement since the traditional method of designing mixes by carrying out trial mixes in the laboratory will no longer be required.

Keywords: Structural properties, concrete, hydrated lime (HL), portland cement (PC), artificial neural network (ANN).

CHAPTER ONE

INTRODUCTION

1.1 Background

Concrete is one of the most important materials in modern building and civil engineering constructions. Today, its versatility in terms of its workability (i.e. its ability to be moulded into various shapes required), makes it very unique (Ajayi, Rasheed, & Mojirade, 2013). Concrete can be defined as a composite material comprising mainly of three phases, namely, coarse aggregate, cement mortar and the interface zone between them (Tareq, 2008).

The characteristics of the interface zone, largely govern the bond between cement paste or mortar and aggregate. But Jaime (2013), defined concrete as a mixture of binders, aggregates and water. Binders are classified into inorganic and organic binders. Examples of inorganic binders are cement, lime and gypsum, while the organic binders are epoxy resin and acrylic emulsion. There are also supplementary binders which are the pulverized fly ash (PFA) and ground granulated blast furnace slag (GGBS).

Conventional concrete, is a composite material containing fine aggregate, coarse aggregate, cement and water in predefined mix proportions. This combination gives concrete its characteristic density, which is normally within the range of $2200kg/m^3$ – $2400kg/m^3$, thereby limiting its use in some structural works (Osunade, 2002).Concrete is used in large quantities, almost everywhere mankind has a need for infrastructure. It is probably the most common material used in the construction industry of most countries of the world (Bhavikatti, 2001).It is strong in compression and has good fire resistance properties. When steel, which is strong in tension, is incorporated into it, a strong and durable material which can withstand various forms of loading and can be formed into various shapes and sizes emerges (Owolabi, 2012). This accounts for its widespread use in civil engineering construction works such as buildings, bridges, dams, etc.

The manufacture and use of concrete lead to a wide range of environment and social consequences. Cement, which is a major component of concrete, exerts similar environmental and social effects (Navdeep, Sudhakara, & Abhijit, 2012). Cement production is a significant source of global carbon dioxide (CO_2) emissions. This gas depletes the ozone layer, i.e. the "greenhouse effect" that has caused a lot of harm to the ecosystem by increasing the atmospheric temperature (Srinivasan, Sathiya, & Palanisamy, 2010). The cement industry is one of the three primary producers of carbon dioxide (CO_2). The other two are the energy production and transportation industries. The common estimation of the emission of CO_2 from the cement production, is given as 0.6 ton for every 1 ton of cement (Jaime, 2013). In China, the statistics in 2005 for the CO_2 emission from cement production was 0.815tonne of CO_2 per ton of cement. As at 2011, cement production contributed 7% to global anthropogenic CO_2 emission; largely due to the sintering of limestone and clay at 1500^0C (Navdeep et al., 2012). The increasing atmospheric temperature due to the emission of CO_2 gas, has led to climatic changes with adverse effects such as flooding, earthquakes, hurricanes, new viruses, etc.

Most cement plants consume much energy and produce a large amount of undesirable products, which affect the environment (Ahmed, Abdurrahman, & Mohammed, 2009). According to Cowper (2013), the manufacture of cement consumes a large amount of energy, which is about 7,600,000KJ per ton or 1.1 ton of cement. Production of cement requires large quantities of energy and developing countries like Nigeria, have low availability of non-renewable energy resources to take care of this need.

Cement production is relatively expensive due to high cost of energy. Thermal and electric energy, account for 40% of the operational costs ("European Commission", 2010). This problem discourages an average potential investor from venturing into cement manufacture. The result is that only a few investors monopolize the market in Nigeria.

Owning a house is one of the most cherished desire of an average Nigerian. Unfortunately, many middle class and low class earners, are not able to buy or build houses of their own because of the high cost of building materials, especially cement. Fifty percent (50%) of the total cost of any construction project goes on cement (Okpala, 1988).In Nigeria, the demand for cement exceeds its supply. Existing cement factories, have their total installed capacity equal to 50% of the country's requirement, while the actual production from these factories, is less than 30% of the country's demand (Apata & Alhassan, 2012).

Concrete is designed by past experience acquired from previous mixes or by making trial batches in the laboratory and testing the concrete. Results obtained from the laboratory test, usually, require some modification to meet with the site requirement. All these traditional procedures are expensive and time consuming, making mix design more difficult and complicated (Shetty, 2006).

The provision of building materials that are affordable to urban and rural dwellers, as well as environmentally friendly, has been seen to be one of the hindrances to improved housing situations in developing countries like Nigeria (Jimoh et al., 2013). Some of the conventional materials are imported and their prices are beyond what the average Nigerian can afford. In order to check the over dependence on these materials, efforts are being directed towards changing some of the materials, such as concrete by wholly or partially substituting their constituents. In the recent years, the use of binding materials of different types, together with cement, has become very wide in the production of concrete. Example of this, can be seen in the blending of portland cement with fly ash, limestone, rice husk ash, pawpaw leaf ash, plantain leaf ash, corn cob ash, hypo sludge, saw dust ash, palm bunch ash, etc. Ternary blended cement, which has the advantage of increase in strength at longer days of hydration, when compared to their controls and binary blends, had been investigated by Ettu, Nwachukwu, Arimanwa, Awodiji, & Opara (2013a).

In Nigeria, there has been reawakened serious awareness on the need to relate research to production, especially in the use of local materials as alternatives for the construction of functional, but low-cost dwelling, both in the urban and rural areas (Joshua and Lawal, 2011). One of such local material that is being researched on is limestone. Therefore, this research work is concerned with the investigation of the properties of concrete in which cement has been partially replaced by hydrated lime as a binder. Besides, models based on the artificial neural network, were also developed for predicting these properties of lime cement concrete.

1.2 Statement of problem

Concrete has been the most widely used construction material for many centuries due to its advantages such as ease in forming structural elements, readily available, and excellent durability relative to other materials (Jayakumar and Abdullahi, 2011). But the increase in the demand of concrete for construction works, has resulted to an increase in the demand for the production of cement, which is a significant source of global carbon dioxide (CO_2) emission. This green-house gas is depleting the ozone layer and thereby causing global warming of the earth.

The large amount of energy required for portland cement production has resulted to high production cost. This has led to the monopolization of the cement industry by few investors who can afford the very high production cost of the cement. The high production cost of cement has also resulted to high cost of the product itself, thereby making it difficult for low and average income earners to own houses. Finally, the traditional method of mix design of concrete is time consuming, and energy demanding. Therefore, with the use of hydrated lime as a partial replacement of portland cement in concrete production and with the use of the developed artificial neural network models for predicting the properties of lime cement concrete mixes, these problems can be minimized.

1.3 Objectives of the study

The main objective of this study, is to investigate the structural characteristics of lime-cement concrete. The specific objectives are as follows:

(i) To characterize the fresh lime cement concrete and its constituent.

(ii) To determine experimentally, the structural characteristics of hardened lime-cement concrete. These characteristics include compressive strength, flexural strength, split tensile strength, shear strength, poisson ratio, modulus of elasticity, and modulus of rigidity.

(iii) To formulate, validate, and test the adequacy of the artificial neural network (ANN) models for predicting the structural characteristics of lime-cement concrete.

(iv) To compare the predicted results of the structural characteristics of lime cement concrete obtained from the artificial neural network models, and the experimental values.

(v) To prepare a user interface for the artificial neural network models.

1.4 Justification of study

This investigation will result to the provision of data on the structural characteristics of lime-cement concrete. This will assist in providing information to structural designers, in the analysis and design of hydrated lime cement concrete structures, since there are no available standard design codes with respect to this type of concrete.

The inclusion of hydrated lime as a partial replacement of portland cement, will assist in reducing the emission of the green-house gases to the atmosphere. This is possible since a reduction in the amount of the clinker content in cement production by hydrated lime, will reduce the amount of CO_2 released into the atmosphere during the calcination of the clinker (Afsah, 2004). Also, the addition of hydrated lime as a partial replacement of clinker, will result to lower calcination temperature, thereby reducing CO_2 emissions from the fossil fuel used to heat up the cement kilns. Hydrated lime in concrete has the ability to re-absorb CO_2 gases from the atmosphere (Spano, 2009).Therefore, since lime production leaves a smaller carbon footprint than OPC, the use of lime cement concrete, will lead to a reduction of green-house gases to the atmosphere.

Lime production requires lower energy consumption when compared to portland cement. The vertical kiln used for the production of lime, tends to operate at temperatures between 800^0C and 1000^0C. This is substantially lower than the 1450^0C, which is needed for the calcination of limestone to produce portland cement (Yang, 2013). Also, quicklime tends to disintegrate during slaking, substantially reducing the demand for the energy-intensive finish grinding.

The production of hydrated lime, requires far less imported technology and equipment. The energy requirement is also lower than that of portland cement. These factors result to the lower production cost of hydrated lime. Lower production cost results into lower prices of lime cement for consumers, thereby leading to affordable housing units. More investors can now venture into cement manufacturing, since the initial investment cost is reduced, thereby generating opportunities for local employment.

The use of the formulated models to predict the structural characteristics of lime-cement concrete, is expected to reduce the labour involved in the mix design process and save time. This will be achieved since the designer do not have to waste materials, energy and time, making trial mixes, curing them, and crushing them in the laboratory. Artificial neural networks have the ability to make accurate predictions even when input data is incomplete or non-linear. Predictions can be easily made for any given number of mixtures as against the use of other mathematical models.

1.5 Scope of study

The scope of this study is limited to determining the structural characteristics of lime-cement concrete. The structural characteristics studied are compressive strength, flexural strength, split tensile strength, shear strength, poisson ratio, modulus of elasticity, and modulus of rigidity. These properties were obtained from experimental works and then, the artificial neural network

(ANN) technique was used to develop models for predicting them. The ANN toolbox in the matlab R2014a software was adopted in the development of the ANN models.

CHAPTER TWO

LITERATURE REVIEW

2.1 Cementing materials

Cementing materials are those materials having physical properties similar to those of portland cement. In particular, they can be poured into a mould where they set and harden to a porous mixture upon drying. They possess excellent setting and hardening properties, when mixed with water (Neville, 2006). There are two types of cementing materials, namely; hydraulic and non-hydraulic cementing materials. Hydraulic cementing materials set and harden in water. An example of a hydraulic cementing material, is portland cement. Non hydraulic cementing materials, sets and hardens in air. As a result, these materials cannot be used in water. An example of a non-hydraulic cementing material, is ordinary lime. Cementing materials may be siliceous or calcerous. Calcium carbonate and silica are the major constituents of cementing materials. Other constituents are, quartz, feldspar, calcite, clay, iron oxide, calcium oxide, copper sulphate, manganese, aluminum, and sulphur (Neville, 2006). Depending on the chemical composition, and the availability in nature, cementing materials are categorized as lime, gypsum, plaster of paris, cement, concrete, and reinforced concrete. Cementing materials are used as adhesives for bricks, stones, and tiles. These materials are also used to make big coherent structures, and building.

2.1.1 Portland cement

A cement is a binder, a substance that sets and hardens as the cement dries and also reacts with carbon dioxide in the air independently, and can bind other materials together (Shetty, 2006). Portland cement is a finely ground gray powder chemically formed by combining raw materials containing calcium oxide (CaO), silica oxide (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3). This mixture is heated to a high temperature and then ground to give a material called clinker, with a small quantity of calcium sulphate ($CaSO_4$).The story of the invention of portland cement is, however attributed to Joseph Aspdin, a Leeds builder and bricklayer, even though similar procedures had been adopted by other inventors. Joseph Aspdin took the patent of portland cement on the 21st October, 1824 (Shetty, 2006). The fancy name of portland cement, was given owing to the resemblance of this hardened cement to the natural stone occurring at Portland in England. In his process, Aspdin mixed and ground hard limestone and finely divided clay into the form of slurry and calcined it in a furnace similar to a lime kiln, till the CO_2 was expelled. The mixture so calcined, was then ground to a fine powder. Perhaps, a temperature lower than the clinkering temperature was used by Aspdin . Later in 1845, Isaac Charles Johnson burnt a mixture of clay and chalk till the clinkering stage to make better cement and established factories in 1851 (Shetty, 2006).

2.1.1.1 Chemical composition of portland cement

Portland cement gets its strength from chemical reactions between the cement and water. The process is known as hydration. It is a process that is best understood by first understanding the chemical composition of cement. The raw materials used for the manufacture of cement consist mainly of lime, silica, alumina and iron oxide (Shetty, 2006). These oxides interact with one another in the kiln at high temperature to form more complex compounds. Because of the complex chemical nature of cement, a shorthand form is used to denote the chemical compounds. The shorthand for the basic oxides or compounds is as shown in Table 2.1.

Table 2.1: Shorthand for basic oxides of cement

Oxide	Chemical Formula	Shorthand
Calcium oxide (Lime)	CaO	C
Silicon dioxide (Silica)	SiO_2	S
Aluminum oxide (Alumina)	Al_2O_3	A
Iron oxide	Fe_2O_3	F
Water	H_2O	H
Sulphate	SO_3	S

Source: (Shetty,2006, p.14).

The cement clinker formed during the production of cement has the following typical composition shown in Table 2.2.

Table 2.2: Compounds of cement clinker

Name of compound	Chemical Formula	Shorthand
Tricalcium silicate	$3CaO.SiO_2$	C_3S
Dicalcium silicate	$2CaO.SiO_2$	C_2S
Tricalcium aluminate	$3CaO.Al_2O_3$	C_3A
Tetra calcium aluminoferrite	$4CaO.Al_2O_3.Fe_2O_3$	C_4AF
Sodium oxide	Na_2O	N
Potassium oxide	K_2O	K
Gypsum	$CaSO_4.2H_2O$	CSH_2

Source: (Shetty,2006, p.15).

The first four compounds in the table above have been identified by R.H. Bogues as the major compounds (Shetty, 2006). In addition to the four major compounds, there are other minor compounds formed in the kiln. Their influence on the properties of cement is minimal. Two of these are the potassium oxide and sodium oxide.

2.1.1.2 Types of portland cement

The NIS 444-1 (2003), makes provision for different types of portland cement as shown;

(a) CEM 1 (Portland cement)

Portland cement, which was originally referred to as ordinary portland cement (OPC) is by far, the most important type of cement. This cement is made up of 95% to 100% clinker and gypsum content and 0% to 5% minor additional constituents of calcareous material (NIS 444-1:2003). It is classified under three standard strengths namely; class 32.5, class 42.5, and class 52.5 depending upon the strength of the cement at 28 days. The higher classes develop strength at a faster rate than the class 32.5.

The manufacture of ordinary portland cement is decreasing all over the world in view of the popularity of blended cement on account of lower energy consumption, environmental pollution, economic, and other technical reasons (Shetty, 2006). It is important to note that OPC in bagged form can no longer be found in the Nigerian open market. Instead, they are made available to the consumers on special request (Adewole, Olutoge, & Habib, 2014).

(b) CEM 11

This cement family is made from portland cement, together with one major secondary constituent (Adewole et al., 2014). Examples of the secondary constituent that could be used are, blast furnace slag, silica fume, pozzolana, fly ash, burnt shale and limestone (NIS 444-1:2003). Seven types of cement are found in this family and they are; portland-limestone cement, portland-slag cement, portland-silica fume cement, portland-pozzolana cement, portland-flyash cement, portland-burnt shale cement and portland-composite cement.

(i) Portland-limestone cement

The two major divisions of this type of cement are the ordinary early strength comprising of CEM 11/A-L and CEM 11/B-L. The CEM 11/A-L has a clinker content of 80% to 94% and limestone content of 6% to 20%. While, the CEM 11/B-L has a clinker content of 65% to 79% and limestone content of 21% to 35% (NIS 444-1:2003). Many producers of cement in Nigeria manufacture ordinary early strength and high early strength of CEM 11/B-L and CEM 11/A-L of strength classes 32.5 and 42.5. However, the most popular products available in the market for construction works are the ordinary early strength of CEM 11/B-L with strength class of 32.5 and CEM 11/A-L with 42.5 strength class (Adewole et al., 2014).

(ii) Portland-slag cement

This comes in two forms, designated as CEM 11/A-S and CEM 11/B-S. CEM 11/A-S is made up of 80% to 94% clinker and 6% to 20% blast furnace slag. While CEM 11/B-S comprises of 65% to 79% clinker and 21% to 35% blast furnace slag (NIS 444-1:2003).

(iii)Portland-silica fume cement

This is designated as CEM 11/A-D. It is composed of 90% to 94% clinker content and 6% to 10% silica fume.

(iv) Portland-pozzolana cement

Portland-pozzolana cement according to the NIS 444-1 (2003) standard, comes in four types and they are; CEM 11/A-P, CEM 11/B-P, CEM 11/A-Q and CEM 11/B-Q. CEM 11/A-P comprises of 80% to 94% clinker content and 6% to 20% natural pozzolana. CEM 11/B-P is made up of 65% to 79% clinker and 21% to 35% natural pozzolana. The letter P stands for the use of a natural pozzolana. In addition, CEM 11/A-Q is made of 80% to 94% clinker content and 6% to 20% natural calcined pozzolana and CEM 11/B-Q consists of 65% to 79% clinker and 21% to 35% natural calcined pozzolana. The letter 'Q' stands for the use of a natural calcined pozzolana. This cement has greater resistance to chemical attacks when compared to Portland cement.

(v) Portland-flyash cement

This type of CEM 11 cement comes in four major types and they are; CEM 11/A-V, CEM 11/B-V, CEM 11/A-W and CEM 11/B-W. The first two are made up of flyash of siliceous origin, represented by the letter 'V'. While, the next two are made up of flyash of calcareous origin, represented by the letter 'W'. CEM 11/A-V is made of 80% to 94% clinker and 6% to 20% siliceous flyash. CEM 11/B-V has clinker content of 65% to 79% and siliceous flyash content of 21% to 35%. On the other hand, CEM 11/A-W and CEM 11/B-W have clinker contents of 80% to 94% and 65% to 79% respectively, and calcareous flyash contents of 6% to 20% and 21% to 35% respectively (NIS 444-1:2003).

(vi) Portland-burnt shale cement

This is of type CEM 11/A-T and CEM 11/B-T. They both have clinker contents of 80% to 94% and 65% to 79% respectively and burnt shale contents of 6% to 20% and 21% to 35% respectively (NIS 444-1:2003).

(vii) Portland composite cement

Portland composite cement is of type CEM 11/A-M and CEM 11/B-M. CEM 11/A-M is composed of 80% to 94% of clinker and 6% to 20% of the sum of two or more of the other main constituents stipulated by the NIS 444-1 (2003) standard. Whereas, CEM 11/B-M is made of 65% to 79% of clinker and 21% to 35% of the sum of two or more of the other main constituents. They have an economic advantage over portland cement, but may require longer curing days to attain and even exceed the 28th day strength of portland cement.

(c) CEM 111 (Blast-furnace cement)

The CEM 111 cement is of three types namely; CEM 111/A, CEM 111/B and CEM 111/C. The CEM 111/A consists of 35% to 64% clinker content and 36% to 65% blast furnace slag. Also, CEM 111/B is made of 20% to 34% clinker content and 66% to 80% blast furnace slag. Further, CEM 111/C is composed of 5% to 19% clinker content and 81% to 95% blast furnace slag (NIS 444-1:2003).

The CEM 111/C is a super sulphate cement with very high sulphate resistance and is recommended for use in foundation, where chemically aggressive conditions exist (Shetty, 2006). Generally, this cement has higher resistance to chemical attacks. Cement with higher content of blast furnace can be used as low heat cements in mass concrete works (Neville, 2006).

(d) CEM IV (Pozzolanic cement)

This is of type CEM IV/A and CEM IV/B. The first type has a clinker content of 65% to 89% and a silica fume, pozzolana or flyash content of 11% to 35%. CEM IV/B has 45% to 64% of clinker and a silica fume, pozzolana or flyash content of 36% to 55% (NIS 444-1:2003). Pozzolanic cement can be used for hydraulic structures, mass concrete structures like dams, bridge piers and thick foundation. They can also be used for marine structure, sewers and sewage disposal works (Shetty, 2006). They provide greater resistance to chemical attacks and are more economical when compared to portland cement.

(e) CEM V (Composite cement)

This comes as type CEM V/A and CEM V/B. CEM V/A has a clinker content of 40% to 64% and 18% to 30% of blast furnace, pozzolana, or siliceous flyash content. Whereas, CEM V/B has a clinker content of 20% to 38% and a blast furnace, pozzolana or siliceous flyash content of 31% to 50%.

The American Society for Testing Materials (ASTM) has designed five major types of portland cement, designated Type I – V. Physically and chemically, these cement types differ primarily in their content of C_3A and in their fineness. In terms of performance, they differ primarily in the rate of early hydration and in their ability to resist sulphate attack. The general characteristics of these types are listed in Table 2.3.

Table 2.3: General features of the main types of portland cement

	Classification	**Characteristics**	**Applications**
Type I	General purpose	Fairly high C_3S content for good early-strength development	General construction (most buildings, bridges, pavement, precast units, etc).
Type II	Moderate sulphate resistance	Low C_3A content (<8%)	Structure exposed to soil or water containing sulphate ions.
Type III	High early strength	Ground more finely,may have slightly more C_3S	Rapid construction and cold weather concreting.
Type IV	Low heat of hydration (slow reacting).	Low content of C_3S (<50%) and C_3A	Massive structures such as dams. Now rare.
Type V	High sulphate resistance	Very low C_3A content (<5%)	Structures exposed to high levels of sulphate ions.
White	White colour	No C_4AF, low MgO	Decorative (otherwise has properties similar to Type I)

Source: (ASTM Standards C 150, 1994, p.14)

2.1.1.3 Properties of cement compounds

The compounds of cement contribute to the properties of cement in the following different ways;

(i) Tricalcium silicate (C_3S)

It constitutes about 45% of the cement and it is a very important constituent from the consideration of strength giving property (Shetty, 2006).The C_3S hydrates and hardens rapidly and it is largely responsible for initial set and early strength. In general, the early strength of portland cement concrete, is higher with increased percentage of C_3S. A convenient approximation rule assumes that C_3S contributes most to the strength development during the first four weeks and C_2S influences the gain in strength from four weeks onwards (Gupta and Gupta, 2004). Cement with higher C_3S content is better for cold weather concreting.

(ii) Dicalcium silicate (C_2S)

It constitutes about 25% of the cement (Shetty, 2006), and it is very important to the strength gaining property of cement. The C_2S hydrates and hardens slowly and contributes largely to strength increase at ages beyond one week. At the end of one year, the two compounds (C_3S and C_2S), weight for weight, contributed approximately equally to the ultimate strength (Gupta and Gupta, 2004).

(iii) Tricalcium aluminate (C_3A)

It liberates a lot of heat during the early stage of hydration and hardening. The C_3A contributes to the strength of cement paste at one or three days, and possibly longer, but cause retrogression at an advanced stage particularly in cement with high C_3A (or $C_3A + C_4AF$) content (Neville, 2006). Cement with low C_3A is more resistant to soils and waters containing sulphates. The amount of tricalcium aluminate present may well be limited as in the case of sulphate resisting portland cement to prevent adverse reactions between the hydrate and sulphates from the environment which can result in swelling and cracking of the cement matrix.

The great advantage of C_3A is its ability to combine with chlorides, thereby removing them from the liquid phase of the cement. Chloride ion as known, is the major cause of corrosion of embedded steel. In general, C_3A in cement is considered undesirable. It contributes little or nothing to the strength of the cement, except at early ages, and when hardened, cement paste is attacked by sulphates. Expansion due to the formation of calcium sulphoaluminate from C_3A, may result in disruption of the hardened paste (Gupta and Gupta, 2004). However, C_3A acts as a flux and thus, reduces the temperature of burning of clinker and facilitates the combination of lime and silica. For this reason, C_3A is useful in manufacture of cement.

(iv) Tetracalcium aluminoferrite (C_4AF)

C_4AF is the product resulting from the use of iron and aluminum raw materials to reduce the clinkering temperature during cement manufacture (i.e. it is a fluxing agent). It hydrates rapidly, but does not contribute much to strength of the cement paste. Most colour effect that makes cement gray, are due to C_4AF and its hydrates.

(v) Potassium oxide (K_2O) and Sodium oxide (Na_2O)

These are minor oxides formed in the kiln during the manufacture of cement. These oxides react with water to form hydroxides that attack siliceous minerals in the aggregates of concrete, resulting to the formation of alkali silicate gels of unlimited swelling types (Shetty, 2006). This process results in the disruption of concrete with the spreading of pattern cracks and eventual failure of concrete structures.

The greater the alkali content in a cement paste, the lower the strength gain (Neville, 2006). Also early strength of cement paste can be abnormally low in the total absence of alkalis. Accelerated strength test, has shown that for up to 0.4% of Na_2O, strength increases with an increase in the alkali content (Neville, 2006).

2.1.2 Lime

Lime is a general term for calcium containing inorganic materials in which carbonates, oxides and hydroxides predominate. Strictly speaking, lime is calcium oxide or calcium hydroxide. It is also the name of the natural mineral (native lime), CaO which occurs in altered limestone xenoliths in volcanic ejecta (Anthony, Bideaux, Bladh, and Nichols, 2005). Lime is a generic term referring to the calcium oxide component of a material. When the term is so used, it should also be followed by another word, for instance, lime in terms of rock type is called limestone and lime in the concrete or mortar is called quicklime, lime putty and hydrated lime (Neville, 2006). The word lime originated with its earliest use as building material and has the sense of sticky or adhering ("Etymology Dictionary", 2013).There are two forms of lime namely; the quicklime and the hydrated lime. The quicklime is produced by heating rock or stone containing calcium carbonates (such as limestone, marble, chalk, shells etc.) to a temperature of around $800^0C-1000^oC$ for several hours in a process known as calcining or sometimes simply 'burning' (Parry, 2013). At this temperature, CO_2 is driven off and calcium carbonate changes to calcium oxide (quick lime). Lime can be used in different forms, which all originate from quick lime.

2.1.2.1 Types of Lime

(a) Quicklime (CaO)

This is an unstable and slightly hazardous product, and therefore, is normally 'hydrated' or 'slaked' by adding water (Pablo, 2013). Its CaO content is always greater than 93% by weight, with the remaining being magnesium oxide (MgO) and very little clay (not > 5%). It is an amorphous white material, which is highly caustic in character. It has a very high affinity for water and carbon dioxide. It is also called fat lime, rich lime or pure lime.

(b) Hydrated lime $Ca(OH)_2$

Hydrated lime is calcium hydroxide in powdered form, produced by the heating of lime stone. It is an inorganic compound with the chemical formula, $Ca(OH)_2$. It is a colourless crystal or white powder, and is obtained from the slaking of quick lime. Yate and Ferguson (2008) defined hydrated lime as lime produced by burning argillaceous or siliceous limestone and reducing them to powder by slaking with water (with or without grinding). It can also be defined as a dry powder manufactured by treating quicklime (CaO) with sufficient water to satisfy its chemical affinity for water, thereby converting the oxides to hydroxides ("National Lime Association Fact Sheet", 2014).Other names for this type of lime are slaked lime, builder lime, and pickling lime.

All natural hydraulic lime, have the property of setting and hardening under water. Slaking of this lime, makes it more stable, easier and safe to handle. To produce dry powdered hydrated lime, just enough water is added for the quicklime lumps to breakdown to a fine powder (Pablo, 2013). This material will have a 'shelf life' of only a number of weeks, depending on the storage conditions. Old hydrated lime would have partially carbonated and become a less effective binder. There are four types of hydrated lime according to ASTM C207 (2006). They are type-S, type-SA, type-N, and type-NA. The hydrated lime is the type of lime used in the construction industry and is studied in this research worked.

(c) Lime putty

When quicklime is hydrated with a large excess of water and adequately agitation, it forms a milky suspension known as "milk of lime". Allowing the solids to settle and drawing off the excess water, yields a paste-like residue, termed 'lime putty'. This is the form of lime that can be used in building applications to obtain best effect. It can be kept almost indefinitely and improves with age (Pablo, 2013). This form of lime is more rarely produced. In the construction industry, lime in its hydrated or putty form, is mixed with aggregate and water to produce concrete or mortar in the usual manner. Atmospheric carbon dioxide contributes to the hardening process. Lime putties generally produce mortars or renders of excellent quality and consistency.

(d) Limestone

Limestone is a sedimentary rock composed largely of the minerals, calcite and aragonite, which are different crystal forms of calcium carbonate ($CaCO_3$). They make up about 10% of the total volume of all sedimentary rocks ("Encarta", 2009). They are used as building materials, as aggregates for the base of roads, as white pigment or filler in products such as toothpaste or paints, and as a chemical feedstock.

Limestone has been used in concrete production for the last 30years, not only for the main purpose of lowering the costs and environmental impact of cement production, but also to increase the concrete durability (Ahmed et al., 2009). More recently, limestone is also used as a filler material to improve the workability and stability of fresh concrete and for a high flowable concrete, such as self-compacting concrete. This makes it necessary to investigate the properties of lime cement concrete. The knowledge of the properties of lime cement concrete will be useful in the design, production and application.

2.1.2.2 Properties of hydrated lime

(a) Physical properties

The Table 2.4 shows the physical properties of hydrated lime as given by the "Cement Australia Safety Data Sheet" (2014).

Table 2.4: Physical properties of hydrated lime

S/NO	PROPERTY	FEATURES
1.	Appearance	White or off white fine powder.
2.	Odour	Slightly earthy odour or odourless
3.	Boiling/Melting Point	Decomposes to water and calcium oxide at 580^0C
4.	Specific Gravity	2.4 - 2.5
5.	Bulk Density	450 – 800Kg/m^3
6.	Solubility in water	Approx. 1.6g/L @ 20^0C
7.	pH	Approx. 12
8.	Particle size	9% < 100µm
9.	Flammability Limits	Non-combustible
10.	Vapour Pressure	Not applicable

Source : ("Cement Australia Safety Data Sheet", 2014, p.3).

(b) Chemical properties

Hydrated lime is an alkaline material that reacts vigorously with acids, generating some heat. It may absorb carbon dioxide from the atmosphere and form calcium carbonate. It is soluble in glycerol, aqueous solution of sucrose, and ammonium chloride ("Cement Australia Safety Data Sheet", 2014).

Table 2.5: Chemical composition of hydrated lime

S/NO	Chemical compound	% Composition
1.	Calcium Hydroxide	90% - 95%
2.	Magnesium Hydroxide	0.5% - 1.0%
3.	Crystalline Silica (Quartz)	< 1.0%
4.	Silicon Dioxide	0.5% - 2%
5.	Aluminum Dioxide	0 - 2%
6.	Iron Oxide	0 - 0.4%

Source: ("Cement Australia Safety Data Sheet",2014, p.2).

2.1.2.3 Comparison of the chemical properties of portland cement and hydrated lime

The Table 2.6 show a comparison of the chemical properties of a typical portland cement to that of a typical hydrated lime.

Table 2.6: Chemical properties of portland cement vs. hydrated lime

S/NO	Chemical compound	Portland cement (% composition)	Hydrated lime (% composition)
1	Calcium oxide (CaO)	60% – 67%	-
2	Calcium hydroxide $Ca(OH)_2$	-	90% - 95%
3	Silicon dioxide (SiO_2)	17% - 25%	0.5% - 2%
4	Aluminium oxide (Al_2O_3)	3% - 8%	0 - 2%
5	Iron oxide (Fe_2O_3)	0.5% - 6%	0 - 0.4%
6	Sulphates (SO_3)	2% - 3.5%	-
7	Alkalis (sodium oxides (Na_2O) and potassium oxides (K_2O)).	0.3% - 1.2%	-
8	Magnesium Hydroxide $Mg(OH)_2$	-	0.5% - 1.0%
9	Crystalline Silica (Quartz)	-	< 1.0%

Source: ("Cement Australia Safety Data Sheet", 2014, p.2;"Civil Engg. Dictionary", 2015a, p.2)

It can be seen that the cement and hydrated lime, comprise of calcium oxides in hydrated or unhydrated forms and silicon oxides that are required for any material to have cementing properties.

2.1.2.4 Lime Cycle

Slaked lime (i.e. calcium hydroxide) is mixed into thick slurry with sand and water to form various kinds of mortar and render for building purposes. Lime mortar was traditionally used in the joints between bricks or stones in masonry building construction. Now cement is usually added to the mixture to form a harder mortar (John, 2011). When the masonry has been laid, the slaked lime in the mortar, slowly begins to react with carbon dioxide to form calcium carbonates (limestone) according to the reaction:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O. \quad (2.1)$$

The carbon dioxide that takes part in this reaction, is principally available in dissolved form found in rainwater, rather than in gaseous form. This process by which limestone is converted to quicklime by heating, then to slaked lime by hydration, and reverted to limestone by carbonation is known as the Lime Cycle (John, 2011).

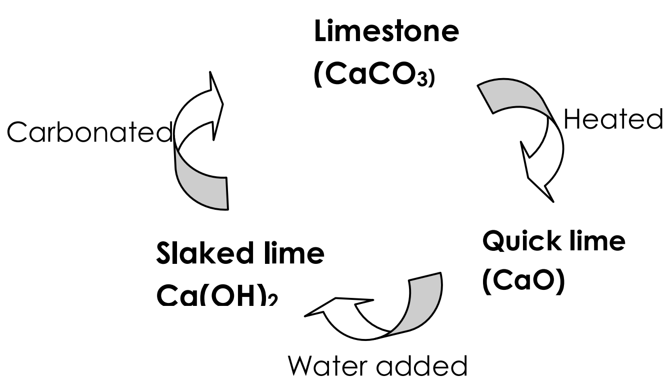

Fig 2.1: Lime Cycle

2.1.2.5 Uses of lime in the construction industry

Different forms of lime find variety of applications. Hydrated lime has proved to be an important admixture in the construction industry. Lime can be used both in mortar and concrete for a number of useful purposes.

(i) Some researchers stated that bond strength can be increased by using hydrated lime (Rizwan, Toor and Ahmad, 2004).

(ii)It imparts ease of retempering, high water retentivity, and resistance against efflorescence in concrete.

(iii)Lime allows buildings to breathe because they are vapour permeable. This reduces the risk of trapped moisture and consequent damage to the building fabric.

(iv)Lime has high sand carrying capacity, and is more flexible under stress. It can accommodate stresses caused by building movement and cyclic changes without excessive cracking.

(v)It results in the autogenous healing of mortar. When hairline cracks develop in a mortar, the hydrated lime reacts with carbon dioxide in the atmosphere. This reaction produces limestone which seals the crack (Holmes, 2002).

(vi)Hydrated lime in concrete is basically used to reduce the permeability of concrete by filling the pores in concrete.

(vii)It improves cohesion and achieves economy through cement replacement.

(viii)Lighter and colored mortars, can be made by using hydrated lime along with a suitable pigment (Rizwan et al., 2004).

(ix)It can be used in hot weather concreting (Rizwan et al., 2004).

(x)Lime has an adhesive property with bricks and stones. So, it can be used as binding material in masonry works (Holmes, 2002).

(xi)It provides a comfortable environment by stabilizing the internal humidity of a building. This is achieved by absorbing and releasing moisture (Holmes, 2002).

(xii)Lime mortar with high free lime content is porous and permeable. Lime mortar can protect adjacent materials like wood, iron, stone and bricks in a building, by handling moisture movement through the building fabric and protecting them from harmful salts (Holmes, 2002).

2.1.2.6 Calcination temperature of limestone

Calcination is the process of heating a substance to a high temperature, but below its melting point so as to bring about thermal decomposition or a phase transition in its physical or chemical constitution (Kamalu and Osoka, 2010). It is a vital process in the production of cement. The term "calcination of lime" refers to the process of thermal decomposition of calcium carbonate into quick lime and carbon dioxide (Kumar, Ramakrishnan, and Hung, 2007).Claiming of calcium carbonate, is a highly endothermic reaction, requiring 3.16GJ of heat input to produce a ton of lime (CaO). The reaction only begins when the temperature, is above the dissociation temperature of the carbonates in the limestone or lime mud. This is typically between 780^0C and 1340^0C (Wicky and Walmsley, 2006).

Kilc and Anil (2006), in their work titled "Effects of limestone characteristic properties and calcination temperature on lime quality", discovered that high calcination temperatures in limekilns, are the major reason for the production of low quality lime. They also proposed a lime calcination temperature of 1000^0C as the optimum. However, Valek, et al. (2014), also recommended an optimum calcining temperature of the range 1000^0C-1100^0C. They discovered that the higher calcining temperature, resulted to lower reactivity and slaking of residue. In general, they concluded that calcination temperatures between the values of 850^0C to 1200^0C, can be used to produce hydraulic lime from a selected raw material.

2.1.2.7 Occurrence of limestone in Nigeria

Limestone occurs only in the sedimentary basins in Nigeria. It can be found mainly in the Benue Trough (lower, middle and upper), Sokoto, Dahomey and Borno (Chad) basins (Fatoye and Gideon, 2013). Limestone-forming environments (i.e. shallow coastal marine condition), appear to have occurred several times in the geological history of the basins. However, the limestone deposits of the Benue trough, appear to contain the largest and most economically viable limestone resources in the country.

Extensive deposits of limestone exist throughout the country. They provide the necessary raw material for the country's cement industry. A few of them are currently being exploited. Most of the limestone deposits are high in quality, containing over 80% calcium carbonates (Fatoye and Gideon, 2013). The Table 2.7 shows the location of limestone deposits in Nigeria.

Table 2.7: Locations of limestone deposits in Nigeria

STATE	LOCATION	ESTIMATED RESERVE (MILLION TONNES)
Ogun	Ewekoro Shagamu Ibeshe	35 10 -
Cross River	Mfamosing Odukpani, Obubra, Ugep,Ikot Ana, Ago, Ibami	30 - -
Benue	Yandev Igumale Ogbologuta Adiga, Tokura	70 110 10.16 -
Ebonyi	Nkalagu Afikpo, Ntezi, Ikwo	174 -
Enugu	Nkanu Odomoke Ngbo	110 54 2
Sokoto	Kalambaina Dange, Shuni, Wamakko	101.6 -
Gombe	Ashaka	-
Bauchi	Pindiga, Kanawa, Deda-Habe	-
Edo	Akoko-Edo Owan, Estako	10 -
Imo	Umu-Obon Okigwe	101 -
Abia	Ohafia, Arochukwu	-
Nassarawa	Awe	-

Source: (Fatoye and Gideon, 2013, p.63).

From the Table 2.7, it can be seen that Nigeria has great deposits of limestone in various parts of the country. These deposits are capable of meeting the raw material demand for the mass production of hydrated lime as partial replacement for cement in the construction industry. For further illustration, a geological map showing limestone and marble deposits in Nigeria is presented in Plate 2.1. Hydrated lime used for this study was sourced from a local producer at Nkalagu in Ebonyi State.

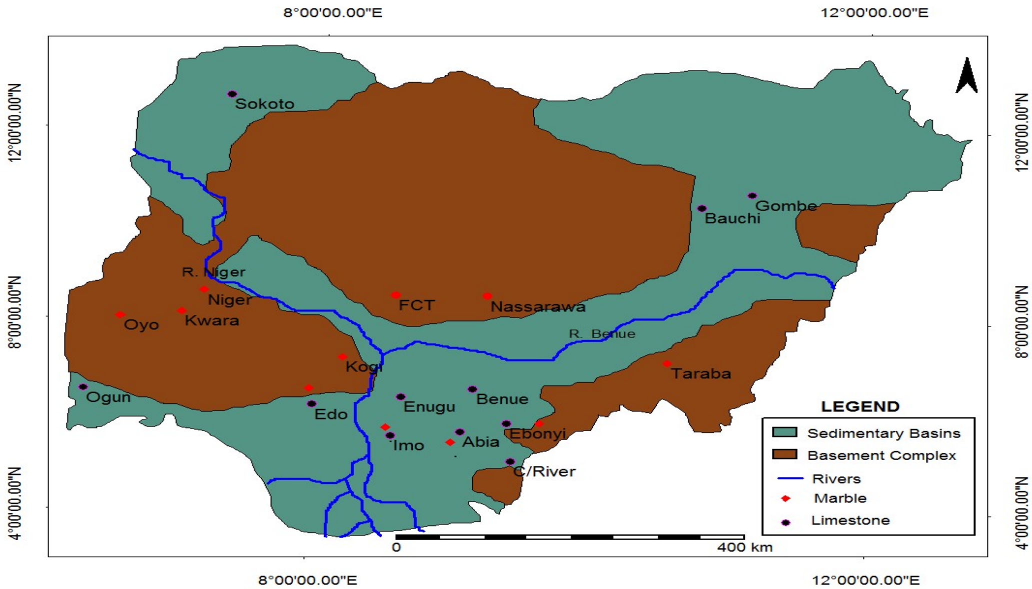

Plate 2.1: Geological map showing limestone and marble occurrences in Nigeria.
Source: (Fatoye and Gideon , 2013, p.2).

2.1.3. Other cementing materials - Pozzolans

Pozzolana also known as pozzolanic ash (pulvis puteolanus in Latin), is a siliceous and aluminous material, which reacts with calcium hydroxides in the presence of water at room temperature (Parry, 2013). In this reaction, insoluble calcium silicate hydrates and calcium aluminate hydrates compounds, which possess cementitious properties, are formed. The designation pozzolana, is derived from one of the primary deposits of volcanic ash used by the Romans in Italy, at Pozzuoli (Shetty, 2006). Nowadays, the definition of pozzolana encompasses any volcanic glass that is used as a pozzolan. Note its difference with the term pozzolan, which exerts no bearing on the specific origin of the material, as opposed to pozzolana, which can only be used for pozzolans of volcanic origin, primarily composed of volcanic glass.

A pozzolan is a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value, but which will in finely divided form and in the presence of water, react chemically with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties (ASTM C618, 2015). The general definition of a pozzolan embraces a large number of materials, which vary widely in terms of origin, composition and properties. Both natural and artificial (man-made) materials, show pozzolanic activity and are used as supplementary cementitious materials. Artificial pozzolans can be produced deliberately, for instance by thermal activation of kaolin-clay to obtain metakaolin, or can be obtained as waste or by-products from high temperature process, such as fly ash, silica fume from silicon smelting, highly reactive metakaolin, and burned organic matter residues rich in silica such as rice husk ash (Parry, 2013).

Scientists have proven that the ancient Greeks began to use natural pozzolan-lime mixture to build water-storage tanks sometimes between 700BC and 600BC (Wilson and Ding, 2007). This technique was then passed on to the Romans about 150BC. According to the Roman engineer Vitruvius Pollio who lived in the first century BC; "The cement made by the Greeks and the Romans were of superior durability, because neither waves could break, nor water dissolve the concrete" (Wilson and Ding, 2007). Many great ancient structures, such as the Colosseum, the Pantheon, the Bath of Caracalla, as well as other structures that are still standing in Italy, Greece, France, Spain and the islands in the Mediterranean Sea, were built with natural pozzolan-lime mixtures. Many of them have lasted more than two thousand years (Wilson and Ding, 2007). After the invention of portland cement, natural pozzolan was used as a concrete strengthening additive to improve characteristics, such as durability, compressive strength, chemical resistance, hydration heat, permeability, etc. In European and the USA, there have been numerous high rise buildings, highways, dams, bridges, harbours, canals, aqueducts and sewer systems built with natural pozzolan-cement mixture. Due to the limited supply of high quality natural pozzolan, in the last 30 years or so, the USA, Europe and other countries have resorted to the use of more readily available, but poorer quality, waste materials such as fly ash that can be used as a substitute for natural pozzolan (Wilson and Ding, 2007).Nowadays, a wide variety of siliceous or aluminous materials, are used for producing pozzolans, the common materials being calcined clays, pulverized fly ash, volcanic ash and ash from agricultural by-products (Parry, 2013).

There are five major sources of pozzolan. Naturally occurring deposit, which is an ash like product of volcanic activity (volcanic ash), occurs when silica rich magma meets with large quantities of underground water in volcanic conduits. Under high temperature and pressure, the steam reacts with dissolved carbon dioxide and sulfur gases and is emitted during a volcanic eruption. It is found in Europe and the Middle East, among other regions (Shetty, 2006). This type of pozzolan is very suitable for use in concrete in wet conditions. Pozzolans also can be derived from fired and crushed clay, such as bricks, and this variety is more durable than the volcanic pozzolan. Furnace slag e.g. the ground granulated blast furnace slag (ggbs) and condensed silica fumes from industrial processes, such as in the manufacturing of steel and silicon metal respectively, can also take the form of a pozzolan, and this type is currently used as concrete admixtures. Another type is organic ash, produced by burning coal or lime, but it is weaker than the other varieties and is generally not suitable for brick and mortar construction. High calcium fly ash is the residue collected from the smokestacks of coal-fired power plants generally using lignite and /or sub bituminous coals. This class C fly ash, is in itself mildly cementitious, and have been combined with lime or even calcium carbonate soils to produce moderately strong concrete. Finally, some pozzolans have been produced by crushing rock and sand, and these have been used in mortars throughout history, but are not commonly used today .

Pozzolans by their diverse and varied nature, tend to have widely varying characteristics. The chemical composition of pozzolans, varies considerably depending on the source and the preparation technique (Parry, 2013). Generally, a pozzolan will contains silica, alumina, iron oxide and a variety of oxides and alkalis, each in varying degrees. This presents problems for small scale manufacturers wishing to use pozzolans in a lime or ordinary portland cement (OPC) pozzolana mix. Where there are no laboratory facilities, available for testing the raw materials, then it is difficult to maintain standards and produce a consistent product. It is also generally agreed that although, the chemical content of a raw material will determine whether or not it is pozzolanic and will react when mixed with lime or OPC, the degree of reaction and subsequent strength of the hydrated mixture, cannot be accurately deduced from just the chemical composition (except for a small number of known pozzolans). In most cases, there are no direct correlation between the chemical content and reactivity. Other characteristics such as fineness and crystalline structure, affect its reactivity (Parry, 2013).

Most pozzolans are plentiful and because current uses for them are limited, they represent a potential source of inexpensive construction material. Some pozzolans can be processed into a material with characteristics similar to portland cement, and so it is feasible that a significant portion of cement in a concrete mixture may be replaced by pozzolans (Ghassan, Mouin, Yaksic, and Kallemeyn, 2011).

2.1.3.1 Advantages of pozzolan in the building industry

The modern use of pozzolan as a cement replacing or enhancing admixture in concrete, began many decades ago, and it’s not new in the construction industry. However, a trend in the past decade towards greater usage, is now redefining acceptable practice. Often restricted by building code to small fractions of the cementitious material in a concrete mix, pozzolans have held a relatively minor role in the concrete industry, especially in the USA and North America (Wilson and Ding, 2007). Three trends are now active that are changing that minor role and they are as follows;

(a) Economy

Portland cement, the primary “glue” for structural concrete, is expensive and unaffordable for a large portion of the world’s population. Some pozzolans for various reasons are also expensive, but the most abundant and widely available fly ash, is not, and typically cost about half as much by weight of cement. Blended cement that replace up to 60% of the portland cement with fly ash, are successfully used in structural applications. Since portland cement, is typically the most expensive constituent of concrete, it implies that there will be greatly improved concrete affordability (Wilson and Ding, 2007).

(b) Durability

A wide variety of environmental circumstances such as reactive aggregates, high sulfate soils, freeze-thaw conditions, exposure to salt water, deicing chemicals and acids are deleterious to concrete. Typically, these problems have been partially overcome by utilizing special cements, increasing strength, and /or minimizing water-cement ratios (Neville, 2006). Various research bodies and field experience, are showing that the careful use of pozzolans is useful in countering all of these problems (and others). Pozzolans are not just filler as many engineers think, but are strength and performance improving additives (Wilson and Ding, 2007). In general terms, the siliceous pozzolans react with the (non-cementitious) calcium hydroxide in hydrated cement paste, to produce (highly cementitious) calcium silicate hydrates that yield higher strength and dramatically reduced permeability (Parry, 2013).

(c) Environment

Portland cement requires a significant amount of heat in its manufacture, making it expensive not just to the consumer, but to the atmosphere as well. The production of cement is responsible for more than 8% of all the greenhouse gases released by human activities (Wilson and Ding, 2007). The high volume use of fly ash, are not just an effective use of "waste" material and an economic savings, but makes possible, a noticeable reduction in greenhouse gas build up. Usage of blended cement is also a way for the cement industry to supply the ever growing world market without having to build new production facilities.

2.2 Aggregates

Aggregates are filler materials that make up between 70% - 80% of the volume of normal concrete (Shetty, 2006).Since they constitute about ¾ of the concrete volume, or more, their properties largely determine the properties of the concrete. For the concrete to be of good quality, the aggregate has to be strong and durable and free of silts, organic matter, oils, and sugars. Otherwise, it should be washed prior to use, because any of these impurities may slow or prevent the cement from hydrating or reduce the bond between the cement paste and the aggregate particles (Neville, 2006). The physical and chemical properties of the aggregate also affect concrete properties. Aggregate size, shape, and grade influence the amount of water required. Aggregate surface texture influences the bond between the aggregate and the cement paste (Neville, 2006). In properly mixed concrete, the paste completely surrounds each aggregate particle and fills all spaces between the particles. The elastic properties of the aggregate influence the elastic properties of the concrete and the pastes resistance to shrinkage. Reactions between the cement paste and the aggregate can either improve or harm the bond between the two and, consequently, the quality of the concrete.

Aggregate is cheaper than cement and thus, it is cheaper to use as much quantity of aggregate and as little of cement as possible. But economy alone is not the only reason for using aggregate in concrete. Aggregate provide better strength, stability and durability to the structure made out of the concrete than cement paste alone (Gupta and Gupta, 2004).

2.2.1 Classification of aggregates according to size.

According to their sizes, aggregates are generally divided into two major types namely;

(i) Coarse aggregate

(ii) Fine aggregate

(i) Coarse aggregate

Coarse aggregate is defined as the aggregate, most of which is retained on the 4.75mm British Standard sieves (Neville, 2006).The most commonly used maximum aggregate size is 20mm.This aggregate play a major role, in giving shape and form to any concrete element cast, and contribute greatly to the overall performance of the element in service. A thorough study of aggregate and their sources is of great importance, since this factor influence their strength and properties, which also affect concrete strength and properties.

(ii) Fine aggregate

These are aggregates passing No.4 (4.75mm) sieve, and predominately retained on the No. 200 (75µm) sieve (Neville, 2006). They have a major function in the concrete, which is to serve as filler material. They help to fill up the spaces left open by the interlocking of the coarse aggregates, and are naturally occurring or manufactured construction materials for the production of concrete.

2.2.2 Classification of aggregates based on bulk density

The mass of aggregate that would fill a container of unit volume, is known as the bulk density of the aggregate (Neville, 2006). The volume referred to, is that occupied by both aggregates and the voids between aggregate. The bulk density clearly depends on how densely the aggregate is packed. This factor is determined by the size distribution and shape of particles. Particles having same size can be packed to a limited extent, but smaller particles can be added in the void between the large ones. This help to increase the bulk density of the packed material. The shape of the particles greatly affect the closeness of packing that can be achieved. For a coarse aggregate, a higher bulk density means that there are fewer voids to be filled by the fine aggregate and cement (Neville, 2006). Based on bulk density, aggregates are classified into normal weight, light weight, and heavy weight.

(i) Normal weight aggregate.

These are aggregates that are used to produce normal weight concrete. According to Naik (1997), the weight of normal weight concrete ranges from 1520kg/m^3 to 1680kg/m^3. Kosmatka, Kerkhoff, and Panarese (2003), stated that the approximate bulk density of aggregate commonly used in normal concrete ranges from 1200kg/m^3 to 1750kg/m^3. Some examples of normal weight aggregates are granite, gravel, limestone, goethite, magnetite, and hematite.

(ii) Light weight aggregate.

These are aggregates used for making insulating light weight concrete. They are either natural or synthetic in nature, and weigh less than 1100 kg/m^3 (ASTM C330, 2014). The lightweight nature, is due to the cellular or high internal porous microstructure, which gives this type of aggregate a low bulk specific gravity. The most important aspect of lightweight aggregate is the porosity. They have high absorption values, which require a modified approach to concrete proportioning. For instance, slump loss in lightweight concrete due to absorption can be an acute problem, which can be alleviated by pre-wetting (but not saturating) the aggregate before batching. Some examples of light weight aggregates used in structural concrete include; expanded clay, shale, slate, foamed slag, sintered fly-ash, vermiculate, pumice, diatomite, scoria, saw dust, and rice husk (Gupta and Gupta, 2004).

(iii) Heavy weight aggregate.

The heavy aggregates are made of aggregates, that are either natural or synthetic in nature, and weigh more than 2080kg/mm^3 (ASTM C637, 2014). They are used in radiation shielding, counterweights and other applications where a high mass-to-volume ratio is desired. Some examples are; limonites, hematite, barite, magnetite, and steel.

In order to produce a durable concrete, the porosity of the aggregate must be kept low, thereby making the concrete dense. The higher the bulk density of aggregate, the more durable the concrete will be.

Aggregates used for this study were observed to be normal weight in nature as shown in Table 4.3 and Table 4.4.

2.2.3 Sieve analysis of aggregates

A sieve analysis is a simple operation of dividing a sample of aggregate into fractions, each consisting of particles of the same size. This procedure helps to reveal the size make up of aggregate particles from the largest to the smallest (Neville, 2006). A graduation curve showing how evenly or unevenly the sizes are distributed is created in the test. How an aggregate is graded has a major impact on the properties and performance of concrete. For example, in Portland cement concrete, graduation influences shrinkage and shrinkage cracking, pumpability, finishability, permeability and other characteristics. The results of a sieve analysis are often plotted on graph with sieve sizes on the horizontal axis, and percentage of fine and coarse passing aggregates on the vertical axis. Size, range, and graduation can be identified on the graph.

The shape of the grain distribution curve indicates the type of soil (ASTM D 2487, 2011). The distribution graph which shows the percentage passing (%) against sieve size (mm) is analyzed based on the two important numerical measure which are coefficient of uniformity (C_u) and Coefficient of curvature (C_c)

Coefficient of uniformity (Cu) = $\frac{D_{60}}{D_{10}}$ (2.2)

where,

D_{10} = The effective particle size with 10% of the sample by weight smaller than its size.

D_{60} = The effective particle size with 60% of the sample by weight smaller than that size

Coefficient of curvature (Cc) = $\frac{(D_{30})^2}{D_{10} X D_{60}}$ (2.3)

where,

D_{30}= The effective particle size with 30% of the sample by weight smaller than that size.

According to the unified soil classification system (ASTM D-2487, 2011), for gravel to be well graded, it must satisfy the following conditions: Cu > 4 and 1 < Cc < 3. If both of these conditions are not met, the gravel is classified as poorly graded. Also, for sand to be classified as well graded, the following condition must be satisfied; Cu ≥ 6 and 1 < Cc < 3. If both criteria are satisfied, sand is classified as well graded, if not, it is poorly graded.

According to IS 383 (1970), fine aggregates can be grouped under four grading zones namely; grading zone I, grading zone II, grading zone III, and grading zone IV, as shown in Table 2.8. The percentage passing 600microns sieve, determine the zone of the fine aggregate. Zone I is a coarse sand, while zone IV is a fine sand.

Table 2.8: Grading zones for fine aggregates.

IS SIEVE	Grading zone I	Grading zone II	Grading zone III	Grading zone IV
10mm	100	100	100	95-100
4.75mm	90-100	90-100	90-100	95-100
2.36mm	60-95	75-100	85-100	95-100
1.18mm	30.70	55-90	75-100	90-100
600microns	15-34	35-59	60-79	80-100
300 microns	5-20	8-30	12-40	15-50
150 microns	0-10	0-10	0-10	0-15
Fineness modulus	4.0 - 2.71	3.37 - 2.10	2.78 - 1.71	2.25 - 1.35

Source: (IS 383,1970, p.11).

Fine aggregate complying with the requirements of any grading zone in Table 2.8 is suitable for concrete, but the quality of concrete produced, will depend upon a number of other factors including the proportions. When concrete of high quality strength and good durability is required, fine aggregate conforming to anyone of the four grading zone may be used. Fine aggregate grading becomes progressively finer as it moves from grading zone I to IV (IS 383, 1970). Therefore, the ratio of the fine aggregate to the coarse aggregate, should be progressively reduced.

Generally, it is recommended that fine aggregate conforming to grading zone IV, should not be used in reinforced concrete, unless tests have been made to ascertain the suitability of the proposed mix proportion.

2.2.3.1 Fineness modulus of aggregates

The result of the sieve analysis is expressed by a number called fineness modulus. It is only a numerical index of fineness, and it gives some ideas of the mean size of particles in the entire body of the aggregates (Gupta and Gupta, 2004). It is obtained by adding the sum of the cumulative percentages by mass of sample aggregates retained on each of a specified series of sieves, and dividing the sum by 100. The specified sieves are 150µm, 300µm, 600µm, 1.18mm, 2.36mm, 4.75mm, and up to the largest sieve size to be used.

The coarser the aggregate, the higher the value of fineness modulus. Fineness modulus less than one, should not be used since it result to an uneconomic mix, while higher values of fineness modulus, results to a harsher mix (Gupta and Gupta, 2004). The fineness modulus of the fine aggregate is required for mix design, since sand gradation has the largest effect on workability. A fine sand with low fineness modulus, will have a higher effect on the paste requirement, for good workability. The fineness modulus for coarse aggregate, is usually not required for mix design purpose. Fineness modulus for each grade zone of aggregate, is shown on Table 2.8.

2.3 Concrete

Concrete is a construction material composed of cement, aggregate (coarse and fine), water and sometimes, chemical additives. The word concrete comes from a Latin word ‘CONCTETUS’ which means hardened or hard. Concrete is used to make pavements, bridges, fences, foundations, electric poles etc. There are many types of concrete available and these different types are created by varying the properties of the main ingredients of the components of concrete.

2.3.1 Types of concrete

There are four types of concrete discussed in the following sub sections. These are cement concrete, lime concrete, lime-cement concrete, and laterized concrete.

2.3.1.1 Cement concrete

This concrete is made by combining coarse aggregates (granite), fine aggregates (sand), Portland cement, and water. The water hydrates the cement to form a gel that holds the aggregates together. This concrete can be modified in a number of ways, by the addition of cementitious materials other than portland cement, or by the use of admixtures, which are materials that are added to the mixture to enhance the properties of the fresh or hardened concrete (Shetty, 2006).Cement concrete normally falls in the category of normal concrete type with density between 2240kg/m^3 - 2400kg/m^3.Generally, it has a setting time of 30minutes – 90minutes, depending on the moisture in the atmosphere, and fineness of the cement. The development of strength starts after 7 days and the common strength values is 10MPa to 40MPa. At about 28 days, 75% - 80% of the total strength is achieved, and at 90 days, ninety five percent (95%) of its strength is achieved ("Grand Solution Manual", 2015).

A lot of research work has been carried out on the properties of cement concrete. Onwuka and Awodiji (2013) studied the flexural strength (modulus of rupture) of cement concrete. In their work, they developed an artificial neural network model that can be used for the prediction of the modulus of rupture of cement concrete given the mix ratios, and vice versa. The minimum error achieved was below four percent (4%) and the maximum correlation coefficient was close to 1. Abdullahi (2012) investigated the effect of aggregate type on the compressive strength of cement concrete. He utilized three types of aggregate to produce normal concrete. These were quartzite, river gravel, and crushed granite. He reported that concrete made from quartzite aggregates, had the highest compressive strength at all ages. This was followed by the concrete made from river gravel and then, those from the crushed granite. He also reported that concrete made from river gravel had the highest workability, which was followed by those from quartzite aggregate, and lastly by concrete made from crushed granite. Suvash and Gideon (2013) studied the mechanical and durability properties of recycled concrete aggregates (RCA) used for normal strength structural concrete. They reported that RCA replacement of thirty percent (30%) of natural aggregate, did not lead to any significant difference in strength and, stiffness of the concrete, when compared to concrete containing hundred percent (100%) natural aggregate. However, increased creep was observed. They also reported that a hundred percent (100%) RCA replacement, did not show reduced strength and stiffness when compared to hundred percent (100%) natural aggregate.

2.3.1.2 Lime concrete

Lime concrete is a concrete made from a mixture of lime, sand, gravel and water ("Civil Engg.Dictionary", 2015b). It was largely used for construction purposes, before it was replaced by portland cement. The main ingredient for this type of concrete is slaked lime, which acts as the binding material. Lime has been used in concrete making since Roman times, either as mass foundation concrete, or as light weight concrete, using a variety of aggregates, combined with a wide range of pozzolan, that help to achieve increased strength and speed of set. Lime concrete was used in the construction of many ancient structures. German archaeologist, Heinrich Schliemann, found concrete floors, which were made of lime, and pebbles in the royal palace of Tirynes in Greece (Hewlett, 2003).This concrete dated roughly to 1400 to 1200BC. Lime mortar was used in Greece, Crete, and Cyrus in 800BC. The Romans used concrete extensively from 300BC to 476AD, a span of more than seven hundred (700) years. During the Roman Empire, Roman concrete was made from quicklime, pozzolans, and aggregates of pumice. Its wide spread use in many Roman structures, freed the Roman construction from the restriction of stones, and brick materials, and allowed for revolutionary new design, in terms of structural complexity, and dimension (Lynne, 2005).

Properly prepared, compacted, and laid lime concrete, is durable under normal exposure. It possesses considerable resistance to sulphate attack, and can be used in foundation, and areas in which soil contains considerable quantities of soluble sulphate, or where subsoil water table is high (IS 2541, 1991). This is so because lime concrete exhibits certain degree of water proofing property, preventing subsoil dampness in floors, and walls. It provides good bases to bear loads, and certain degree of flexibility ("Civil Engg. Dictionary", 2015b). Lime concrete exhibit volumetric stability, and the effect of temperature fluctuations on the volume change, is negligible. Over the years, there is a renewed interest in the use of lime concrete, due to its environmental and potential health benefits, when used with other lime products. Lime mortar enables other natural and sustainable products, such as wood, hemp, and straws to be used effectively in construction, because of its ability to control moisture. It allows building components like woods, and bricks to be re-used and recycled, because they can be easily cleaned off the mortar (Holmes, 2002). Lime plaster is not toxic; therefore, it does not contribute to air pollution, unlike some modern paints (Holmes, 2002).

Some of its drawbacks are that it requires longer time to gain strength than the cement concrete, since it takes a longer time to cure. Lime concrete does not harden under water, but stays soft, so that there are situations where it can-not be used. They cause rashes on human skin, such that persons dealing with lime, should be provided with suitable rubber gloves ("Civil Engg. Dictionary", 2015b). For better quality of lime, it is important to compact, and cure lime concrete properly.

Cachim, Moraise, Coroado, Lopes and Velosa (2012) investigated the fire behavior of lime concrete. Hydraulic lime was replaced by metakaolin in different percentage. Fire test at different temperature of 200^0C, 400^0C, 600^0C, and 830^0C, and different durations of 30mins and 60mins were performed. They reported that a 20% replacement of hydraulic lime by metakaolin, leads to an improved performance at room temperature, and fire loading.

2.3.1.3 Lime-cement concrete

Lime-cement concrete in the context of this study, can be defined as a mixture of cement, hydrated lime, fine aggregate (river sand), coarse aggregate (granite chippings), and water. In the beginning of the 20^{th} century, there was high usage of hydrated lime as an admixture in poured concrete (Mira et al., 2002). The principal advantages for this admixture were improved water tightness and impermeability. Thus, the main lime concrete application was in foundations, dams, tunnels, reservoirs, bridge footings, highway pavements, silos, and stadium. However, this use has largely decreased due to the increased strength, and finer grinding of portland cement, and the introduction of chemical admixtures (Mira et al., 2002). The increase in the environmental degradation of the planet that people live in, due to the activities of humans, has resulted into the need for the use of environmentally friendly, and energy saving materials in the construction industry. As a result of this need, many researches have been carried out, and are still on-going, on possible ways of replacing cement used in concrete with supplementary cementing materials (e.g. lime), that are environmentally friendly.

Rizwan et al. (2004) in their work, titled “Exploiting Huge Natural Resources of Lime in Pakistan for construction”, discovered that the compressive strength of concrete modified with lime, was less than that of normal concrete. The compressive strength of concrete decreased with an increase in percentage of lime. But, at the age of 56 days and beyond, the difference between the compressive strength of normal and the modified concrete, was lesser than the difference at the age of 7 days. They also reported that the 24 hour water absorption of concrete reduced with increase in percentage of lime in concrete. The workability of the normal concrete reduced to some extent, when lime was added to it. They recommended that a twenty percent (20%) replacement of cement with lime was more effective in concrete than with forty percent (40%) for the mix ratios, 1:1.5:3 and 1:2:4.

Ahmed et al. (2009), in their study on the compressive and tensile strengths of concrete, used limestone ($CaCO_3$) as a compensating material for cement. They also investigated the effect of higher temperatures on these properties and discovered from their study, that compressive strength of the concrete increased with increasing percentage of limestone up to fifteen percent (15%). The compressive strength decreased with increase in temperature. At 400^0C, a higher value of decrease in compressive strength, was observed than at 200^0C temperature. Also, the slump of concrete relatively increased with higher values of the percentage of limestone powder replacement. Sountharajan and Sivakumar (2013) investigated the "effect of the lime content in marble powder for producing high strength concrete". They reported that the ten percent (10%) replacement of cement with marble powder, gave a 28 day compressive strength value of 49.30MPa. This was higher than the control test value by twelve percent (12%). They also observed that at fifteen percent (15%) replacement of marble powder containing lime, with cement, the compressive strength was reduced. However, the strength reduction did not restrict the applicability of the marble powder in the field when the grade of concrete, is designed for M30. A similar trend was observed for split tensile strength. Higher replacement of marble powder of up to ten percent (by weight of cement), exhibited higher split tensile values of 4.35N/mm^2 at 28 days and the increase was 24.29% compared to that of the control. From their work, they concluded that high strength concrete, is achieved when marble powder was replaced at ten percent (10%) by weight of cement in concrete. They also noted that the workability of concrete decreased as the marble content increased.

Mira et al. (2002), investigated the "effect of lime putty addition on structural and durability properties of concrete". The following different types of cement, were used for the concrete preparation: namely portland cement, pozzolanic cement and portland cement with the addition of twenty percent (20%) fly ash. The measured concrete properties, were compressive strength, setting time, length change, porosity, carbonation depth, and degree of steel bar corrosion. They discovered that the lime putty addition, had a positive effect on the properties of concrete that contained pozzolan and a slightly negative effect on the properties of pure portland cement. This behavior was correlated with the availability of active silica of cementitious materials. The active silica of pozzolans reacts with the added calcium hydroxide, giving constituents, which improve the concrete stability and durability.

Holland, Nichols and Nichols (2012), studied the use of lime in concrete as a cement replacement. From their work, they observed that the compressive strength of concrete decreased with an increase in lime replacement of portland cement. They also observed that as the lime content was increased, the water content had to be increased to maintain an acceptable level of workability. Finally, they found out that an increase in the water content, may increase the strength properties of the lime rich mixes without significant reduction in the workability as measured by slump. Cizer, Balen and Gemert (2008), investigated the microstructure and strength development of blended lime-cement mortars for conservation purposes. They worked on cement-lime mortar composed of 30%, 50% and 70% cement replacement with hydrated lime, and lime putty by mass. They observed that cement hydration contributed to the early strength development, while carbonation started after 3 days, and contributed to the early stage strength development until 180 days. The degree of carbonation was more pronounced with increased lime content and porosity of the mortar. At 90 days, this reaction was still in progress. They also observed that all blended mortars, revealed lower compressive and flexural strength than that of the reference cement mortar. This was due to the lower cement content and higher porosity. Long term compressive strength development, was achieved after 180 days. Unlike the cement mortar, the mortar blended with lime hydrate and lime putty exhibited an elastic-plastic deformation before failure occurred. This property is preferred for repair mortars that need to adapt to differential settlements and to allow for more deformation under critical stresses in masonry.

Tyagher, Utsev and Iorliam (2012), researched on the suitability of groundnut shell ash (GSA)/ Lime mixture in the production of concrete. Their aim was to determine the percentage of GSA/lime and water-cement ratio that would give the 28 day minimum compressive strength of $20N/mm^2$. Groundnut shell ash that passed through the 150μm sieve, was used for the work. This ash was mixed with 45% slaked lime and was used to partially replace ordinary portland cement in various proportions. The design mix was 1:2:4 and the water-cement ratios of 0.45, 0.55, and 0.65 by weight, were investigated. They concluded that for a mix of 1:2:4, the proportion of GSA/lime up to twenty percent (20%) gave the 28^{th} day maximum strength of $20N/mm^2$ at water-cement ratio of 0.65. They recommended this concrete as a structural concrete. Namagga and Atadero (2009), investigated the use of high lime fly ash as a replacement for cement and filler material. They discovered that the replacement of high lime fly-ash in concrete generally increased the ultimate strength of concrete. A twenty five percent (25%)-thirty five percent (35%) fly ash replacement provided the most optimal strength results. Beyond thirty five percent (35%) fly ash replacement, the rate of gain of compressive strength decreased, but maintained its strength value above the desired design strength. More air entrainer admixture, was required for increasing amounts of fly ash used.

Ravasan, Azardoust and Arash (2013), worked on the re-use of sedimentary lime and incinerator ash for the production of structural concretes. In their work, different amounts of incinerator ash as fine aggregates replacement, and sedimentary lime substitution of cement for the production of structural concretes, were considered. Lime was used to replace twenty five percent (25%), fifty percent (50%), seventy five percent (75%), and hundred percent (100%) of the total cement volume, and ash particles were used as a partial replacement for sand by 50% of concrete mixtures. They reported that the fresh concrete mixtures exhibited lower unit weight and acceptable workability compared to plain concrete. They also reported that at 28 days, the compressive strength of concrete mixtures decreased below the value of the plain concrete. They suggested that the best volume for replacing lime with normal cement in order to produce a structural concrete, should be less than twenty five percent (25%) of cement volume in concrete mixture. In the case where lime and incinerator ash are to be used, an optimal mix of 50% incinerator ash replacement with sand, and twenty five percent (25%) lime replacement with cement, should be used.

Dhir, Limbachiya, Mc Carthy and Chaipanich (2007) investigated the use of portland limestone cement for use in concrete construction. -They observed that there were minor differences in performance between portland cement concrete, and fifteen percent (15%) portland lime cement concrete of the same cement content and water-cement ratio. They stated that there was an adverse effect with increasing limestone content, beyond fifteen percent (15%) of the cement content for the other properties of concrete studied. Blair (2010),in his study on building green with blended cement, reported that cement and concrete strengths are normally not reduced by using five percent (5%) to ten percent (10%) limestone. The cement containing five percent (5%) limestone, showed the greatest accelerated strength gain at early age. He observed that finer grinding of the cement, helped to increase the strength of the concrete. Ogunbode and Olawuyi (2008), carried out research on the strength characteristics of laterized concrete using lime-volcanic ash. They studied the effect of calcium oxide on the strength of volcanic ash laterized concrete. Volcanic ash (VA) and calcium oxide (CaO) were combined in the percentages of ninety percent (90%) to ten percent (10%) and eighty percent (80%) to twenty percent (20%) respectively; while ordinary portland cement (OPC) based-concrete with a 28 day target strength of 25N/mm^2 served as control. The sand replacement by laterite, varied between zero percent (0%) and twenty percent (20%) for the laterized specimen. Their results showed that compressive strength increased as the hydration period increased, and that the presence of calcium oxide boosted the strength properties of volcanic ash laterized concrete. An optimal mix of twenty percent (20%) of laterite to twenty percent (20%) of CaO and eighty percent (80%) of VA, gave a good compressive strength value of 22.07N/mm^2 at 28 days, and this can be adopted for construction of building and infrastructure in the rural areas.

The summary of related works on lime cement concrete, carried out by various researchers as previously discussed are presented in Table 2.9.

Table 2.9: Summary of related works on lime cement concrete

S/No.	Researchers	Area of research interest	Area covered	Areas not covered
1.	Rizwan et al. (2004)	Worked on lime cement concrete using hydrated lime	i. Compressive strength ii. Durability iii.Water absorption	i. Did not consider other structural characteristics of the concrete. ii. Prediction models were not developed.
2.	Ravasan et al. (2013)	Worked on lime cement concrete using sedimentary lime/incinerator ash	i. Compressive strength. ii. Workability	"
3.	Ahmed et al. (2009)	Worked on effects of higher temperature on lime cement concrete using limestone ($CaCO_3$)	i. Compressive strength ii. Tensile strength iii. Workability	"
4.	Sounthararajan & Sivakumar (2013)	Worked on lime cement concrete, using the lime content in marble powder.	i. Compressive strength ii. Split tensile strength iii. Workability	"
5.	Mira et al. (2002)	Worked on lime cement concrete, using : i. lime putty ii. Pozzolanic cement iii. Portland cement	i. Compressive strength. ii. Setting time iii. Length changes iv. Carbonation depth v. Degree of steel corrosion.	"
6.	Holland et al. (2012)	Worked on lime cement concrete using hydrated lime lime putty, and fly-ash	i. Compressive strength ii. Workability	"
7.	Cizer et al. (2009)	Worked on lime cement mortar using hydrated lime and lime putty.	i. Compressive strength ii. Flexural strength iii. Slump	"
8.	Tyagher et al. (2012)	Worked on lime cement concrete, using groundnut shelll ash/lime mixture.	Compressive strength	"
9.	Dhir et al (2007)	Worked on lime cement concrete, using limestone	Compressive strength	"
10.	Blair (2010)	Worked on lime cement concrete using limestone	Compressive strength	"
11.	Ogunbode & Olawuyi (2008)	Worked on lime volcanic ash cement concrete	Compressive strength	"

2.3.1.4 Laterized concrete

Laterized concrete is defined as concrete in which laterite fines replace sand. This replacement could be partial or wholly. Concrete in which sand components is partially or wholly replaced by laterite is called laterized concrete (Ata, 2007). While concrete with wholly replaced sand, is referred to as terracrete. Ata (2007) stated in his work, that Adepegba in 1975, discovered that laterized concrete mixes, require more water than normal concrete for equal proportions and weights of dry normal concrete and of dry laterized concrete mix. Adepegba also recommended that for structural laterized concrete, the water-cement ratio for mixes of 1:1:2 and 1:1.5:3 by weight is 0.65. This water-cement ratio would yield compressive strength of about 23.59N/mm^2 for 1:1:2 and 21.45N/mm^2 for 1:1.5:3 by weight in 28 days. The water-cement ratio recommended for 1:2:4 mix by weight, is 0.75. This will yield about 18.50N/mm^2 in 28 days. Ata (2007) pointed out that similar work carried out by Rai and his colleagues, revealed that the water absorption of laterized concrete, were higher than that of ordinary concrete. The workability of concrete for a given water-cement ratio, decreases with an increasing replacement level of sand with laterite as fine aggregate. They recommended that part substitution of sand with laterite of less than or equal to fifty percent (50%), hold guarantee as far as strength and serviceability requirement, are concerned.

Osadebe and Nwokonobi (2007) reported that Lasisi and his colleagues in 1984 obtained a linear relationship between the laterite-cement ratio (Y) and the optimum water-cement ratio (x). This equation was given as $Y = 0.9 + 3.85x$. They also discovered that difference in strength results of a laterized concrete of same mix and water-cement ratio, would arise if there is difference in the chemical composition of the soil, method of compaction, age of concrete, and difference in maximum size of aggregate used. Osadebe and Nwokonobi (2007) discovered that elasticity modulus, rigidity modulus, flexural strength and poisson's ratio were higher at the optimum mix proportion (1:1:2) than at the conventional mix ratio (1:2:4) in cement concrete for water cement ratio of 0.791.Research has also proved that increase in shear and tensile strengths of laterized concrete, can be obtained as grain size ranges and curing ages increase. Also greater values of shear and tensile strength, are obtained for rectangular specimens than those from the cylindrical specimens (Osunade, 1994). Several authors maintained that laterized concrete, would require slightly more cement than normal concrete would require to obtain a mix which would yield the same compressive strength as normal concrete (Ogunbode and Akanmu, 2012).

2.3.2 Properties of concrete

The knowledge of properties of hardened concrete is very important, as these properties change continuously with time and ambient conditions (Gupta and Gupta, 2004) Concrete mixtures can be designed to provide a wide range of mechanical and durability properties to meet the design requirement of a structure. Testing of hardened concrete plays an important role in controlling and confirming the quality of cement concrete works (Shetty, 2006). It helps to confirm that the concrete used at the site has developed the required quality. The following mechanical properties of concrete, shall be investigated; compressive strength, flexural strength, split tensile strength, shear strength, poisson ratio, static modulus of elasticity, and shear modulus or modulus of rigidity.

2.3.2.1 Compressive strength

Compressive strength is defined as the capacity of a material or structure to withstand load tending to reduce its size. It is the resistance of a material to breaking (rupture), under compression (Gupta and Gupta, 2004). According to Neville (2006), the compressive strength shows the best possible strength the concrete can reach in perfect conditions and it is given by the following formula:

$$f_c = P/A \qquad (2.4)$$

where, fc= compressive strength, P = crushing load (N) and A = cross sectional area of the specimen (mm^2).

The compressive strength of concrete is its property commonly considered in structural design. It is a key value for design of structures since most of the desirable characteristics properties of concrete are qualitatively related to its compressive strength (Shetty,2006). Some materials fracture at their compressive strength limit (e.g. concrete) while others deform irreversibly.

Compressive strength is often measured in a universal testing machine. Measurement of this strength, is affected by the specific test method and the conditions of measurement. They are usually reported in relationship to a specific technical standard. In determining the compressive strength of concrete, compression test is carried out on specimen that are cubical or cylindrical in shape. Sometimes, the compressive strength is determined using parts of a beam tested in flexure (Shetty, 2006). The end parts of the beams are left intact after failure in flexure and because the beam is usually of square cross-section, this part of the beam could be used to find out the compressive strength. The cube specimen, is normally of size 150mm x 150mm x 150mm when the largest aggregate size does not exceed 20mm (Neville, 2006). Cylindrical test specimen has a length equal twice the diameter. They are 150mm in diameter and 300mm long (Shetty, 2006). The test specimens are loaded into a compression testing machine or a universal testing machine where the compressive strength, also known as the crushing strength is reported to the nearest 0.5MPa. When testing a cylindrical specimen, it is necessary that the top surface, should be in contact with the platen of the testing machine. This surface when finished with a float, is not smooth enough for testing and requires further preparation. This is a major disadvantage of cylinder tested in compression. When using part of a beam tested in flexure, it is reasonable to assume the strength of the modified cube of same size. This is due to a slight increase in the ultimate strength as a result of the restraint of the overhanging parts of the cube (Neville, 2006).

Many research works, have been carried out on the compressive strength of various types of concrete. Ettu et al. (2013a), in their work, investigated the compressive strength of ternary blended cement concrete containing oil palm bunch ash (OPBA) and plantain leaf ash (PLA).

Ordinary portland cement (OPC) was partially replaced with pozzolan (i.e. oil palm bunch ash (OPBA) and plaintain leaf ash (PLA) in percentages of 5, 10, 15, 20 and 25 and the compressive strength at 3, 7, 14, 21, 28, 50 and 90 days, were determined. For equal proportions of OPBA and PLA, the five percent (5%) pozzolan replacement of OPC, gave the highest value of compressive strength of 27N/mm^2, while that of the control was 24.60N/mm^2. Their results showed that high concrete strength values, could be obtained with OPC-OPBA-PLA ternary blended cement at 50 days of hydration and above. Similar works carried out by Ettu, Ibearugbulem, Ezeh and Anya (2013b), also showed that ordinary portland cement (OPC) - corn cob ash (CCA) – pawpaw leaf ash (PPLA) ternary blended cement concrete, could also be used for various civil engineering and building works. Ogunbode and Olawuyi (2008) showed that the compressive strength of laterized concrete using lime-volcanic ash cement, increased as the hydration period increased, and that the presence of calcium oxide boosted the strength properties of the volcanic ash laterized concrete. Ajayi, Rasheed and Mojirade (2013), carried out an exploratory assessment of the strength characteristics of millet husk ash (MHA) blended cement laterized concrete with the view to determining its suitability as an alternative building material. The percentage replacement of sand with laterite (LAT) and that of cement with MHA was 0, 10 and 20 percent. These were cured for 7, 21 and 28 days respectively with the view of establishing the ash and laterite contents that can be used in cement and sand matrix. The results obtained showed that the best strength performance, was obtained at 10 percent MHA and 0 percent LAT and 10 percent LAT and 10 percent MHA with strength of 19.04N/mm^2 and 20.01N/mm^2 respectively. The control value was 32.98N/mm^2 at 28days. They therefore, concluded that this type of concrete can be used in light weight structures such as masonry walls and walkways.

2.3.2.2 Flexural strength

Flexural strength is the ability of a beam or slab to resist failure in bending (Okere, 2006). It is measured by loading unreinforced 150mm x 150mm concrete beam with a span 3 times the depth (usually 450mm). The theoretical maximum tensile stress or flexural strength reached in the bottom fiber of the test beam is known as the modulus of rupture (Neville, 2006). Therefore, the flexural strength is expressed as modulus of rupture (MOR) in N/mm^2 and is given by the formula:

$$\text{Flexural strength (MOR)} = PL/bd^2 \qquad (2.5)$$

where;

MOR = modulus of rupture (N/mm^2); P = maximum applied load indicated by the testing machine (N); L = span length (mm); b = average width of specimen (mm); and d =average depth of specimen (mm).

International Concrete Repair Institute defined MOR as a measure of the ultimate load carrying capacity of a beam tested in flexure (TDT, 2008). Concrete as known, is relatively strong in compression and weak in tension. In reinforced concrete members, little dependence is placed on the tensile strength of concrete, since steel reinforcing bars, are provided to resist all tensile forces. However, tensile stresses are likely to develop in concrete due to drying shrinkage, rusting of steel reinforcement, temperature gradients and many other reasons (Shetty, 2006). Therefore, the knowledge of tensile strength of concrete is of importance. For instance, a concrete road slab is called upon to resist tensile stresses from two principal sources; wheel load and volume changes in the concrete. Wheel loads may cause high tensile stresses due to bending when there is an inadequate sub-grade support. Volume changes resulting from changes in temperature and moisture, may produce tensile stresses due to warping and due to the movement of the slab along the sub-grade. Although, concrete is not normally designed to resist direct tension, the knowledge of tensile strength is of value in estimating the load under which cracking will develop (Neville, 2006).

The absence of cracking is of considerable importance in maintaining the continuity of a concrete structure and in many cases, in the prevention of corrosion of reinforcement. The expression of the modulus of rupture given earlier by Neville (2006), was qualified by the term “theoretical” because it is based on the elastic beam theory, in which the stress-strain relation is assumed to be linear, so that the tensile stress in the beam is assumed to be proportional to the distance from its neutral axis. In reality, there is gradual increase in strain with an increase in stress above, about half of the tensile strength. In consequence, the shape of the actual stress block under loads nearing failure, is parabolic and not triangular. The modulus of rupture thus over-estimates the tensile strength of concrete. The correct value of the tensile strength is about ¾ of the theoretical Modulus of Rupture (Neville, 2006).

Direct measurement of tensile strength of concrete, is difficult. Neither specimen nor testing apparatus which assure uniform distribution of the ‘pull’ applied to the concrete have been designed. The value of modulus of rupture depends on the dimension of the beam and the manner of loading (Shetty, 2006). The systems of loading used in finding out the flexural tension are; central point loading and the Third point loading. In central point loading, maximum fiber stress will occur below the point of loading where the bending moment is maximum. In the case of symmetrical two point loading, the critical crack, may appear at any section, not strong enough to resist the stress within the middle third, where the bending moment is maximum. It can be expected that the two point loading, will yield a lower value of the modulus of rupture than the center point loading. Some researchers in a bid to determine mechanical properties of concrete, have worked on flexural strength using different methods.

Okere (2006), in her work showed that a concrete mix can be regarded as a simplex lattice. She used the Henry Scheffes’ simplex design and the Osadebe’s regression theories to carry out the optimization process for the flexural strength of the concrete. These theories proved successful and the maximum modulus obtainable using the Scheffes’ model, was 6.9N/mm^2. Lepech and Li (2003) in their work “Preliminary Findings on Size Effect in Engineered Cementitious Composite (ECC) Structural Members in Flexure” found out that while reinforced concrete beams exhibited a significant reduction in flexural strength over a series of beams measuring up to 1.4m in length. The Engineered Cementitious Composite (ECC) and reinforced ECC beams showed no significant changes in flexure. This phenomenon is due to the ductile nature of the ECC material. The ECC flexure specimens, are unlikely to fail in a brittle manner, negating brittle fracture modes closely associated with size effect in concrete. Elinwa and Ejeh (2005) in their work on sisal concrete, showed that the MOR of sisal concrete, is about twenty four percent (24%) - twenty eight percent (28%) more than that of plain concrete. This finding depended on the length of the fiber and its volume. They measured the effects of variation of water- cement ratio on the MOR using the same size of beam, and came up with the finding that the MOR of concrete varies at different water/cement ratios.

2.3.2.3 Splitting tensile strength

The tensile strength is one of the basic and important properties of the concrete. It is the resistance of a material to a force tending to tear it apart, measured as the maximum tension the material can withstand without tearing ("American Heritage Dictionary", 2009). It is the measure of the ability of a material to resist a force that tends to pull it apart, and is expressed as the minimum tensile stress (force per area) needed to spilt a material apart. Tensile strength can also be seen as the measure of the ability of a material to withstand a longitudinal stress, expressed as the greatest stress that the material can stand without breaking. Concrete is not usually expected to resist the direct tension because of its low tensile strength and brittle nature. However, the determination of tensile strength of concrete, is necessary, so as to obtain the load at which the concrete member may crack. This cracking is a form of tension failure.

There are three tests used to measure strength in tension: direct tension test, flexure test and the splitting tension test. It has been well established that the simplest and the most reliable method, which generally provides a lower coefficient of variation, is the splitting tensile test of a cylindrical specimen (ASTM-1585,2004). Splitting tensile strength is generally greater than direct tensile strength and lower than flexural strength (modulus of rupture). It is used in the design of structural lightweight concrete members, to evaluate the shear resistance provided by concrete and to determine the development length of reinforcement (ASTM-1585,2004). Due to the difficulties associated with the direct tension test, a number of indirect methods, have been developed to determine tensile strength. The splitting tensile tests are well known indirect test used for determining the tensile strength of concrete. The test consists of applying a compressive line load along the opposite generators of a concrete cylinder placed with its axis horizontal between the compressive platens. Due to the compression loading a fairly uniform tensile stress, is developed over nearly $^2/_3$ of the loaded diameter as obtained from an elastic analysis. The magnitude of this tensile stress, O_{sp} (acting in a direction perpendicular to the line of action of applied loading) is given by the formula (IS: 5816, 1970):

$$O_{sp} = 2P/\Pi dl \qquad (2.6)$$

where, P = maximum applied load, d = diameter of the cylindrical specimen and l = length of the specimen.

A knowledge of the ratio of splitting tensile strength to uniaxial compression strength, allows for the estimation of strength of very high strength concrete under confinement. This knowledge, could reduce costs associated with triaxial testing programs for very high strength concrete.

Arivalang (2012), in his study on the split tensile strength properties of basalt fiber concrete member, discovered that the compressive strength and the split tensile strength of basalt fiber concrete specimen, were higher than those for the control concrete specimen at all ages. Also, strength difference between basalt fiber concrete specimen and the control concrete specimen, were high at the beginning age of curing. The concrete attained splitting tensile strength in the range of 123% - 125% at 28days when compared to the control at 28days.Wakchaure et al. (2012), conducted split tensile test on plain cement concrete with natural sand as fine aggregate and the other with artificial sand. They discovered that the tensile strength difference between the two concretes, were marginal, the values being; 3.78N/mm^2 for the natural sand concrete and 3.71N/mm^2 for artificial sand concrete. They also reported that the split tensile strengths for all specimen, were more than ten percent (10%) of compressive strength of the concretes. Jayaraman, Senthilkumar and Saravanan (2012), carried out tensile test on concrete made using lateritic sand and limestone filler as fine aggregates. The laterite was varied from zero percent (0%) to hundred percent (100%), while the limestone filler, was varied at intervals of twenty five percent (25%). They observed that at 0.55 water/cement ratio, the tensile strength ranged between 10.06N/mm^2 to 15.5 N/mm^2 for all the mixes they considered. The concrete was found to be suitable for structural works, where laterite content did not exceed fifty percent (50%).

2.3.2.4 Shear strength

Shear strength is the maximum load required to cut off a specimen in a way that the resulting pieces, are entirely clear of each other (Shetty, 2006).It can also be seen as a material's ability to resist forces that can cause the internal structure of the material to slide against itself. It is thus, a definitive strength of a material exposed to shearing load and experienced just before a material ruptures. It is the maximum shear stress, which a material can withstand without rupture. A shear load is a force that tends to produce a sliding failure on a material along a plane that is parallel to the direction of the force. Neville (2006), defined shear strength as a measure of the shear load divided by the cross-sectional area of the specimen, and is represented mathematically by the formula;

$$\tau = F/A, \qquad (2.7)$$

where τ = shear strength, F = shear load and A = cross-sectional area of the specimen.

In structural engineering, the shear strength of a component is important for designing the dimensions and material to be used for the manufacture/construction of components (e.g. beams, plates, bolts etc.). In reinforced concrete beams, the main purpose of stirrups is to increase the shear strength of the material.

2.3.2.5 Poisson's ratio

Poisson's ratio is the ratio of the lateral strain to the longitudinal strain for a uniaxial loaded concrete specimen (Neville, 2006). It is named after Simeon Poisson and it's the negative ratio of transverse strain to axial strain (Greaven, Greer, Lake and Rouxel, 2011). When a material is compressed in one direction, it usually tends to expand in the two other directions perpendicular to the direction of compression. This phenomenon is called the "Poisson's effect". Poisson's ratio is a measure of this effect. This effect is caused by slight movements between molecules and the stretching of molecular bonds within the material lattice to accommodate stress. When the bonds elongates in the stress direction, they shorten in the other directions. This behavior multiplied millions of times throughout the material lattice, is what drives the phenomenon. Poisson's ratio is generally denoted by the letter μ. It is given by the formula:

$$\mu = \delta_t / \delta_c, \tag{2.8}$$

where μ = poisson's ratio, δ_t = tensile stress at cracking in flexure, δ_c = compressive stress at cracking in compression.

For normal concrete, the value of poisson ratio lies in the range of 0.15 and 0.20when actually determined from strain measurements (Shetty, 2006). It can also be determined from ultrasonic impulse velocity method by finding out the fundamental resonant frequency of the longitudinal vibration of concrete beam. It can then be calculated from the Equation (2.9) (Neville, 2006).

$$(V^2 / 2nL)^2 = (1 - \mu) / ((1 + \mu)(1 - 2\mu)) \tag{2.9}$$

Where, v = pulse velocity (mm/s), n = resonant frequency (Hz) and L = length of beam (mm).

The value of poisson's ratio determined dynamically, is usually slightly higher than that determined using the static method. It ranges between 0.2 to 0.24. Poisson's ratio characterizes the elastic response of concrete. It can be determined experimentally by measuring the radial or circumferential expansion of a standard concrete cylinder, subjected to compression loading (Shetty, 2006). It increases significantly and progressively with the increase in sustained stress (Giacco, 1992).

Atta et al (2005) discovered that poisson's ratio of laterized concrete, ranges between 0.25 and 0.35 and increases with age at a decreasing rate. They also found out that the method of curing, compaction and water-cement ratio, had little influence on the poisson's ratio. The value of the poisson ratio of laterized concrete, increased as the mix became less rich. Osadebe & Nwakonobi (2007), determined the value of poisson ratio for an optimum mix proportion of 1:1:2 (i.e. cement: laterite: gravel) at water-cement ratio of 0.65 to be 0.26, while that of the conventional mix proportion (1:2:4) at water-cement ratio of 0.791 is 0.21.

2.3.2.6 Static modulus of elasticity

An elastic modulus is the mathematical description of an object or substance's tendency to be deformed elastically (non-permanently), when a force is applied to it. It is seen as the slope of the stress-strain curve, in the elastic deformation region of a given material (Askeland and Pradeep., 2006). It is a measure of stiffness or resistance to deformation in hardened concrete (Okere, 2012). Modulus of elasticity is a material property, that describes its stiffness, and is therefore one of the most important properties of solid materials like concrete (Shetty, 2006). From Hooke's law, the modulus of elasticity is defined as the ratio of the stress to the strain on a material. It is determined by subjecting a cube or cylinder specimen to uniaxial compression and measuring the deformation by means of dial gauges fixed between certain gauge lengths (Shetty, 2006). This gauge gives the reading of the strain and load applied. Dividing the load by the area of cross-section, will give the stress. A series of reading are taken and the stress-strain relationship, is established. Another way to determine the modulus of elasticity is by subjecting concrete beam to bending and then using the formulae for deflection and substituting other parameters. The modulus of elasticity found out from actual loading, is called static modulus of elasticity (Shetty, 2006).

In view of the peculiar and complex behavior of stress-strain relationship, the modulus of elasticity of concrete is defined in an arbitrary manner. In concrete, since no part of the graph is straight, the modulus of elasticity is found out with reference to the tangent drawn on the curve at the origin. This modulus is referred to as the tangent modulus (Neville, 2006). Its result is satisfactory only at low stress values. Tangents can also be drawn at any other point of the stress-strain curve. The modulus of elasticity calculated at this reference point, is called tangent modulus and is only satisfactory for stress level in the vicinity of the point considered (Shetty, 2006). There is no doubt that the modulus of elasticity increases with an increase in the compressive strength of concrete (Neville, 2006). This is so because, the stronger a concrete is, the stronger the gel and hence the lesser the strain it will experience under a given load. Because of the lower strain, the modulus of elasticity will be higher (Shetty, 2006).

There is no agreement on the precise form of relationship between the modulus of elasticity and compressive strength. This is so because the modulus of elasticity of concrete, is affected by the modulus of elasticity of the aggregates and by the volumetric proportion of aggregate in the concrete. This value of the elasticity of aggregate, is rarely known, so some expression allow for the modulus of elasticity of aggregate by a coefficient, which is a function of the density of the concrete, usually density raised to power 1.5 (Neville, 2006). According to ACI 318 (1995), the modulus of elasticity, is proportional to the strength of concrete raised to power 0.5. Some other standards use the power index 0.33 instead of 0.5 and also add a constant term to the right hand side of the equation. For concrete with strength levels up to 83N/mm^2, ACI 363R (1992) recommends that:

$$E_c = 3.32(f_c^1)^{0.5} + 6.9 \quad (2.10)$$

where f_c^1 = compressive strength in N/mm^2 and E_c = secant modulus of elasticity of concrete for structural calculations in $10^3 N/mm^2$.

The Indian standard, IS 456 (2000), gives the modulus of elasticity of concrete, E_c to be;

$$E_c = 5000 f_{ck}^{0.5} \quad (2.11)$$

Where, E_c is in N/mm^2.

The actual measured value may differ by ± 20% from the values obtained from the above expression (Shetty, 2006). Neville (2006) reported that Kakizak in 1992, found that the modulus of elasticity E_c, using empirical units is approximately related to strength f_c^1 by the expression;

$$E_c = 33\rho^{1.5}(f_c^1)^{0.5} \quad (2.12)$$

In the SI unit, this expression becomes;

$$E_c = 43\rho^{1.5}(f_c^1)^{0.5} * 10^{-6} \quad (2.13)$$

Where ρ is density in (N/mm^3), E_c is in $10^3 N/mm^2$ and f_c^1 is in N/mm^2.

Ata (2007) discovered that the modulus of elasticity of laterized concrete lies between $7000 N/mm^2$ and $9500 N/mm^2$. This value increases with an increase in the curing age of concrete. He stated that the richer the mix; the higher the modulus of elasticity. Osadebe and Nwakonobi (2007) in their work reported that the highest value of elastic modulus for laterized concrete at the optimum mix ratio of 1:1:2 (i.e. cement : laterite : gravel) at a water-cement ratio of 0.65 was $18{,}888.9 N/mm^2$. They also concluded that the compressive strength and water-cement ratio had significant effects on the modulus of elasticity of laterized concrete.

2.3.2.7 Modulus of rigidity

This is a measure of a material's resistance to shear. It is the ratio of unit shearing stress to unit shearing strain ("Dictionary of construction", 2013). It was also defined as the deformation of a substance or object when acted upon by opposing stress. Simply put, it is the ratio of shear stress to shear strain (Neville, 2006) and is defined by;

$$G = E / 2(1 + \upsilon) \qquad (2.14)$$

where, E = modulus of elasticity (N/mm^2); υ = poisson's ratio.

Hence, the modulus of elasticity and poisson's ratio, are all that is required, assuming the material is in pure shear in the bending plane. It applies to both elastic and inelastic deformation. It is used to determine how elastic or bendable materials will be, if they are sheared (which is being pushed parallel from opposite sides). At tiny levels, the modulus of rigidity relates to atoms sliding over one another. This helps to explain why temperature and pressure also affect it (Neville, 2006). The colder an object, the more pressure it is under, the more rigid or stiff it becomes. At high temperature and pressure, most material starts to melt and become easier to bend. The bigger the shear modulus, the more rigid the material, since for the same change in the horizontal distance (strain), one will need a bigger force (stress). There is no change in volume in this deformation. The planes of atoms merely slide sideways over one another. That is why the area (which determines the number of atomic bonds), is important in defining the stress and not just the force. Modulus of rigidity can be experimentally determined from the slope of a stress-strain curve created during tensile test conducted on a sample of the material (Shetty, 2006). This is achieved by placing a rod of a given material into a clamp and applying force at a measured distance away from the clamp to only one side of the rod. Predicting this property can be very difficult. It is not normally determined by direct measurement (Neville, 2006).

Osadebe and Nwakonobi (2007) discovered that the value of modulus of rigidity at optimum mix proportion of 1:1:2 (cement, laterite and gravel) at 0.65 water-cement ratio for laterized concrete was about 7,500N/mm^2, while that of the conventional mix proportion of 1:2:4 at water-cement ratio of 0.791, gave a value of about 4,200N/mm^2. In the work carried out by Ata (2007), values of modulus of rigidity for laterized concrete ranged from 5000N/mm^2 to 6000N/mm^2. He also discovered that any water-cement ratio that will give laterized concrete high strength, will increase its modulus of elasticity and modulus of rigidity.

2.3.3 Workability of fresh concrete

Workability can be defined as the amount of useful internal work, necessary to produce full compaction (Neville, 2006). ASTM C125 (2011) defines it as the property, determining the effort required to manipulate a freshly mixed quantity of concrete, with minimum loss of homogeneity. According to ACI 116R (2000), workability is defined as the property of freshly mixed concrete or mortar, which determines the ease and homogeneity with which it can be mixed, placed, consolidated, and finished. A concrete which is considered workable for mass concrete foundation, is not workable for concrete to be used in roof construction. Therefore, workability of concrete is dependent on the type of work, thickness of section, extent of reinforcement, and mode of compaction to be used during construction (Shetty, 2006). A comprehensive knowledge of the workability of concrete is required by the concrete technologist when designing a concrete mix. Assumption of right workability with proper understanding backed by experience, will make concreting operation economical and durable.

Workability of fresh concrete can be measured by the following test: Slump test, Flow test, Vee Bee consistometer test, Compacting factor test, and Kelly Ball test (Shetty, 2006). Of all these test, only the slump test shall be discussed.

2.3.3.1 Slump test of fresh concrete

This is a test used extensively in site work all over the world. The slump test helps to measure the consistency of fresh concrete and is very useful in detecting variations in the uniformity of a mix of given nominal proportions (Neville, 2006). Additional information on workability and quality of concrete can be obtained by observing the manner in which concrete slumps. The deformation shows the characteristics of concrete with respect to its tendency to segregate.

The slump test is prescribed by ASTM C143 (2010). The mould for the slump test is a frustum of a cone, 300mm high. It is placed on a smooth surface with the smaller opening at the top, and filled with concrete in three layers. Each layer is tamped 25 times with a standard 16mm diameter rod, rounded at the end, and the sawing and rolling motion of the tamping rod. The mould is held firmly against the base during the entire operation. Immediately after filling, the cone is slowly lifted with the aid of the handle attached to the mould, and the unsupported concrete will now slump. The decrease in the height of the slumped concrete is called "slump".

Concrete mixes having slump values ranging between zero 0 – 25mm are termed “very low slump concrete” and can be used in building roads. Concrete mixes having slump values between 25mm – 50mm are termed “low slump concrete” and find application in the construction of foundations with light reinforcements. Concrete mixes having slump values between 50mm – 100mm are termed “medium slump concrete” and they are used in manual compacted flat slabs, normal reinforced concrete constructions, and for heavily reinforced sections compacted using vibrations. Finally, concrete mixes having slump values ranging between 100mm – 175mm are called “high slump concrete” and can be used for sections with congested reinforcement that are not manually vibrated (ASTM C143, 2010).

2.3.4 Density of hardened concrete

Density is simply a mass to volume ratio. The density of concrete is a measure of its unit weight (Gupta and Gupta, 2004). It can be determined by simple dimensional checks, followed by weighing and calculations. Its value depends on the amount and density of aggregates, the amount of entrained air, and the water and cement content. Concrete density is inversely proportional to its porosity (Shetty, 2006).

The main objective of monitoring the density of concrete is to check strength. A reduced density of normal concrete almost always means a higher water content, which means lower strength (Neville, 2006). The density of both fresh and hardened concrete is of interest to the engineer for so many numerous reasons including, its effect on durability, strength, and resistance to permeability. The determination of the density of hardened concrete helps to check the conformance with specification for any concrete, and show difference from place to place with a mass of concrete (ASTM C642, 2006).

According to Naik (1997), the density for light weight concrete varies from 1350kg/m^3 to 1850kg/m^3. That for normal weight concrete, varies from 2200kg/m^3 to 2400kg/m^3. Finally, density of heavy weight concrete, varies from 3360kg/m^3 to 3840kg/m^3. They can however be produced with density up to 5820kg/m^3, using iron as both fine and coarse aggregates.

2.3.5 Concrete grade

The grade of concrete is determined by its compressive strength at 28 days after pouring. The higher the compressive strength of the concrete, the stronger the concrete will be. IS 456 (2000) specifies three groups of concrete grades namely: ordinary concrete, standard concrete, and high strength concrete. The ordinary concrete has specific characteristic compressive strength, ranging from 10N/mm^2 to 20N/mm^2. That for the standard concrete, range from 25N/mm^2 to 55N/mm^2. Finally, those for the high strength concrete range from 65N/mm^2 to 80N/mm^2.

Concrete grade lower than 20N/mm^2, are low load bearing concrete, and should be used for plain concrete constructions, lean concrete, simple foundations, foundation for masonry walls, and other simple or temporary reinforced concrete construction (IS 456, 2000). The ordinary and standard concrete grades were used to carry out this research work.

2.4 Artificial neural network (ANN)

An artificial neural network is an information paradigm that is inspired by the way biological nervous systems, such as the brain, process information (Stergiou and Siganos, 2009). It is from the artificial intelligence family, and is a type of information processing system based on modeling the neural system of the human brain (Sathyabalan, Selladurai and Sakthivel, 2009). It is an information processing system that has certain performance characteristics in common with biological neural networks (Fausett, 1994).The key element of this paradigm is the novel structure of the information processing system. It is composed of a large number of highly interconnected processing elements (neurons), working in unison to solve specific problems. Artificial neural networks like people, learn by examples. An ANN is configured for a specific application, such as pattern recognition or data classification, through a learning process. Learning in biological systems involves adjustments to the synaptic connections that exist between the neurons. This is true of ANNs as well. Commonly, neural networks are adjusted or trained, so that a particular input leads to a specific target output. Such a situation is shown in Fig 2.2. The network is adjusted based on a comparison of the output and the target, until the network output marches the target.

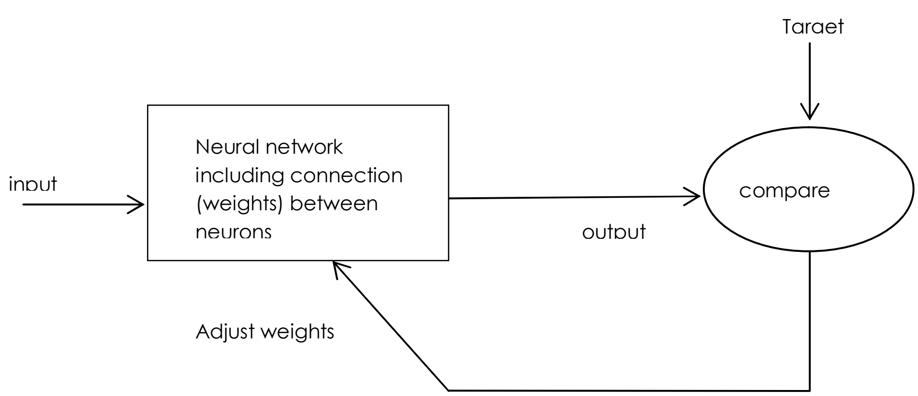

Fig 2.2: Neural net block diagram

Artificial neural networks have been developed, as generalization of mathematical models of human cognition or neural biology, based on the assumption that;

(i) Information processing occurs in many simple elements called neurons.

(ii) Signals are passed between neurons over connected links.

(iii) Each connected link has an associated weight, which in a typical neural network, multiplies the signal transmitted.

(iv) Each neuron applies an activation function (usually non-linear) to its net input (sum of weighted input signal) to determine its output signal. According to Haykin (2009), a neural network is a massively parallel distributed processor that has a natural propensity for storing experiential knowledge, and making it available for use. It resembles the brain in two respects namely;

(i) Knowledge is acquired by the network through a learning process.
(ii) Inter-neuron connection strengths known as synaptic weights, are used to store the knowledge.

A neural network is characterized by the following:

(a) Its pattern of connections between the neurons (called its architecture).

(b) Its method of determining the weights on the connections (called its training or learning algorithm).

(c) Its activation function (usually non-linear).

It consists of a large number of simple processing elements called neurons, units, cells or nodes. Each neuron is connected to other neurons by means of directed communication links, each with an associated weight. The weight represents information being used by the net to solve a problem

(Razavi, Jumaat and Ahmed, 2011). Neural network can be applied to a wide variety of problems, such as storing and recalling data or pattern, classifying pattern, performing general mapping from input pattern to output pattern, grouping similar patterns or finding solutions to constrained optimization problem. Each neuron has an internal state, called its activation or activation level, which is a function of the input it has received. Typically, a neuron sends its activation as a signal to several other neurons. It is important to note that a neuron can send only one signal at a time, although that signal is broadcast to several other neurons.

2.4.1 The human brain

The brain is made up very large number of neurons, that are massively interconnected (Haykin, 2009). Each neuron is a specialized cell, which can propagate an electrochemical signal. It has 3 types of components that are of particular interest in understanding an artificial neuron namely, its branching dendrites (inputs), soma (cell body) and axon (branching output structure) as shown in Fig 2.3.

The many dendrites receive signals from other neurons. The signals are electric impulses that are transmitted across a synaptic gap by means of a chemical process. The action of the chemical transmitter modifies the incoming signals (typically by scaling the frequency of the signals that are received) in a manner similar to the action of the weights in an artificial neural network. The strength of signal received by a neuron (and therefore its chances of firing), critically depends on the efficacy of the synapses. Each synapse actually contains a gap. Learning consists of principally altering the 'strength' of synaptic connections. For example, in the classic pavlovian conditioning experiment (Fausett, 1994); where a bell is rung just before dinner is delivered to a dog. The ringing of the bell is associated with eating food. The synaptic connection between the appropriate part of the auditory cortex, and the salivary glands are strengthened, so that when the auditory cortex is stimulated by the sound of the bell, the dog starts to salivate.

The soma or cell body sums the incoming signals, when sufficient input is received that exceeds a certain level (the firing threshold), the cell fire; that is, it transmits a signal over its axon to other cells. It is often supposed that a cell either fires or does not at any instant of time, so that transmitted signals can be treated binary. However, the frequency of firing varies and can be viewed as a signal of either greater or lesser magnitude. This corresponds to looking at discrete time steps and summing all activity (signals received or signal sent) at a particular point in time. The transmission of the signal from a particular neuron, is accomplished by an action potential resulting from differential concentrations of ions on either side of the neuron's axon sheath (the brain's "white matter"). The ions most directly involved are potassium, sodium and chloride.

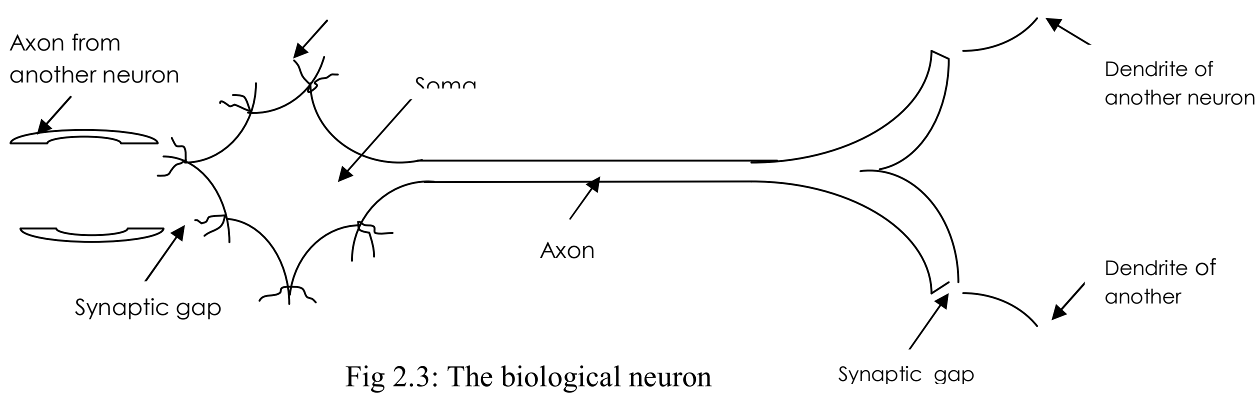

Fig 2.3: The biological neuron
Source: (Fausett, 1994, p. 6)

2.4.2 The artificial neuron

A neuron is an information processing unit that is fundamental to the operation of a neural network. The Fig. 2.4 shows the model of a neuron, which forms the basis of designing a large family of neural networks (Haykin, 2009).

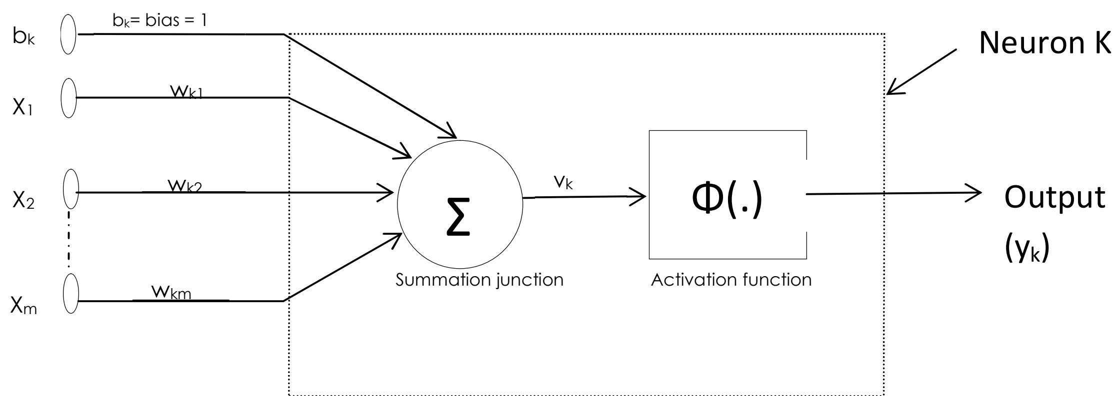

Fig 2.4: Non-linear model of a neuron, labeled K
Source: (Haykin, 2009, p.11)

Here, the following three basic elements of the neural model are identified.

(a) A set of synapses or connecting links, each of which is characterized by a weight or strength of its own. Specifically, a signal x_j at the input of synapse j connected to neuron K, is multiplied by the synaptic weight w_{kj} (Note that the first subscript in w_{kj}, refers to the neuron in question, and the second subscript refers to the input end of the synapse to which the weight refers). Unlike the weights in the brain, the synaptic weight of an artificial neuron, may lie in a range that includes negative as well as positive values.

(b) An adder for summing the input signals, weighted by the respective synaptic strengths of the neuron. The operation described here, is a linear combiner.

(c) An activation function for limiting the amplitude of the output of a neuron. It is referred to as a "squashing function", in that it limits the permissible amplitude range of the output signal to some finite value.

The neural model also includes an externally applied bias denoted by b_k. This has the effect of increasing or decreasing the net input of the activation function, depending on whether it is positive or negative, respectively. Mathematically, the neuron K described can be represented by the following equations (Haykin, 2009);

$$u_k = \sum_{j=1} w_{kj} x_j \qquad (2.15)$$

$$v_k = u_k + b_k \qquad (2.16)$$

$$y_k = \phi(u_k + b_k) \qquad (2.17)$$

where;

u_k (not shown in diagram) is a linear combiner output due to input signals

v_k= activation potential

y_k = output signal of the neuron

$x_1, x_2, \ldots, x_m$ are input signals

$w_{k1}, w_{k2}, \ldots, w_{km}$ are respective synaptic weights of neuron K

b_k = bias; and ϕ = activation function.

2.4.3 Network architecture

Network architecture can be defined as the manner in which the neurons of a neural network are structured (Haykin, 2009). In general, there are three fundamental classes of network architecture and they include:

(i) Single–layered feed-forward networks

(ii) Multi-layered feed-forward networks

(iii) Recurrent networks

(i) Single-layered feed-forward networks

In this type of neural network, the neurons are organized in layers. In the simplest form of a layered network, there is an input layer which consist of the source nodes that projects directly onto an output layer of neurons (computation nodes), but not vice versa. In other words, this network is strictly of a feed forward type as illustrated in Fig 2.5 for the case of three nodes in both the input and output layers. Such a network is called a single-layered network, with the designation "single-layered" referring to the output layer of computation nodes (neurons). Generally, the input layer of source nodes is not counted, since no computation is performed there (Haykin, 2009).

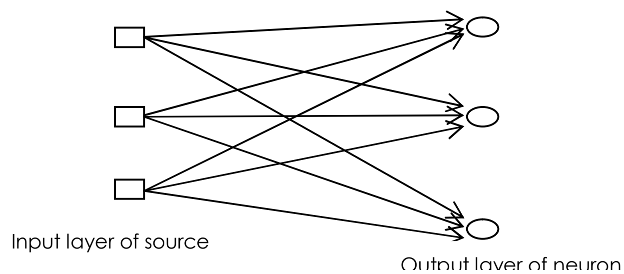

Fig 2.5: Feed forward network with a single layer of neurons
Source: (Haykin, 2009, p.21)

(ii) Multi-layered feed forward networks

This second class of a feed forward neural network distinguishes itself by the presence of one or more hidden layers, whose computation nodes, are correspondingly called hidden neuron or hidden units. The term "hidden" refers to the fact that this part of the neural network is not seen directly from either the input or output side of the network. The function of the hidden neuron is to intervene between the external input and the network output in some useful manner. The neurons in this layer gradually discover the salient feature that characterizes the training data. They do this by performing a non-linear transformation on the input data into a new space called the feature space (Haykin, 2009).

The source node in the input layer of the network, supply respective elements of the activation pattern (i.e. the input vector), which constitutes the input signal applied to the neurons (computation nodes) in the second layer (i.e. the first hidden layer). The output signals of the second layer are used as inputs to the third layer, and so on for the rest of the network. Typically, the neurons in each layer of the network have as their inputs the output signals of the preceding layer only. The set of the output signals of the neurons in the output (final) layer of the network constitutes the overall response of the network to the activation pattern supplied by the source nodes in the input (first layer). Fig 2.6 illustrates the layout of a multi-layer feed forward neural network for the case of a single hidden layer. The neural network in Fig 2.6 is said to be fully connected in the sense that every other node in each layer of the network is connected to every other node in each layer of the adjacent forward layer. When some of the communication links (synaptic connections) are missing from the network, the network is termed "partially" connected (Haykin, 2009).

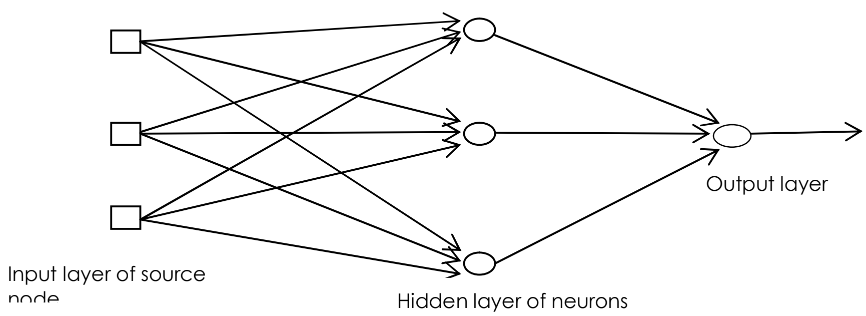

Fig 2.6: Fully connected feed forward network with one hidden layer and one output layer
Source: (Haykin, 2009, p. 22)

(iii) Recurrent network

A recurrent neural network distinguishes itself from a feed forward neural network, in that it has at least one feed-back loop. For example, a recurrent network may consist of a single layer of neurons with each neuron feeding its output signal back to the input of all the other neurons. The presence of feed-back loops, has a profound impact on the learning capacity of the network and on its performance. The feed-back loops involve the use of particular branches composed of unit time delay elements, which result in a non-linear dynamic behavior, assuming the neural network contains non-linear unit (Haykin, 2009).

2.4.4 Learning process of the neural network

Just as there are different ways we learn from our own surrounding environment, so it is with the neural networks. The learning process through which the neural network functions are as follows:

(a) Learning with a teacher

(b) Learning without a teacher

(a) Learning with a teacher

Learning with a teacher is also referred to as supervised learning. This is illustrated in Fig 2.7. In conceptual terms, we may think of the teacher as having knowledge of the environment, with that knowledge being represented by a set of input-output examples (Haykin, 2009). The environment is however, unknown to the neural network. Suppose that the teacher and the neural network are both exposed to a training vector (i.e., example) drawn from the same environment, by virtue of the built-in knowledge, the teacher will be able to provide the neural network with a desired response for the given training vector. The desired response represents the "optimum" action to be performed by the neural network. The network parameters, are adjusted under the combined influence of the training vector and the error signal. The error signal is defined as the difference between the desired response and the actual response of the network. This adjustment is carried out iteratively in a step by step fashion with the aim of eventually making the neural network emulate the teacher. In this way, knowledge of the environment available to the teacher, is transferred to the neural network through training and stored in the form of "fixed" synaptic weights, representing long term memory. When this condition is reached, the teacher can be dispensed and the neural network, is allowed to deal with the environment completely by itself. This form of supervised learning, is the basis for error correction learning.

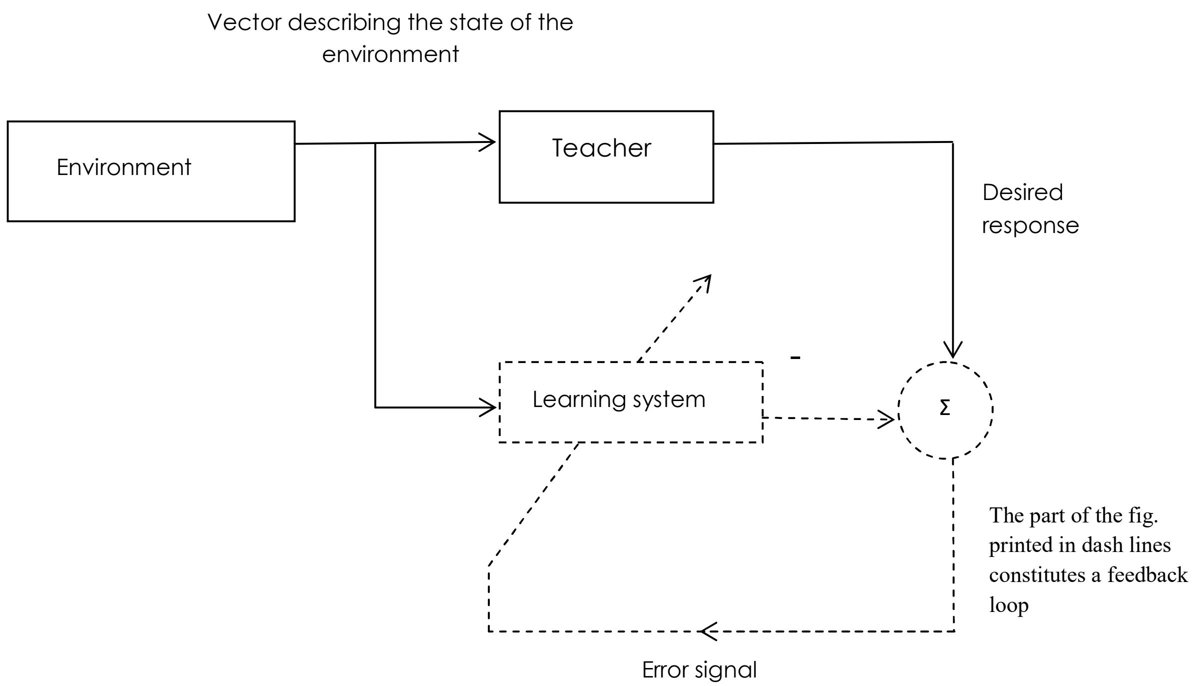

Fig 2.7: Block diagram of learning with a teacher.
Source: (Haykin, 2009, p. 35)

(b) Learning without a teacher

Learning without a teacher means that there is no teacher to oversee the learning process. That is to say, there are no labeled examples of the function to be learned by the network. This learning process can be divided into two categories, namely;

(i) Reinforced learning

(ii) Unsupervised learning

(i) Reinforced learning

In reinforced learning, the learning of an input-output mapping, is performed through continued interaction with the environment in order to minimize a scalar index of performance (Haykin, 2009). The Fig 2.8 shows the block diagram of one form of a reinforcement learning system built around a critic that converts a primary reinforcement signal received from the environment into a higher quality reinforcement signal, called the heuristic reinforcement signal, both of which are scalar inputs (Haykin, 2009).

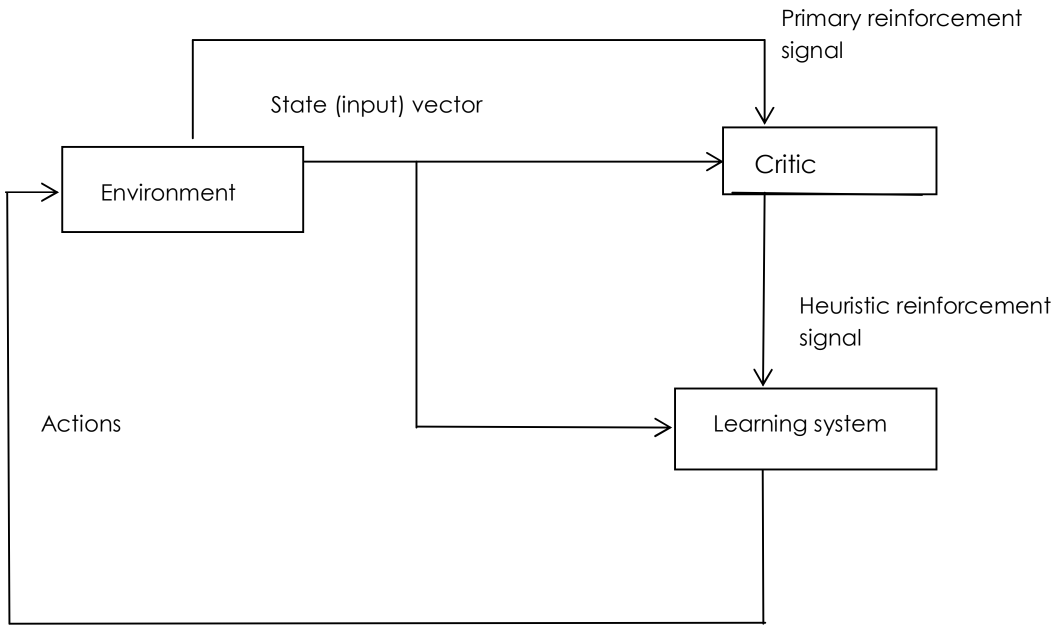

Fig 2.8: Block diagram of reinforcement learning system.
Source: (Haykin, 2009, p. 36)

The system is designed to learn under delayed reinforcement, which means that the system observes a temporal sequence of stimuli also received from the environment, which eventually results in the generation of the heuristic reinforcement signal. The goal of the reinforcement learning is to minimize the expectation of the cumulative cost of actions taken over a sequence of steps, instead of simply the immediate cost. It may turn out that certain actions taken earlier in that sequence of time steps, are in fact the best determinants of the overall system behavior. The function of the learning system, is to discover these actions and feed them back to the environment.

The delayed reinforcement learning is appealing, because it provides the basis for the learning system to interact with the environment, thereby developing the ability to learn to perform a prescribe task solely on the basis of the outcomes of its experience that result from the interaction (Haykin, 2009).

(ii) Unsupervised learning

In unsupervised learning, or self-organized learning, there is no external teacher or critic to oversee the learning process as indicated by Fig 2.9. Rather, provision is made for a task independent measure of the quantity of representation that the network is required to learn, and the free parameters of the network are optimized with respect to that measure (Haykin, 2009).For a specific task independent measure, once the network has become tuned to the statistical regularities of the input data, the network develops the ability to form internal representations for encoding features of the input and thereby, creating new classes automatically.

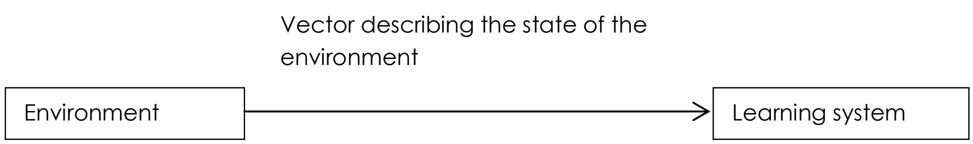

Fig 2.9: Block diagram of unsupervised learning.
Source: (Haykin, 2009, p. 37).

To perform unsupervised leaning, a competitive learning rule may be adopted. This can be seen in the use of a neural network that consist of two layers i.e. an input layer and a competitive layer. The input layer receives the available data. The competitive layer consists of neurons that compete with each other (in accordance with a learning rule), for the opportunity to respond to features contained in the input data. In its simplest form, the network operates in accordance with a "winner-takes-all" strategy. In such a strategy, the neurons with the greatest total input "win" the competition and turns on; all the other neurons in the network then switch off.

2.4.5 Activation function.

The basic operation of an artificial neuron involves summing its weighted input signal and applying an output or activation function. For the input units, this function is the Identity function.

Typically, the same activation is used for all neurons in any particular layer of a neural network, although this is not required. In most cases, a non-linear activation function is used. In order to achieve the advantages of multilayer nets, compared with the limited capabilities of single layer network, non-linear functions are required (Fausett, 1994).

(i) Identity function

Here, $f(x) = x$ for all x

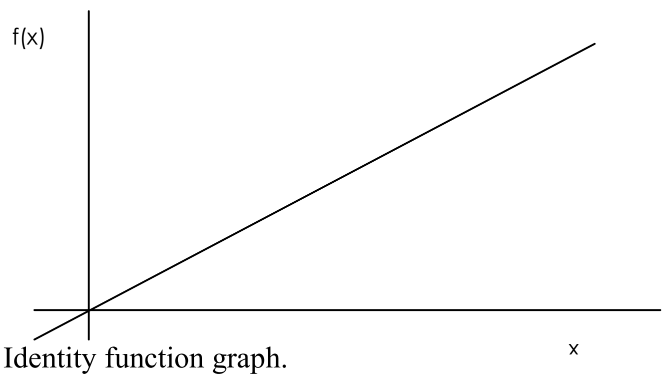

Fig 2.10: Identity function graph.

(ii) Binary step function (with threshold, θ)

Single layer networks often use a step function to convert the net input which is a continuously valued variable, to an output unit that is a binary (1 or 0) or bipolar (1 or -1). The use of threshold (θ) in this regards is to indicate the total network input necessary to cause a neuron to fire i.e. send signals. The binary step function is also known as the threshold function or Heavside function.

$$f(x) = \begin{cases} 1 & \text{if } X \geq \theta \\ 0 & \text{if } X < \theta \end{cases} \qquad (2.18)$$

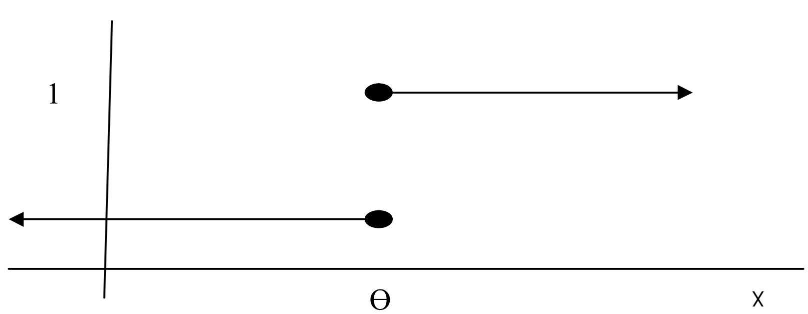

Fig 2.11: Binary step function graph

(iii) Sigmoid function

Sigmoid functions (S-shaped curves) are useful activation functions. The logistic function and the hyperbolic tangent functions are the most common. They are, especially advantageous for use in neural network trained by back propagation, because the simple relationship between the values of the derivative at the point reduces the computational burden during training. Sigmoid output neurons are often used for pattern recognition problems.

(a) Binary sigmoid

A sigmoid function with the range from 0 to 1 is often used as the activation function for neural networks in which the desired output values either are binary or are in the interval between 0 and 1. To emphasize the range of the function, we call it the binary sigmoid. It is also called the logistic sigmoid (Fausett, 1994).

Here, $f(x) = 1/ [1 + \exp(-\sigma x)]$ (2.19)

where σ = steepness parameter

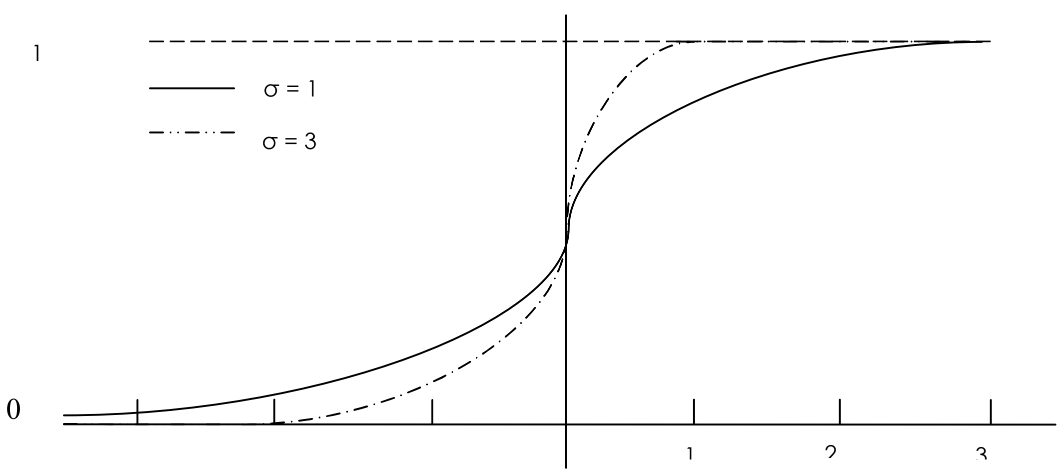

Fig 2.12: Binary sigmoid graph. Steepness parameter $\sigma = 1$ and $\sigma = 3$

(b) Bipolar sigmoid (Tan-sigmoid)

The bipolar sigmoid also known as the tan sigmoid is closely related to the hyperbolic tangent function, which is also often used as the activation function when the desired range of output values is between -1 and 1 (Fausett, 1994).

Here, $g(x) = 2f(x) - 1 = 2/[1 + \exp(-\sigma x)] - 1$ (2.20)

$$g(x) = \frac{1 - \exp(-\sigma x)}{1 + \exp(-\sigma x)} \qquad (2.21)$$

$$g'(x) = \frac{\sigma}{2}[1 + g(x)]\,[1 - g(x)] \qquad (2.22)$$

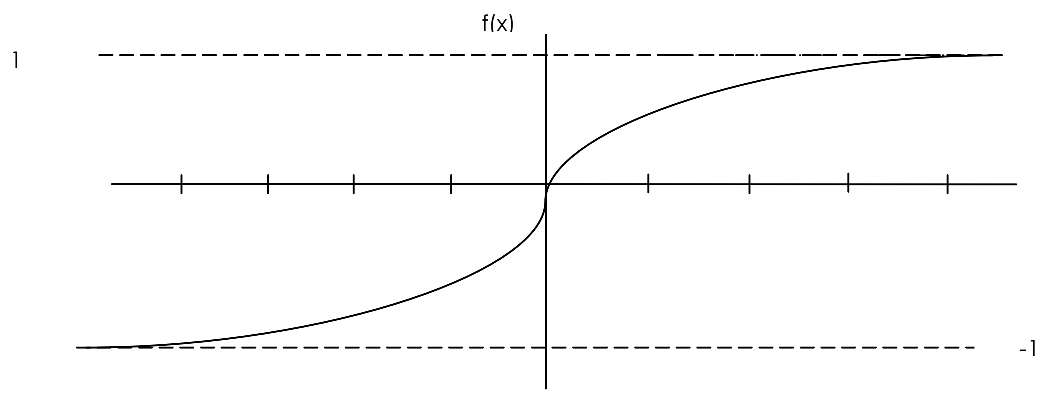

Fig 2.13: Tan-sigmoid (bipolar sigmoid) graph

(iv) Hyperbolic Tangent

For binary data (rather than continuously valued data in the range from 0 to 1), it is usually preferable to convert to form and use the bipolar sigmoid or hyperbolic tangent (Fausett, 1994).

Here, $$h(x) = \frac{\exp(x) - \exp(-x)}{\exp(x) + \exp(-x)} = \frac{1 - \exp(-2x)}{1 + \exp(-2x)} \qquad (2.23)$$

$$h'(x) = [1 + h(x)]\,[1 - h(x)] \qquad (2.24)$$

It is important to note that the range of the activation function should be appropriate for the range of target values for a particular problem. Therefore, this may result to the modification of the above common activation functions presented. When considering the speed of learning, the preferred choice is to use a sigmoid function that is, an odd function of its argument. This condition is satisfied by the hyperbolic function.

2.4.6. Standard back propagation neural network

There are many algorithms for training neural networks; most of them can be viewed as a straight forward application of optimization theory and statistical estimation. They include: Back propagation (using conjugate gradient descent, levenberg-marquardt, etc), simulated annealing, evolutionary computation methods, use of particle swarm optimization and other swarm intelligence techniques. But, the best known example of a neural network training algorithm is the back propagation **(**Fausett, 1994**)**. This is because it is the easiest algorithm to understand.

Back propagation (of error) or the generalized delta rule, is simply a gradient descent method to minimize the total squared error of the output computed by the network (Onwuka, & Awodiji, 2013). The gradient vector of the error surface is usually calculated. This vector points along the line of the steepest descent from its current position. So one knows that if one moves along it, a 'short' distance, one will decrease the error. A sequence of such moves will find a minimum of some sort. By its general nature, a back propagation network (a multilayer feed forward, network trained by back propagation), can be used to solve problems in many areas. Applications using back propagation and its variations can be found in virtually every field that uses neural network for problems that involves mapping a given set of inputs to a specific set of target outputs (i.e. networks that use supervised learning). As is the case with most neural networks, the aim is to train the network to respond correctly to input patterns that are used for training (memorization) and the ability to give reasonable (good) responses to input that is similar, but not identical, to that used in training (generalization). The training of a neural network involves 3 stages (Fausett, 1994).

(i) Feed forward of the input training data.

(ii) The calculation and back propagation of the associated error.

(iii) The adjustment of the weights.

After training, application of the network involves only the computations of the feed forward phase. Even if training is slow, a trained network can produce its output very rapidly.

Numerous variations of back propagation, have been developed to improve the speed of the training process. Example of this variation can be seen in the work of Sudarsan and Ramesh (2007). In their work, they combined the features of the feed forward neural networks and the genetic algorithms to develop a hybrid neural network model for the design of concrete beams. The effect of this hybridization of neural networks resulted to considerable improved efficiency (i.e. enhanced speed of training) of the network.

A back propagation neural network, is a layered network consisting of an input layer, an output layer and at least, one layer of a non-linear processing element known as the hidden layer. The input layer of the neural network, receives signals from the external environment. Input units do not process information. They simply distribute information to other units. The hidden layer receives signals from the input layer and transmits an output signal based on a transfer or activation function to the subsequent layer. Within each layer, neurons usually have the same activation function and the same patterns of connections to every output neuron. The arrangement of the neurons into layers and the connection pattern within and between layers, is called the 'Network Architecture".

The Fig 2.14 shows a multilayer, feed forward neural network architecture with one layer of hidden unit. The term feed forward means that information is processed only in one direction. A weight is associated with each connection from input to hidden units and from hidden units to output units. Each unit in the input layer, is connected to every unit in the hidden layer; likewise each unit in the hidden layer, is connected to each unit of the next hidden layer (if more than one hidden layer is present) or to each unit of the output layer. Bias unit has been employed to every layer of hidden and output unit. These bias terms act like weights on connections from units whose output is always 1. Only direction of information flow for the feed forward phase of operation, is shown. During back propagation phase of learning, signals are sent in the reverse direction.

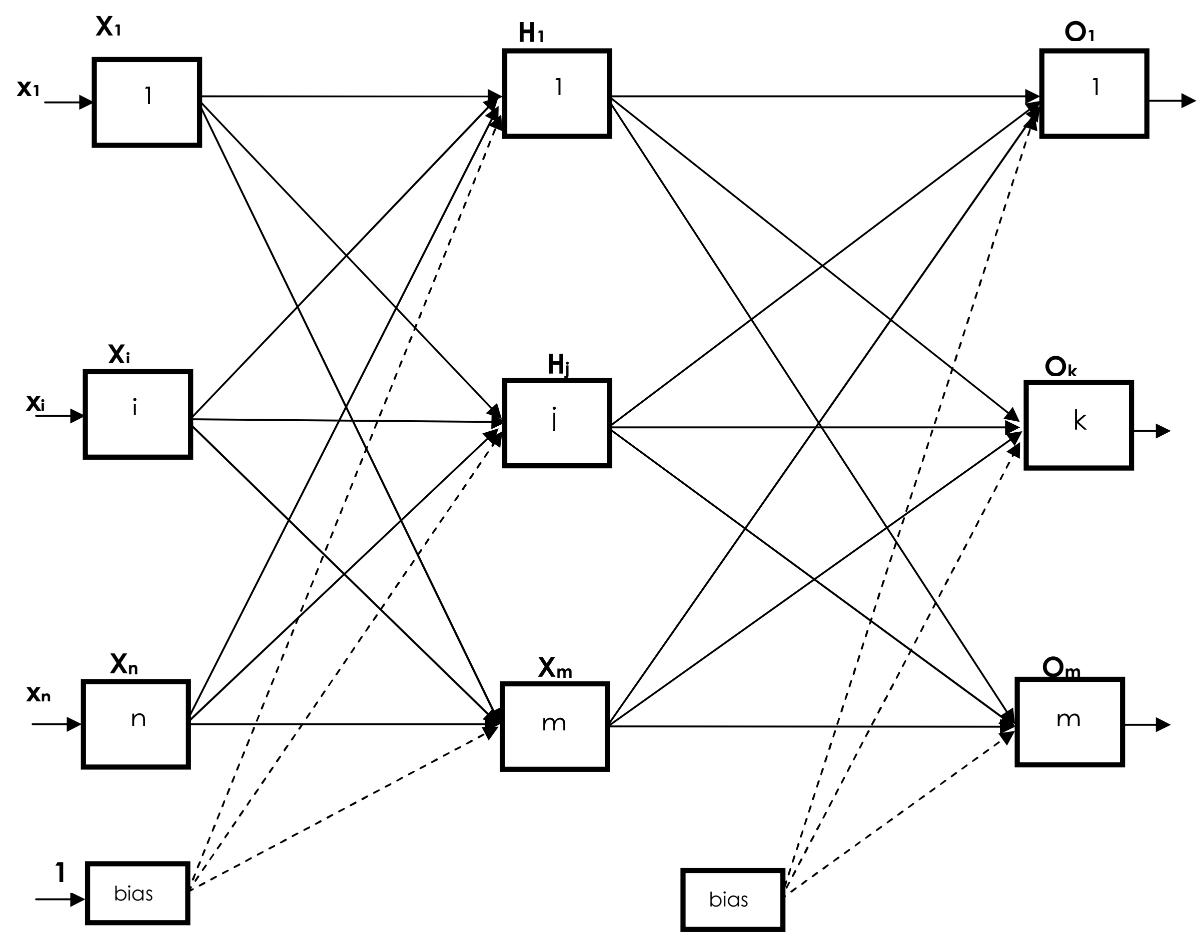

Fig 2.14: Back propagation neural network with one hidden layer having 3 units and an output layer having 3 units

2.4.6.1 Feed-forward computation

The input vector representing the pattern to be recognized, is incident on the input layer and distributed to subsequent hidden layers and finally to output layer via weighted connections. Each neuron in the network operates by taking the sum of its weighted input and passing the result through a non-linear activation function (Onwuka and Awodiji, 2013).These processes are as presented below.

(i) Each input unit(X_i, i = 1,…,n) receives input signal x_i and broadcasts this signal to all units in the layer above (the hidden units)

(ii) Each hidden units (H_j, j = 1,…,m) sums its weighed input signals. The net input, net_{pj} to the hidden unit H_j, is described as;

$$net_{pj} = v_{oj} + \sum_{i=1}^{n} x_i v_{ij} \quad (2.25)$$

x_i= input value from neuron i

v_{ij}= weight from neuron i(source) to neuron j(destination)

v_{oj}= bias on hidden neuron j

The output, 'h_j' of the hidden unit (H_j) as a function of its net input, is given by:

$$h_j = f(net_{pj}) \quad (2.26)$$

where f = sigmoid function = 1/[1 + exp(-x)]

but in this case, x = net_{pj}

Therefore, $h_j = 1/[1 + \exp(-net_{pj})]$ (2.27)

In the above Equation (2.27), the activation function, is applied to the net input in unit H_j, and this signal is sent to all units in the layer above (output units).

(iii) Each output units (O_k, k = 1,….,p) sums its weighted input signals. The net input to the output unit (net_{pk}), is described as;

$$net_{pk} = w_{ok} + \sum_{j=1}^{m} h_j w_{jk} \quad (2.28)$$

w_{ok}= bias on output neuron k

w_{jk}= weights from node j to node k.

The output signal from unit, O_k i.e. (o_k) is obtained by applying its activation function to its weighted input signals.

$$o_k = f(net_{pk}) \quad (2.29)$$

f = sigmoid function (activation function)

Therefore, $o_k = 1/[1 + \exp(-net_{pk})]$ (2.30)

The set of calculations that results in obtaining the output state of the network, is carried the same way for training as well as in the testing phase. The test mode just involves presenting input set to input units and calculating the resulting output state in a single forward pass.

2.4.6.2 Back propagation of error using the Levenberg-Marquardt algorithm

The very first thing required to be recognized in the training is the need for a measure of classes of network to an established desired value. This measure is network error. Since the network deals with supervised training, desired value is known for the given training set. For back propagation algorithm, an error measure known as the mean square error is used (Onwuka and Awodiji, 2013). The mean square error is defined as;

$$E_p = \sum_{k=1}^{p} ½ (t_k - o_k)^2 \quad (2.31)$$

where,

t_k = target (desired) value of O_k output unit

o_k = actual output obtained from O_k output unit.

E_p = mean square error.

In training phase of back propagation learning algorithm, the total error of the network is minimized by adjusting the weights. The Levernberg-Marquardt method is used for this. Each weight may be thought of as a dimension in N – dimensional error space. In error space, the weights act as independent variable and the shape of the corresponding error surface is determined by error function in combination with the training set.

The Levenberg-Marquardt method (LM) is a standard technique used to solve non-linear least square problems. Least square problems arise when fitting a parameterized function to a set of measured data points by minimizing the sum of the squares of the errors between the data points and the function. This method involves an iterative improvement to parameter values in order to reduce the sum of the squares of the errors between the function and the measured data points. The LM method is actually a combination of two minimization methods i.e. the gradient descent method and the Gauss-Newton method. In the first method, the sum of the squared errors is reduced by updating the parameters in the steepest-descent direction. In the second method, the sum of the squared errors is reduced by assuming the least square function to be locally quadratic, and finding the minimum of the quadratic (Gavin, 2016).

Applying the LM algorithm, Eqn. 2.31 can be re-written as:

$$E_p(\beta) = \sum_{k=1}^{p}[t_k - f(o_k, \beta)]^2 \qquad (2.32)$$

where,

t_k = target (desired) value of O_k output unit

$f(o_k, \beta)$ = actual output obtained from O_k output unit.

$E_p(\beta)$ = mean square error; β = parameter vector

o_k = measured vector; f = functional relationship

To solve Eqn. (2.32), an initial value must be assumed for β

(i) When there is only one minimum, β can be assumed to be $\beta^T = [1, 1, \ldots, 1]$.

(ii) When there is multiple minima, a global minimum is reached if only the initial guess of the parameter β is close to the final solution.

For each iteration, β is replaced by '$\beta + \delta$' where δ is the error correction. Therefore, Eqn. (2.32) becomes;

$$E_p(\beta + \delta) = \sum_{k=1}^{p} [t_k - f(o_k, \beta + \delta)]^2 \tag{2.33}$$

Approximating the function $f(o_k, \beta + \delta)$ by their linearization (Taylor series), will give;

$$f(o_k, \beta + \delta) \approx f(o_k, \beta) + [(\partial f/\partial\beta)(o_k, \beta)]\, \delta \tag{2.34}$$

But $(\partial f/\partial\beta)(o_k, \beta) = J_k$; where J_k is the Jacobian matrix from output O_k.

Eqn. (2.34) can be re-written as;

$$f(o_k, \beta + \delta) \approx f(o_k, \beta) + J_k\delta \tag{2.35}$$

Substituting Eqn. (2.35) to Eqn. (2.33) will give:

$$E_p(\beta + \delta) = \sum_{k=1}^{p} [t_k - f(o_k, \beta) - J_k\delta]^2 \tag{2.36}$$

Note that at the minimum of the sum of squares $E_p(\beta)$, the gradient of E_p w.r.t 'β' will be zero.

Re-writing Eqn. (2.36) in vector form gives;

$$E_p(\beta + \delta) = \| t - f(\beta) - J\delta \|^2 \tag{2.37}$$

Differentiating Eqn. (2.37) w.r.t. 'δ' and setting the results to zero will give;

$$J\delta = t - f(\beta) \quad (2.38)$$

Multiplying both sides by the transpose of the Jacobian matrix will give;

$$(J^T J)\,\delta = J^T\,[t - f(\beta)] \quad (2.39)$$

where,

J = Jacobian matrix whose kth row equals J; J^T = Transpose of the Jacobian matrix;

f and t = vectors with k^{th} components $f(o_k, \beta)$ and t_k respectively

Levenberg's contribution was to replace the Eqn. (2.39) with a "damped version" as shown in Eqn. (2.40);

$$(J^T J + \lambda I)\,\delta = J^T\,[t - f(\beta)] \quad (2.40)$$

where,

I = Identity matrix given as the increment δ to the estimated parameter vector β

λ= Non negative damping factor. This is adjusted in each iteration.

It was discovered that when the damping factor 'λ' in Eqn. (2.39) was large, inverting the term $(J^T J + \lambda I)$ will not be used. Therefore, Marquardt made a new addition to the Levenberg algorithm by replacing the identity matrix 'I' with a diagonal elements of $J^T J$. This resulted to larger movement along the directions where the gradient is smaller and avoided slow convergence. The Levenberg-Marquardt algorithm is given in Eqn. (2.41) as:

$$[J^T J + \lambda_{diag}(J^T J)]\,\delta = J^T\,[t - f(\beta)] \quad (2.41)$$

Eqn. (2.41) can be solved to obtain 'δ' which is used to compute the weight changes accordingly. The value of 'δ' that best minimizes the Eqn. (2.41) becomes the solution to the non-linear least square problem (Lourakis, 2005). The Levenberg-Marqaurdt training algorithm is implemented in the neural network toolbox of Matlab by typing the function 'trainlm'.

2.4.7 Damping parameter

When the reduction of the sum of the squares (E_p) is rapid (i.e. parameters are close to their optimal values), a smaller value of damping factor (λ) can be used. This brings the algorithm closer to the Gauss-Newton algorithm. When the reduction of the sum of squares is insufficient (i.e. parameters are far from their optimal values), the value of the damping factor (λ) can be increased. This leads to an algorithm closer to the gradient descent direction (Gavin, 2016).

The absolute values of any choice of damping parameter depends on how well-scaled the initial problem is. Marquardt recommended starting with a value λ_0 and a factor $v > 1$. Initially setting $\lambda = \lambda_0$ and computing the residual sum of squares $E_p(\beta)$ after one step from the starting point with the damping factor of $\lambda = \lambda_0$ and secondly with λ_0/v. if both of these are worse than the initial point, then the damping is increased by successive multiplication by 'v' until a better point is found with a new damping factor of $\lambda_0 v^k$ for some k. if the use of a damping factor λ/v results in a reduction in squared residual, then damping factor is taken as the new value of λ (and the new optimum location is taken as that obtained with this damping factor) and the process continues. If using λ/v results in a worse residual, but using λ resulted in a better residual, then λ is left unchanged and the new optimum is taken as the value with λ as damping factor.

2.4.8 Initialization

A good choice for the initial values of the synaptic weights and thresholds of the network can be of tremendous help in a successful network design. When synaptic weights are assigned large initial values, it is likely that the neurons in the network will be driven into saturation (i.e. the values of the derivative of the sigmoid function are very small). If this happens, the local gradients in the back-propagation algorithm assume small values, which in turn will cause the learning process to slow down. However, if the synaptic weights are assigned small initial values, the back-propagation algorithm may operate on a flat area around the origin of the error surface; this is particularly true for the case of the sigmoid functions such as the hyperbolic tangent function (Haykin, 2009). Unfortunately, the origin is a saddle point, which refers to a stationary point where the curvature of the error surface across the saddle is negative and the curvature along the saddle is positive. For these reasons, the use of both large and small values for initializing the synaptic weights should be avoided.

The proper choice lies between these two extreme cases. This choice will determine if the network will reach a global (or only a local) minimum of the error and, if so, how quickly it converges. A common procedure is to initialize the weights (and biases) to random values between -0.5 and 0.5 (or between -1 and 1) (Fausett, 1994). The values may be positive or negative because the final weights after training may be either sign also.

2.4.9 Local minima

Sometimes during the training of the network, it could be trapped in local minima rather than proceeding towards global minima for the error function. This can be avoided either by changing the learning parameter or by changing the number of hidden units.

2.4.10 Normalizing inputs

Normalization is the process of preprocessing each input variable of the network so that its mean value, averaged over the entire training sample, is close to zero, or else it will be small when compared to its standard deviation (Haykin, 2009). Normalization of the training data set is required before presenting it to the network for its learning, so that it satisfies the activation function range. Normalization is also necessary if there is a wide difference between the ranges of features values. Normalization process enhances the learning speed of the network and it avoids the possibility of early network saturation. The 'mapminmax' was used to normalize the input/targets to fall within the range of -1 to 1.

2.4.11 Pattern Presentation

There are two ways to pattern presentation and weight adjustment of the network.

(a) Stochastic (sequential) pattern.

This is the method involving the propagating of the error back into the network, and adjusting weight after each training pattern is presented. It is also called single pattern training mode of back propagation learning. This method is computationally faster than the batch mode. Highly redundant data pose computational problems for the estimation of the Jacobian. This is especially true when the training data sample is large and highly redundant (Haykin, 2009)

(b) Epoch (Batch) pattern.

An epoch is one cycle through the entire set of training vectors. Typically, many epochs are required for training a back propagation neural network. For most problems, when using the neural network toolbox software, epoch training is significantly faster and produces smaller errors than single pattern training. This is used in the present study for training the neural network.

2.4.12 Benefits of using the neural network

It is apparent that a neural network derives its computing power through, first, its massively parallel distributed structure and second, its ability to learn and therefore generalize (Fausett, 1994). Generalization refers to the neural network's production of reasonable outputs for inputs not encountered during training (learning). These two information capacities make it possible for neural networks to find good approximation solutions to complex (large-scale) problems that are intractable. According to Haykin (2009), neural networks offer the following useful benefits:

(i) Non linearity

An artificial neural network can be linear or non-linear. A neural network made up of an interconnection of non-linear neurons is itself non-linear and its non-linearity is distributed throughout the network. Non-linearity is a highly important property, particularly if the underlying physical mechanism responsible for generation of the input signal (e.g. speech) is inherently non-linear.

(ii) Input - output mapping

A proper paradigm of learning, called learning with a teacher or supervised learning, involves modification of the synaptic weights of a neural network by applying a set of labeled training examples, or task examples. Each example consists of a unique input signal and a corresponding desired (target) response. The network is presented with an example picked at random from the set, and the synaptic weights (free parameters) of the network are modified to minimize the difference between the desired response and the actual response of the network produced by the input signal in accordance with an appropriate statistical criterion. The training of the network is repeated for many examples in the set, until the network reaches a steady state where there are no significant changes in the synaptic weights (Haykin, 2009).

The previously applied training examples may be re-applied during the training session, but in a different order. Thus, the network learns from the examples by constructing an input – output mapping for the problem at hand. This approach is similar to the study of non-parametric statistical inference, which is a branch of statistics dealing with model free estimation. The term non parametric statistics inference signifies the fact that no prior assumptions are made on a statistical model for the input data.

(iii) Adaptivity

Neural networks have a built-in capability to adapt their synaptic weights to changes in the environment (Haykin, 2009).In particular, a neural network trained to operate in a specific environment, can be easily retrained to deal with minor changes in the operating environment.

(iv) Evidential response

In the context of pattern classification, a neural network, can be designed to provide information not only about which particular pattern to select, but also about the confidence in the decision made. This latter information may be used to reject ambiguous patterns, should they arise, and thereby improve the classification performance of the network (Haykin, 2009).

(v) Contextual information

Knowledge is represented by the very structure and activation state of a neural network. Every neuron in the network is potentially affected by the global activity of all other neuron in the network. Consequently, contextual information is dealt with naturally by a neural network.

(vi) Fault tolerance

A neural network implemented in hardware form, has the potential to be inherently fault tolerant, or capable of robust computation, in the sense that its performance degrades gracefully under adverse operating conditions. For example, if a neuron or its connecting links are damaged, recall of a stored pattern is impaired in quality. However, due to the distributed nature of information stored in the network, the damage has to be extensive before the overall response of the network is degraded seriously. Thus, in principle, a neural network exhibits a graceful degradation in performance rather than a catastrophic failure (Haykin, 2009).

(vii) VLSI implementability

The very massively parallel nature of a neural network makes it potentially fast for the computation of certain task. This same feature makes a neural network well suited for implementation using very-large-scale-integrated (VLSI) technology (Haykin, 2009). One particular beneficial virtue of VLSI is that it provides a means of capturing truly complex behavior in a highly hierarchical fashion.

(viii) Uniformity of analysis and design

Basically, neural networks enjoy universality as information processors. The same notation is used in all domains involving the application of neural networks.

(ix) Neurobiological analogy

The design of a neural network is motivated by analogy with the brain, which is living proof that fault-tolerant parallel processing is not only physically possible, but also fast and powerful. Neurobiologists use artificial neural network as a research tool for the interpretation of neurobiological phenomena. On the other hand, engineers look to neurobiology for new ideas to solve problems more complex than those based on conventional hardwired design techniques (Haykin, 2009).

2.4.13 Application of neural network

Artificial neural network has been applied to several fields. These include:

(i) Medicine

Artificial neural networks are ideal in recognizing diseases using scans since there is no need to provide a specific algorithm on how to identify the disease (Stegious and Siganos, 2009). What is needed is a set of examples that are representatives of all the variations of the disease. The quantity of examples is not as important as the quality. The examples need to be selected very carefully if the system is to perform reliably and efficiently. ANN has also been applied in the modeling of the human cardiovascular system, and electron noses.

(ii) Monitoring the condition of machines/engine management

Neural network can be instrumental in cutting costs by bringing additional expertise to scheduling the preventive maintenance of machines. A neural network can be trained to distinguish between the sounds a machine makes when it is running normally versus when it is on the verge of a problem. After the training period, the expertise of the network can be used to warn a technician of an upcoming breakdown, before it occurs and causes costly unforeseen “downtime”. Example of this is seen in the use of neural network to monitor the state of aircraft engines. By monitoring vibration levels and sound, early warning of engine problem can be given. Also, the British rail has been testing a similar application i.e., monitoring diesel engines. Neural networks have been used to analyze the input of sensors from an engine. The neural network controls the various parameters within the engine functions, in order to achieve a particular goal, such as minimizing fuel consumption (Stegious and Siganos, 2009).

(iii) Marketing

Neural networks have been used to improve marketing mailshots. One technique is to run a test mailshot, and look at the pattern of returns from this. The idea is to find a predictive mapping from the data known about the clients, to how they have responded. This mapping is then used to direct further mailshots (Stegious and Siganos, 2009).

(iv) Signature analysis

Neural networks have been used as a mechanism for comparing signatures made (e.g. in a bank) with those stored. This is one of the first large scale application of neural networks in the USA, and is also one of the first to use a neural network chip (Stegious and Siganos, 2009).

(v) Investment analysis

Neural network has also been used to predict the movement of stocks, currencies etc. from previous data. They have been used to replace earlier simpler linear models.

2.5 Graphical user interface (GUI)

Webster (2016), defines a graphical user interface (GUI), as a program that allows a person to work easily with a computer by using a mouse to point to small pictures and other elements on the screen. The GUI can be seen as a visual way of interacting with a computer using items such as windows, icons, and menus used by most operating systems. Isabella and Retna (2012), define the GUI as a program interface that takes advantage of the computer's graphical capacities, in other to make the program work easier. It therefore provides the user, an immense way to interact with the software.

The advantages of a GUI are ease of use, higher productivity and better accessibility. Electronic device with GUI often let users accomplish tasks at a faster rate over devices that employ older interfaces (Isabella and Retna, 2012). The GUI for predicting the structural characteristics of lime cement concrete was developed in this study.

CHAPTER THREE
MATERIALS AND METHODS

3.1 Materials

The materials used for this research work include portland cement, hydrated lime, river sand, granite chippings, and water.

(a) Cement

The dangote cement, which is a brand of portland cement was used for this study. It was obtained from the local markets in Owerri municipal, Imo state. It has been reported by Awodiji (2012) to satisfy the requirement of BS 12 (1978). The grade 32.5 was used for this study.

(b) Hydrated lime.

Hydrated lime (HL) is calcium hydroxide in powdered form, produced by the heating of limestone. It is an inorganic compound with the chemical formula $Ca(OH)_2$. The hydrated lime is the type of lime used for this study. It was sourced from Nkalagu, in Ebonyi State. Table 4.7 presents the result of the chemical property test for the hydrated lime and it showed that the lime satisfied the requirement of ASTM C207 (2006) and NIS 444-1 (2003).

(c) Aggregates

Aggregates greatly affect the durability and structural performance of concrete. Two sets of aggregates were used. They include the fine aggregate and the coarse aggregate.

(i) Fine aggregate

Fine aggregate in the form of river sand was used for this study. It was obtained from Otamiri river in Owerri-West local government area of Imo State. The fine aggregates consisted of natural sand from the river bed, with most of its particles smaller than 5mm. It was washed and sun dried for seven days to eliminate traces of clay, silt and organic matter. This aggregate was sieved to determine its particle size distribution and its bulk density was 1656.022kg/m^3 as shown in Table 4.3.

(ii) Coarse aggregate

The coarse aggregate used for this study was granite chippings. It was obtained from Setraco quarry site in Okigwe, Imo State.The maximum size of this aggregate was 19mm. The coarse aggregates were washed, and sundried for seven days in other to free them from excess dust and impurities. Sieve analysis to determine the particle size distribution of the granite chippings was carried out, alongside the bulk density test. Bulk density of the granite chipping was calculated to be 1706.225kg/m^3 as stated in Table 4.4.

(d) **Water**

Water is an important ingredient of concrete, as it actively participates in the chemical reaction with cement. Since it helps to form the strength giving cement gel, its quality and quantity is to be looked into very carefully.

A popular yard-stick to the suitability of water for mixing concrete is that, if water is good for drinking, it is fit for making concrete. This does not appear to be a true statement for all conditions. Some water containing a small amount of sugar would be suitable for drinking but not for mixing concrete and conversely water suitable for making concrete may not necessarily be fit for drinking. Impurities in water may interfere with the setting of the cement, may adversely affect the strength of the concrete or cause straining of its surface, and may also lead to corrosion of the reinforcement. For these reasons the suitability of water for mixing and curing purposes should be considered. Water used for this research work, was obtained from borehole water supply at the Federal Polytechnic Nekede, Owerri.

3.2 Methods

Three methods were used in the conduct of this research and they are; experimental methods, prediction methods, and statistical methods.

3.2.1 Characterization of the fresh lime cement concrete and its constituent using experimental methods.

The following experimental methods were carried out in other to characterize, the properties of fresh lime cement concrete;

(a) Sieve analysis to determine the grade size distribution of the fine and coarse aggregate according to BS 812 part 103.1 (1985).
(b) Bulk density test on the aggregates according to ASTM C29 (2011).
(c) Slump test on concrete according to BS EN 12350-2 (2009)
(d) Initial and final setting time test for the cement and lime paste using the Vicat apparatus according to BS 4550-3-3.6 (1978).
(e) Chemical property test for the hydrated lime according to ASTM C25 (2011).

3.2.1.1 Sieve analysis to determine the grain size distribution of aggregates.

One of the physical properties of aggregates that influence the property of concrete is the grading of aggregate. This is also known as the grain size distribution analysis of aggregate or sieve analysis. It is the operation of dividing a sample of aggregate into various fractions each consisting of particles of the same size. It is conducted to determine the particle size distribution in a sample of aggregate which is called gradation. The knowledge of the grading of aggregate, will help a mix designer prescribe a concrete that could be compacted to a maximum density with a reasonable amount of work, and for a given water-cement ratio. The grading of aggregate will affect the workability of the concrete mix. The finer the aggregate, the greater the water-cement ratio needed to make the concrete workable.

This test was carried out in the laboratory on the fine aggregate (river sand) and on the coarse aggregate (granite chippings) in accordance to BS 812 part 103.1 of 1985. Equipment used include, sieve sizes of different diameters; a scoop which was used to collect the sample; a weighing balance that was used to determine the mass of sample, sieves and pan; and a brush used to remove dirt from the sieves. The samples were spread out and left to dry for up to 4 days to ensure that no free water was entrapped. Sieving was done manually by shaking with the hands.

(a) **Sieve analysis of river sand (fine aggregate)**

The sieve analysis of the fine aggregate obtained from Otamiri River was carried out to determine the various sizes of particles present in the sample. A mass of 1000g was used to carry out this test and the sieve sizes used were 4.75mm, 2.00mm, 1.40mm, 0.85mm, 0.425mm, 0.212mm, and 0.150mm.They were all stacked according to their sizes starting from the largest to the smallest. The required mass of river sand was weighed out using the weighing balance and then poured into the first sieve. The sieve was covered with a lid and a pan attached to its base. This whole set up was shaken manually for a very long time until no more mass could pass through again. The mass retained was weighed and recorded. This procedure was repeated for all the sieve sizes according to how they were stacked and the mass retained on each sieve as well as in the pan, was weighed and recorded respectively. A grading curve showing the percentage passing vs. sieve sizes was then plotted. Results of this test are presented in Table 4.1 and Fig 4.1.

(b) **Sieve analysis of granite chippings (coarse aggregate)**

The sieve analysis of the coarse aggregate obtained from Setraco quarry in Okigwe local government area of Imo State was carried out to determine the various sizes of particles present in the sample. A mass of 1000g was used to carry out this test and the sieve sizes used were 22.4mm, 19.00mm, 14.00mm, 13.20mm, 10.00mm, 9.50mm, 6.70mm, and 2.80mm. The same procedure as recorded for the sieve analysis of the fine aggregate, was repeated for all the sieve sizes according to how they were stacked, and the mass retained on each sieve as well as in the pan, was weighed and recorded respectively. A grading curve showing the percentage passing vs. sieve sizes was then plotted. Results of this test are presented in Table 4.2 and Fig 4.2.

3.2.1.2 Bulk density test of aggregates

The bulk density of an aggregate is the mass or weight of the aggregate required to fill a container of a specific unit volume. The higher the bulk density of aggregate, the more durable the concrete produced from it will be. The bulk density test was conducted on surface dried aggregates (i.e. the river sand, and granite chippings respectively) according ASTM C29 (2011).

(a) Apparatus.

The following apparatus were used for the test: a cylindrical container of known volume (cutter), weighing balance, a trowel, and a tamping rod of 25mm diameter.

(b) Test procedure

(i) The cutter was weighed on the weighing balance and its mass was recorded as M_1.

(ii) The volume of the cutter was then determined and also recorded as V.

(iii) The cutter was then filled with aggregate (sand/or granite chippings) in three layers. Each layer was tampered with the tampering rod 25 times. After the top layer was tampered, the top surface was struck off, using the trowel such that the cutter was exactly filled.

(iv) The cutter and its content were placed on the weighing balance, and their weight was recorded as M_2.

(v) The mass of the sample (M_3), was then determined by subtracting the mass of the cutter from the mass of the cutter plus sample as shown in Table 4.3.

(c) Calculation

The bulk density of the aggregates, were calculated using the formula:

$$\text{Bulk density of aggregate } (\rho) = M_3/V = (M_2 - M_1)/V \qquad (3.1)$$

where;

M_1 = mass of cutter (kg)

M_2 = mass of cutter (kg) + mass of sample (kg)

M_3 = mass of sample (kg)

V = volume of cutter (m^3)

Results obtained are presented in Table 4.3 and Table 4.4.

3.2.1.3 Slump test on concrete.

This test is used extensively at the site of work. It does not measure the workability of concrete but is useful for finding the variations in the uniformity of a mix of given nominal proportions and specifies procedure for determining the consistency of concrete where the nominal maximum size of the aggregate does not exceed 38mm.

(a) Apparatus

The mould for the slump test was a frustum of a cone having internal diameter of bottom and top as 200mm and 100mm respectively, and a height of 300mm. The mould was made of metal of at least 1.6mm thickness, having smooth internal surface. Suitable metal handles were attached to it in other to facilitate in lifting the mould in a vertical direction. A tamping rod, 600mm long and of diameter 16mm was used.

(b) Test procedure

The test procedure for measuring slump is as follows;

(i) The internal surface of the mould was cleaned thoroughly and oiled. The mould was then placed on a smooth leveled metal plate, with the smaller opening at the top.

(ii) The mould was held firmly in place, while filling it with concrete. It was filled in four layers, each about 75mm in thickness. Each of the layer was tampered with twenty five strokes of the rounded end of the tamping rod. The stokes were distributed uniformly over the whole area of the cross section of the mould.

(iii) After the top layer was tampered, the top surface was struck by the rolling motion of the tamping rod such that the mould was exactly filled. Any leakage of mortar between the mould and the base was immediately wiped out.

(iv) The mould was then slowly and carefully lifted up in the vertical direction. This allowed the unsupported concrete to subside or slump.

(c) Calculation

The decrease in the height of the center of the slumped concrete is called "slump" and was calculated using the formula:

$$S = H - h \qquad (3.2)$$

Where,

S = slump (mm)

H = height of the mould (mm) h = height of the slumped concrete.

Slump values obtained for the lime cement concrete, are recorded in Table 4.5.

3.2.1.4 Initial and final setting time test for the cement paste and lime paste

Setting is the term used to describe the stiffening of the cement. It refers to a change from a fluid to a rigid stage. The initial and final setting times of the ordinary portland cement paste, and the hydrated lime paste were determined using the Vicat apparatus in accordance to BS 4550-3-3.6 (1978).

(a) Determination of the Initial Setting Time.

Initial setting time is regarded as the time elapse between the moments that the water is added to the cement to the time that the paste starts losing its plasticity. The initial setting time was determined with a 1mm diameter needle, attached to the plunger of the Vicat apparatus. This needle, acting under the self-weight of the plunger was used to penetrate a paste of standard consistency placed in a special mould (i.e. the apparatus mould) when the paste stiffens sufficiently for the needle to penetrate no deeper than a point 5mm from the bottom (or to a depth 33mm – 35mm from the top.)

(b) Determination of the Final Setting Time

Final setting time is the time elapse between the moment the water is added to the cement and the time when the paste has completely lost its plasticity and has attained sufficient firmness to resist certain definite pressure.

A similar needle fitted with a metal attachment hollowed out so as to leave a circular cutting edge 5mm in diameter and set 0.5mm between the tips of the needle, was used. The cement was considered as finally set when upon lowering, the attachment gently cover the surface of the test block, the center needle made an impression, while the circular cutting edge of the attachment failed to do so. In other words, the paste had attained such hardness that the center needle did not pierce through the paste more than 0.5mm. The initial and final setting times are presented in Table 4.6

3.2.1.5 Chemical property test for the hydrated lime

A standard laboratory test was carried out on the hydrated lime in accordance to the ASTM C25 (2011) standard, to verify the quality of the hydrated lime. The result of this test is stated in Table 4.7.

3.2.2 Structural characteristics test on the hardened lime cement concrete using experimental methods

The tests carried out on the hardened lime cement concrete include; compressive strength, flexural strength, splitting tensile strength, shear strength, static poisson ratio, modulus of elasticity, and modulus of rigidity.

3.2.2.1 Compressive strength test

Compressive strength of concrete is the maximum compressive stress that, under a gradually applied load, a given concrete volume can sustain without fracture. For structural design, the compressive strength is taken as the criterion of the quality of concrete. The compressive strength test is the most common test on hardened concrete. This is partly because it is an easy test to perform, and partly due to the fact that many desirable characteristics of concrete are qualitatively related to its strength. They are the most common performance measure, used by engineers in designing buildings and other structures.

(a) Concrete cube specimen

The specimen produced for the compressive strength test, was the concrete cube of size 150mm x 150mm x 150mm. This was prescribed according to BS 1881-116:1983. Three concrete specimens were prepared for each mix proportion at curing ages of 7, 14, 21, and 28 days. Since there were 30 different mix proportions, a total of 360 concrete cubes were produced.

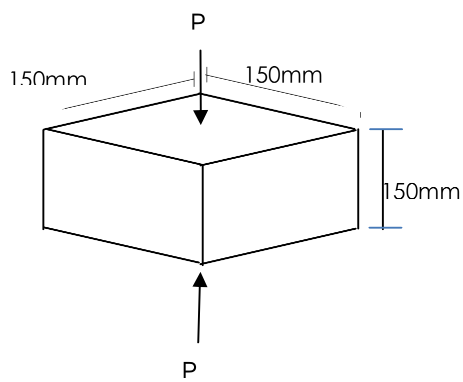

Fig 3.1: Concrete cube specimen for compressive strength test.

(b) **Production of concrete specimen**

Batching of the components of the concrete was by weight and mixing was done manually on a smooth concrete pavement. Required proportion of OPC and hydrated lime were mixed with the fine aggregate-coarse aggregate mix. Water was then added gradually and the entire concrete heap was mixed thoroughly to ensure homogeneity. The workability of the mixtures were measured using the slump test and wet densities were determined.

The inside of the various moulds were coated lightly with oil and then placed on a clean, level, and firm surface. These moulds were made of metals having sufficient thickness to prevent spreading or warping. For each mould, the required concrete samples were used to fill to about half their volume and a 25mm steel rod was used to compact the concrete by tampering 25 times.

The moulds were then filled to overflowing and compacted again by tampering another 25 times. A trowel was then used to level off the top of the moulds. Each sample in the mould was carefully marked for identification. The specimens were demoulded after twenty four (24) hours.

(c) Curing of concrete specimens

The concrete specimens were cured in open water tanks immediately after being demoulded, twenty four (24) hours after production. They were completely immersed in the water tanks for 7 days, 14 days, 21 days, and 28 days. This procedure was carried out in order to maintain moist condition over a period of time so as to ensure that there is reduction in permeability, increase in durability of concrete, and reduction in the rate at which initial drying shrinkage occurs, in other to minimize cracking and provide water for hydration.

(d) Test procedure

The compressive strength test was conducted on the 150mm x 150mm x 150mm concrete cubes using the universal testing machine according to BS 1881-116:1983, to determine their failure loads.

(i) The concrete cubes were brought out of the curing tank and allowed to dry. They were weighed and thereafter placed in contact with the platens of the universal testing machine.

(ii) The testing machine was loaded at a constant note until fracture (failure) occurred on the concrete cube. Three concrete cubes for each mix proportion, were loaded to failure.

(iii) The loading causing failure (crushing load), were noted and the average compressive strengths were determined. Consequently the value of the respective concrete cube densities were determined and the test results are presented in Table A1 to Table A8 of Appendix A.

(e) Calculation

The crushing loads recorded were used to calculate the compressive strength of the lime cement concrete using the formula:

$$F_c = \frac{P}{A} \tag{3.3}$$

where,

F_C= compressive strength of concrete (N/mm^2)

P= crushing load (N) A= cross sectional area of the specimen (mm^2).

Results of this test can be obtained from Table A1 to Table A8 of Appendix A.

3.2.2.2 Flexural strength test

Direct measurement of tensile strength of concrete is difficult. The beam test has been found to be dependable to measure the flexural strength of concrete. The strength shown by concrete against bending is known as flexural strength. In this test, the theoretical maximum tensile stress reached in the bottom fiber of a test beam is known as the modulus of rupture. The value of the modulus of rupture depends upon the size of the specimen and the arrangement of the loading on the beam. This strength is relevant to the design of highways and airfield pavements, where tensile stresses are likely to develop in concrete due to drying shrinkage, rusting of steel reinforcement, and temperature gradients.

(a) Concrete specimen

The specimen produced for the flexural strength test, was the 150mm x 150mm x 600mm concrete prototype beam specimen prescribed according to BS 1881-118 (1983) Three concrete specimens were prepared for each mix proportion at curing ages of 7, 14, 21, and 28 days. Since there were 30 different mix proportions, a total of 360 concrete prototype beams were produced.

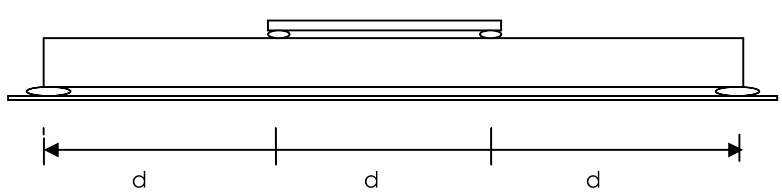

Fig 3.2: Principle of the Third Point Loading method of flexural testing of concrete beams

(b) **Production of concrete specimen**

Batching of the components of the concrete was by weight and mixing was done manually on a smooth concrete pavement. Required proportion of OPC and hydrated lime were mixed with the fine aggregate-coarse aggregate mix, also at required proportions. Water was then added gradually and the entire concrete heap was mixed thoroughly to ensure homogeneity. The workability of the mixtures were measured using the slump test and wet densities were determined.

The inside of the various moulds were coated lightly with oil and then placed on a clean, level, and firm surface. These moulds were made of metals having sufficient thickness to prevent spreading or warping. For each mould, the required concrete samples were used to fill to about half their volume and a 25mm steel rod was used to compact the concrete by tampering 25 times. The moulds were then filled to overflowing and compacted again by tampering another 25 times. A trowel was then used to level off the top of the moulds. Each sample in the mould was carefully marked for identification. The specimens were demoulded after twenty four (24) hours.

(c) Curing of concrete specimens

The concrete specimens were also cured in open water tanks immediately after being demoulded, twenty four (24) hours after production. They were completely immersed in the water tanks for 7 days, 14 days, 21 days, and 28 days.

(d) Apparatus

The universal testing machine conforming to BS 1881, Part 118 (1983) was used. The hydraulic machine consist of a frame to hold the specimen, a hand operated jack, and a pressure gauge to read the load.

(e) Test Procedure

The test procedure for measuring the flexural strength of the lime cement concrete are as follows:

(i) The bearing surfaces of the supporting and loading blocks were wiped clean, and any loose sand or other material were removed from the surfaces of the specimen where they are to make contact with the blocks.

(ii) The specimen was then placed in the machine in such a manner that the load was applied to the uppermost surface as cast in the mould, along two lines spaced 20cm or 13cm apart. The axis of the specimen was carefully aligned with the axis of the loading device, making sure that the load applying block and the support blocks were in contact with the surface of the specimen. A load between 3% to 6% of the estimated ultimate load was then applied.

(iii) The load was increased until the specimen failed, and the maximum load applied to the specimen during the test was recorded and presented in Table A9 to Table A16 of Appendix A. The appearance of the fractured faces of the concrete were noted.

(f) Calculation of Modulus of Rupture

The flexural strength of the specimen is expressed as the modulus of rupture (MOR) which is calculated from the maximum reading recorded by the pressure gauge and the corrected load (P) placed on the beam. Then, multiplying the maximum reading (P) by the normal span length (L) and divide by the product of the multiplication of the depth squared by the width.

$$MOR = PL/bd^2 \qquad (3.4)$$

where;

MOR = modulus of rupture (N/mm^2).

P = maximum applied load indicated by the testing machine (N).

L =span length (mm). b= average width of specimen (mm).

d = average depth of specimen (mm).

The results of the flexural strength test can be seen in Table A9 to A16 of Appendix A.

3.2.2.3 Splitting tensile strength test

The splitting tensile strength test is another method for determining the tensile strength of concrete. The advantages of this test is that, it is simple to perform, gives more uniform results than other tension test (e.g. the flexural strength test), and the test result is believed to be closer to the true tensile strength of concrete, than the modulus of rupture (MOR). The same type of specimen and same testing machine, can be used for both compression and tension tests. Finally, splitting strength is 5% to 12% higher than the direct tensile strength.

a) Concrete specimen

The specimen produced for the splitting tensile strength test, was the 150mm x 300mm concrete cylinders prescribed according to BS 1881-117 (1983). Three concrete specimens were prepared for each mix proportion at curing ages of 7, 14, 21, and 28 days. Since there were 30 different mix proportions, a total of 360 concrete cylinders were produced.

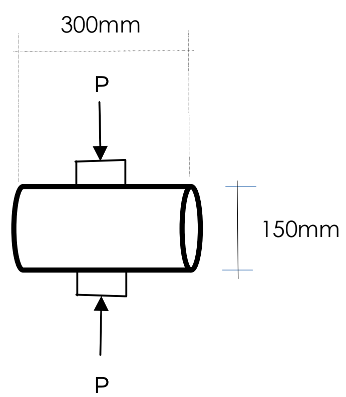

Fig 3.3:   Concrete cylindrical specimen for the splitting tensile strength test.

(b) **Production of concrete specimen**

The same procedure for the mixing of specimen as in compression and flexural testing of the concrete was adopted. The difference was that the homogenously mixed concrete was placed into cylindrical metal moulds of sizes, 150mm x 300mm. Each sample in the mould was carefully marked for identification. The specimens were later demoulded, after twenty four (24) hours of casting.

(c) Curing of concrete specimens

The concrete specimens were also cured in open water tanks immediately after being demoulded. They were completely immersed in the water tanks for 7 days, 14 days, 21 days, and 28 days.

(d) Apparatus

The universal testing machine conforming to BS 1881, Part 118 (1983) was used. The hydraulic machine consist of a frame to hold the specimen, a hand operated jack, and a pressure gauge to read the load.

(e) Test Procedure

The cylindrical splitting tension test was conducted using the universal testing machine, according to BS1881, Part 117 (1983) and the following procedure was carried out:

(1) The cylindrical specimen was placed horizontally, between the platens or loading surfaces of the testing machine. The platen was not allowed to rotate in a plane perpendicular to the axis of the cylinder.

(2) Load was applied against the specimen along its center line. This load was applied at a constant rate of increase in tensile stress of 0.02N/mm^2 to 0.04 N/mm^2.

(3) The load was increased until failure of the specimen took place by splitting, in the plane containing the vertical diameter of the specimen.

(f) Calculation of splitting tensile strength

The horizontal splitting tensile strength of the lime cement concrete was calculated using the formula;

$$O_{sp} = 2P/\Pi dl \quad (3.5)$$

where,

P = maximum applied load (N)   d = diameter of the cylindrical specimen (mm)

l = length of the specimen (mm).

The results are shown in Table A17 to Table A24 of Appendix A.

3.2.2.4 Shear strength

Shear is the action of two equal and opposite parallel forces applied in planes that are a short distance apart. It causes the internal structure of the concrete material to slide against itself. Therefore, the shear strength of concrete, is its ability to resist the shear forces acting on it. The direct determination of shear is very difficult. In structural engineering, the shear strength of a component is important for designing the dimensions and material to be used for the manufacture/construction of components (e.g. beams, plates, bolts etc.). In reinforced concrete beams, the main purpose of stirrups is to increase the shear strength of the material.

According to Neville (2006), shear strength is a measure of the shear load divided by the cross-sectional area of the specimen. This definition was used to determine the shear strength of the lime cement concrete as shown in Equation 3.6.

$$\tau = F/A, \tag{3.6}$$

where,

τ = shear strength (N/mm^2)   F = shear load (N)

A = cross-sectional area of the specimen (mm^2).

The results of the shear strength of the lime cement concrete, are presented on Table A25 to Table A32 of Appendix A.

3.2.2.5 Poisson's ratio

Poisson ratio is the ratio between lateral strain and longitudinal strain developed due to the application of axial compression. This axial compression and lateral extension is of interest in the analysis of structures. The lower the poisson ratio, the more resistance the concrete is to bending. The values of poisson ratios for the various mixes were determined from the formula given by Neville (2006) as shown in Equation 3.7;

$$\mu = \delta_t / \delta_c, \quad (3.7)$$

where,

μ = poisson's ratio δ_t = tensile stress at cracking in flexure (N/mm^2)

δ_c = compressive stress at cracking in compression (N/mm^2). Results of poisson ratio for the concrete can be obtained from Table A33 to A40 of Appendix A.

3.2.2.6 Static modulus of elasticity

The modulus of elasticity is a measure of the stiffness or resistance to deformation of a material. The modulus of elasticity of concrete is used in the calculation of structural deformations. In the case of reinforced concrete structures, it is used to determine the stresses developed in simple elements, and also to determine moments, deflections, and stresses in more complicated structures. Modulus of elasticity for the lime cement concrete were determined using the formula given by Neville (2006) as shown in Equation (3.8), and the results obtained are recorded in Table A41 to Table A48 of Appendix A.

$$E_c = 43\rho^{1.5}(f_c^1)^{0.5} * 10^{-6} \quad (3.8)$$

where,

E_c = modulus of elasticity ($10^3 N/mm^2$) ρ = density (N/mm^3)

f_c^1 = compressive strength (N/mm^2).

3.2.2.7 Shear modulus / modulus of rigidity

This is the ratio of the shear stress to the shear strain. It is used to determine how elastic or bendable materials will be, if they are sheared (i.e. being pushed parallel from opposite sides).The higher the modulus of rigidity, the more resistance to deformation via shear stress. This property is not normally determined by direct measurement. The Equation 3.9, given by Neville (2006), was adopted in calculating this property for the lime cement concrete and the results obtained are stated in Table A49 to Table A56 of Appendix A.

$$G = E / 2(1 + \upsilon) \tag{3.9}$$

where,

E = modulus of elasticity (N/mm^2)

υ = poisson's ratio.

3.2.3 Formulation and validation of artificial neural network (ANN) models using prediction method.

Data for this study were generated experimentally. The concrete under study was a five component mixture; therefore, five starting set of mix ratios (N1 to N5) were used to generate extra twenty five mix ratios using the Henry Scheffes simplex lattice (Anyanwu, 2011). This gave a total of thirty mix ratios. These mixes were then used to experimentally generate results of the structural characteristics of lime cement concrete. Table 3.1 to Table 3.3 shows the mix proportions of concrete specimens used for the study. The values of the structural characteristics of lime cement concrete obtained, were then used to formulate seven (7) artificial neural networks for predicting these properties. This was implemented using the neural network toolbox found in the Matlab R2014a software. Furthermore, slump test, and 28th day compressive strength test, were carried out on the first five trial mixes. These mixes had no portland cement replacement with hydrated lime.

Table 3.1: Mix proportions for concrete cubes

S/NO	Mix No.	MIX RATIO					MIX PROPORTIONS IN WEIGHT FOR ONE CUBE (Kg)				
		W/C	CEMENT	LIME	SAND	GRANITE	WATER	CEMENT	LIME	SAND	GRANITE
1	N1	0.600	0.900	0.100	3.000	6.000	0.510	0.765	0.085	2.550	5.100
2	N2	0.570	0.850	0.150	2.000	4.000	0.692	1.032	0.182	2.429	4.857
3	N3	0.550	0.800	0.200	2.500	5.000	0.550	0.800	0.200	2.500	5.000
4	N4	0.530	0.700	0.300	1.500	3.000	0.819	1.082	0.464	2.318	4.637
5	N5	0.500	0.600	0.400	1.000	2.000	1.063	1.275	0.850	2.125	4.250
6	N12	0.585	0.875	0.125	2.500	5.000	0.585	0.875	0.125	2.500	5.000
7	N13	0.575	0.850	0.150	2.750	5.500	0.538	0.781	0.138	2.527	5.054
8	N14	0.565	0.800	0.200	2.250	4.500	0.620	0.878	0.220	2.468	4.936
9	N15	0.550	0.750	0.250	2.000	4.000	0.668	0.911	0.304	2.429	4.857
10	N23	0.560	0.825	0.175	2.250	4.500	0.614	0.905	0.192	2.468	4.936
11	N24	0.550	0.775	0.225	1.750	3.500	0.748	1.054	0.306	2.380	4.760
12	N25	0.535	0.725	0.275	1.500	3.000	0.827	1.121	0.425	2.318	4.637
13	N34	0.540	0.750	0.250	2.000	4.000	0.656	0.911	0.304	2.479	4.857
14	N35	0.525	0.700	0.300	1.750	3.500	0.714	0.922	0.408	2.380	4.760
15	N45	0.515	0.650	0.350	1.250	2.500	0.922	1.163	0.627	2.237	4.474
16	C1	0.585	0.875	0.125	2.500	5.000	0.590	0.880	0.130	2.500	5.000
17	C2	0.575	0.850	0.150	2.750	5.550	0.526	0.777	0.137	2.513	5.073
18	C3	0.550	0.775	0.225	1.750	3.550	0.743	1.046	0.304	2.361	4.790
19	C4	0.525	0.700	0.300	1.750	3.550	0.708	0.944	0.405	2.361	4.790
20	C5	0.517	0.650	0.350	1.250	2.500	0.922	1.163	0.627	2.237	4.474
21	C6	0.580	0.863	0.138	2.625	5.500	0.556	0.826	0.132	2.514	5.027
22	C7	0.550	0.763	0.238	1.875	3.750	0.706	0.978	0.305	2.406	4.812
23	C8	0.563	0.813	0.188	2.250	4.500	0.617	0.891	0.257	2.469	4.937
24	C9	0.543	0.732	0.268	1.825	3.650	0.713	0.961	0.352	2.395	4.791
25	C10	0.560	0.799	0.201	2.325	4.650	0.597	0.852	0.215	2.479	4.957
26	C11	0.567	0.817	0.183	2.165	4.330	0.643	0.927	0.278	2.455	4.910
27	C12	0.557	0.790	0.210	2.150	4.300	0.636	0.902	0.240	2.453	4.907
28	C13	0.553	0.775	0.225	2.100	4.200	0.644	0.903	0.262	2.446	4.891
29	C14	0.562	0.813	0.188	2.225	4.450	0.623	0.899	0.208	2.464	4.929
30	C15	0.560	0.790	0.210	2.100	4.200	0.652	0.920	0.245	2.446	4.891

Table 3.2: Mix proportions for concrete prototype beams

S/NO	Mix No.	MIX RATIO					MIX PROPORTION IN WEIGHT FOR ONE BEAM (Kg)				
		W/C	CEMENT	LIME	SAND	GRANITE	WATER	CEMENT	LIME	SAND	GRANITE
1	N1	0.600	0.900	0.100	3.000	6.000	2.250	3.380	0.380	11.250	22.500
2	N2	0.570	0.850	0.150	2.000	4.000	3.060	4.550	0.800	10.720	21.440
3	N3	0.550	0.800	0.200	2.500	5.000	2.430	3.530	0.880	11.030	22.060
4	N4	0.530	0.700	0.300	1.500	3.000	3.230	4.770	2.050	10.230	20.460
5	N5	0.500	0.600	0.400	1.000	2.000	4.690	5.630	3.750	9.380	10.750
6	N12	0.585	0.875	0.125	2.500	5.000	2.580	3.860	0.550	11.030	22.060
7	N13	0.575	0.850	0.150	2.750	5.500	2.330	3.450	0.610	11.150	22.300
8	N14	0.565	0.800	0.200	2.250	4.500	2.730	3.870	0.970	10.890	21.770
9	N15	0.550	0.750	0.250	2.000	4.000	2.950	4.020	1.340	10.710	21.430
10	N23	0.560	0.825	0.175	2.250	4.500	2.710	3.990	0.850	10.890	21.770
11	N24	0.550	0.775	0.225	1.750	3.500	3.330	4.690	1.360	10.580	21.170
12	N25	0.535	0.725	0.275	1.500	3.000	3.650	4.940	1.880	10.230	20.450
13	N34	0.540	0.750	0.250	2.000	4.000	2.890	4.020	1.340	10.710	21.430
14	N35	0.525	0.700	0.300	1.750	3.500	3.150	4.200	1.800	10.500	21.000
15	N45	0.515	0.650	0.350	1.250	2.500	4.070	5.130	2.760	9.870	19.740
16	C1	0.586	0.875	0.125	2.500	5.000	2.600	3.870	0.550	5.520	22.100
17	C2	0.575	0.850	0.150	2.750	5.550	2.320	3.430	0.610	11.100	22.410
18	C3	0.550	0.775	0.225	1.750	3.550	3.280	4.620	1.340	10.430	21.160
19	C4	0.525	0.700	0.300	1.750	3.550	3.130	4.170	1.790	10.430	21.160
20	C5	0.517	0.650	0.350	1.250	2.500	4.070	5.130	2.760	9.870	19.740
21	C6	0.580	0.863	0.138	2.625	5.500	2.450	3.680	0.580	11.060	22.180
22	C7	0.550	0.763	0.238	1.875	3.750	3.120	4.320	1.350	10.620	21.460
23	C8	0.563	0.813	0.188	2.250	4.500	2.720	2.710	0.620	7.510	15.020
24	C9	0.543	0.732	0.268	1.825	3.650	3.140	4.240	1.550	10.570	21.140
25	C10	0.560	0.799	0.201	2.325	4.650	2.550	3.440	1.260	8.580	17.160
26	C11	0.567	0.817	0.183	2.165	4.330	3.250	4.690	1.050	12.420	24.840
27	C12	0.557	0.790	0.210	2.150	4.300	2.800	4.530	1.060	10.820	21.610
28	C13	0.553	0.775	0.225	2.100	4.200	2.840	4.530	1.160	10.790	21.760
29	C14	0.562	0.813	0.188	2.225	4.450	2.750	3.970	0.920	10.870	21.740
30	C15	0.560	0.790	0.210	2.100	4.200	2.880	4.040	1.080	10.790	21.560

Table 3.3: Mix proportions for concrete cylinders

S/NO	Mix No.	MIX RATIO					MIX PROPORTIONS IN WEIGHT FOR ONE CYLINDER (Kg)				
		W/C	CEMENT	LIME	SAND	GRANITE	WATER	CEMENT	LIME	SAND	GRANITE
1	N1	0.600	0.900	0.100	3.000	6.000	0.840	1.260	0.140	4.200	8.400
2	N2	0.570	0.850	0.150	2.000	4.000	1.140	1.700	0.300	4.000	8.000
3	N3	0.550	0.800	0.200	2.500	5.000	0.907	1.318	0.330	4.118	8.235
4	N4	0.530	0.700	0.300	1.500	3.000	1.349	1.782	0.764	3.816	7.637
5	N5	0.500	0.600	0.400	1.000	2.000	1.750	2.100	1.400	3.500	7.000
6	N12	0.585	0.875	0.125	2.500	5.000	0.964	1.441	0.206	4.118	8.236
7	N13	0.575	0.850	0.150	2.750	5.500	0.871	1.287	0.277	4.162	8.325
8	N14	0.565	0.800	0.200	2.250	4.500	1.021	1.445	0.362	4.065	8.129
9	N15	0.550	0.750	0.250	2.000	4.000	1.100	1.500	0.500	4.000	8.000
10	N23	0.560	0.825	0.175	2.250	4.500	1.012	1.491	0.316	4.065	8.129
11	N24	0.550	0.775	0.225	1.750	3.500	1.232	1.736	0.504	3.920	7.840
12	N25	0.535	0.725	0.275	1.500	3.000	1.362	1.846	0.700	3.818	7.637
13	N34	0.540	0.750	0.250	2.000	4.000	1.080	1.500	0.500	4.000	8.000
14	N35	0.525	0.700	0.300	1.750	3.500	1.176	1.568	0.672	3.920	7.840
15	N45	0.515	0.650	0.350	1.250	2.500	1.518	1.916	1.032	3.684	7.369
16	C1	0.585	0.875	0.125	2.500	5.000	0.864	1.441	0.206	4.118	8.235
17	C2	0.575	0.850	0.150	2.750	5.550	0.866	1.280	0.226	4.140	8.355
18	C3	0.550	0.775	0.225	1.750	3.550	1.222	1.722	0.500	3.900	7.900
19	C4	0.525	0.700	0.300	1.750	3.550	1.167	1.556	0.667	3.889	7.889
20	C5	0.517	0.650	0.350	1.250	2.500	1.518	1.916	1.032	3.685	7.369
21	C6	0.580	0.863	0.138	2.625	5.500	0.915	1.361	0.217	4.141	8.282
22	C7	0.550	0.763	0.238	1.875	3.750	1.162	1.611	0.502	3.962	7.924
23	C8	0.563	0.813	0.188	2.250	4.500	1.127	1.468	0.339	4.065	8.130
24	C9	0.543	0.732	0.268	1.825	3.650	1.174	1.583	0.580	3.946	7.892
25	C10	0.560	0.799	0.201	2.325	4.650	1.048	1.403	0.353	4.082	8.071
26	C11	0.567	0.817	0.183	2.165	4.330	1.059	1.526	0.342	4.044	8.089
27	C12	0.557	0.790	0.210	2.150	4.300	1.047	1.485	0.395	4.040	8.080
28	C13	0.553	0.775	0.225	2.100	4.200	1.061	1.487	0.432	4.029	8.058
29	C14	0.562	0.813	0.188	2.225	4.450	1.025	1.482	0.342	4.059	8.117
30	C15	0.560	0.790	0.210	2.100	4.200	1.074	1.515	0.403	4.028	8.056

3.2.3.1 Workflow for the design of the neural network process

The work flow for the general neural network design process had seven primary steps namely:

(i) Collection and preparation of data

(ii) Creating the network.

(iii) Configuration of the network.

(iv) Initializing the weights and biases.

(v) Training the network.

(vi) Validating the network.

(vii) Using the network.

(i) Collection and preparation of data

Experimental data were obtained from laboratory studies. These data were the mix ratios of concrete (i.e. water-cement ratio, portland cement, hydrated lime, river sand and granite chippings) with their corresponding values of the structural characteristics of lime cement concrete. The mix ratios with their corresponding curing ages were the training inputs while the structural characteristics of compressive strength, flexural strength, splitting tensile strength, shear strength, poisson ratio, modulus of elasticity and modulus of rigidity were the training targets respectively. These inputs and outputs are stored in a matrix form in the network. The inputs and output values were processed using the "mapminmax" and "removeconstantrows" processing functions. The "mapminmax" helped to normalize the input and output values to fall within a bipolar range i.e. [-1, 1], while the "removeconstantrows" helps to remove inputs/targets that were constant. All of these helped to prevent the network from being 'saturated'. Saturation results in a small network gradient which leads to a very slow training process. Therefore the standard practice was to normalize the data before applying them to the network.

The data was then divided into three subsets. The first subset was the training set, which was used for computing the gradient and updating the network weights and biases. The second set was the validation set that was used in monitoring the training process. The third subset was the test set. It was not used in monitoring the training process rather it was used to compare different models and plot the test set error during training. The processing function used for dividing these data to their various subsets was the ‘dividerand’. It divided the data randomly. The ratios for training, validation and testing were set at 0.70, 0.15 and 0.15 respectively.

(ii) Creating the network

After the data had been collected and prepared, the next step was to create the network. To achieve this, a feed forward neural network with six input neurons (representing the water-cement ratio, portland cement, hydrated lime, river sand, granite chippings, and curing age respectively) and one output neuron (representing the structural property being studied) was developed. This was achieved by using the network command ‘newff’.

(iii) Configuration of the network

Configuration of the network has to do with specifying the network parameter i.e. the network’s processing functions e.g. the activation function for the different layers, the training algorithms etc. The network input and output process functions can be override by adjusting the network properties after the network is created. To see a cell array list of processing functions assigned to the input and the outputs of a network,use the command line; ‘net.inputs{1}.processFcns’ and ‘net.outputs{2}.processFcns’ respectively.

(iv) Initializing the weights and biases

Weights are values associated with a connection path between two processing elements in a neural network. They contain fundamental information concerning the problem being solved. Biases are same as weights only that their output is always 1. Before training the feed forward network, these weights and biases were initialized. The configure command automatically initialized the weights but one can reinitialize them using the command line: ‘net = init(net)’. Each time a feed forward network was initialized; the network parameters were different and this produced different solutions.

(v) Training the network

Once network weights and biases were initialized, the network was then ready for training. The multilayer feed forward network was trained for function approximation (non-linear regression) or pattern recognition. The training process required a set of examples of proper network behaviour i.e. network inputs 'p' and target outputs 't'. The process of training required tuning the values of the weights and biases of the network to optimize network performance using the mean square error (mse).

(vi) Validating the network.

When the training was complete, the network performance was checked to determine if there was need for any changes to be made to the training process, the network architecture or the data sets. The first thing was to check the training records using the command line 'tr ='. This function key track of several variables during the course of training, such as the value of the performance function, magnitude of the gradient, the regression plot etc.

(vii) The use the network

After the network was trained and validated, the network object was used to calculate the network response to any input. Fig 3.4 presents a flow chart for the development of the backpropagation neural network.

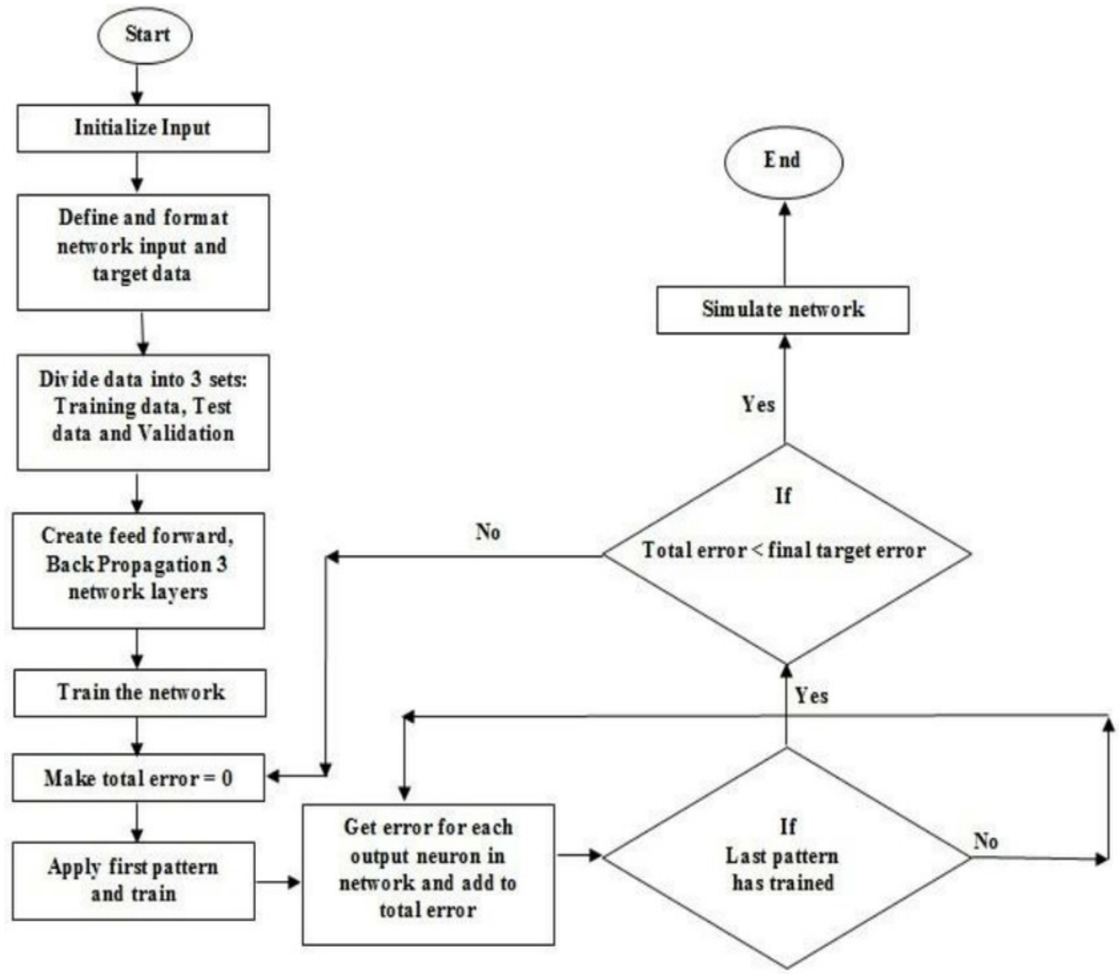

Fig 3.4: Flow chart for the development of a back-propagation neural network

3.2.4 Adequacy of network predictions using statistical methods

The adequacy of the network predictions against the experimental values were tested using two statistical methods namely; student's t-test and percentage error method.

(a) The student's t-test

The student's t-test is represented by the formula:

$$T = \{DA*(N^{0.5})\}/ S \quad (3.10)$$

where;

$DA = (\sum D_i) / N$ $\quad\quad$ $S = \sum S^2$

$Di = YM - YE$ $S^2 = \sum (DA - Di)^2/(N - 1)$

YE = Represent experimental responses.

YM = Represent neural network model responses.

N -Represent the number of responses.

(b) Percentage error

The percentage error between the ANN predictions and the experimental results were determined using the formula:

$$\text{Percentage error} = \{(YE - YM) / YE\} * 100\% \quad (3.11)$$

where;

YE = Represent experimental responses.

YM = Represent neural network model responses.

These tests were used to check the adequacy of the various network predictions against their experimental values. This was achieved by testing for the null hypothesis (H_o), which stated that there was no significant difference between the experimental and the theoretically expected results at a t-level of 0.05. The alternative hypothesis H_1, is the hypothesis that becomes the available alternative when the null hypothesis is rejected. When H_o is true, then the results determined from the artificial neural network models, may not be exactly the same as those of the experimental values. However, the percentage differences are marginal.

3.2.5 Graphical user interface (GUI) for predicting properties of lime cement concrete

A GUI for predicting the structural characteristics of lime cement concrete was developed. This was achieved using the Matlab R2014a software.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

Results of the various test performed for the characterization of the fresh lime cement concrete and its constituent materials; structural properties of the hardened concrete; formulation, and validation of the neural networks models developed; test of adequacy of network predictions; as well as the comparison of the network predictions against the experimental values, are all presented in this section.

4.1.1 Properties of fresh lime cement concrete and its constituent

Results of the experimental works, carried out on the fresh lime cement concrete and its constituents are presented in this section as follows;

4.1.1.1 Sieve analysis of river sand and granite chippings

Sieve analysis was carried out on the fine aggregate (i.e. sand), and the coarse aggregate (granite chippings). The results obtained are presented in Table 4.1 and Table 4.2 respectively. Grading curves for these aggregates are presented in Fig 4.1 and Fig 4.2 respectively.

Table 4.1: Grain size distribution of Otamiri river sand.

S/No	Seive size (mm)	Mass of sieve (g)	Mass of sieve & sample (g)	Mass of sample retained (g)	Cumulative Mass of sample retained (g)	Mass of sample passing (g)	% passing	% retained
1.	4.75	374.38	405.18	30.80	30.80	969.20	96.92	3.08
2.	2.00	422.78	507.06	84.28	115.08	884.92	88.492	11.508
3.	1.40	373.09	514.50	141.41	256.49	743.51	74.351	25.649
4.	0.85	328.04	645.02	316.98	573.47	426.53	42.653	57.347
5.	0.425	319.21	612.74	293.53	867.00	133.00	13.30	86.700
6.	0.212	317.61	406.36	88.75	955.75	44.25	4.425	95.575
7.	0.150	268.47	307.09	38.62	994.50	5.63	0.563	99.437
8	Pan	371.29	376.92	5.63	1000.00	0	0	379.296

Fineness modulus = 379.296 ÷ 100 = 3.79

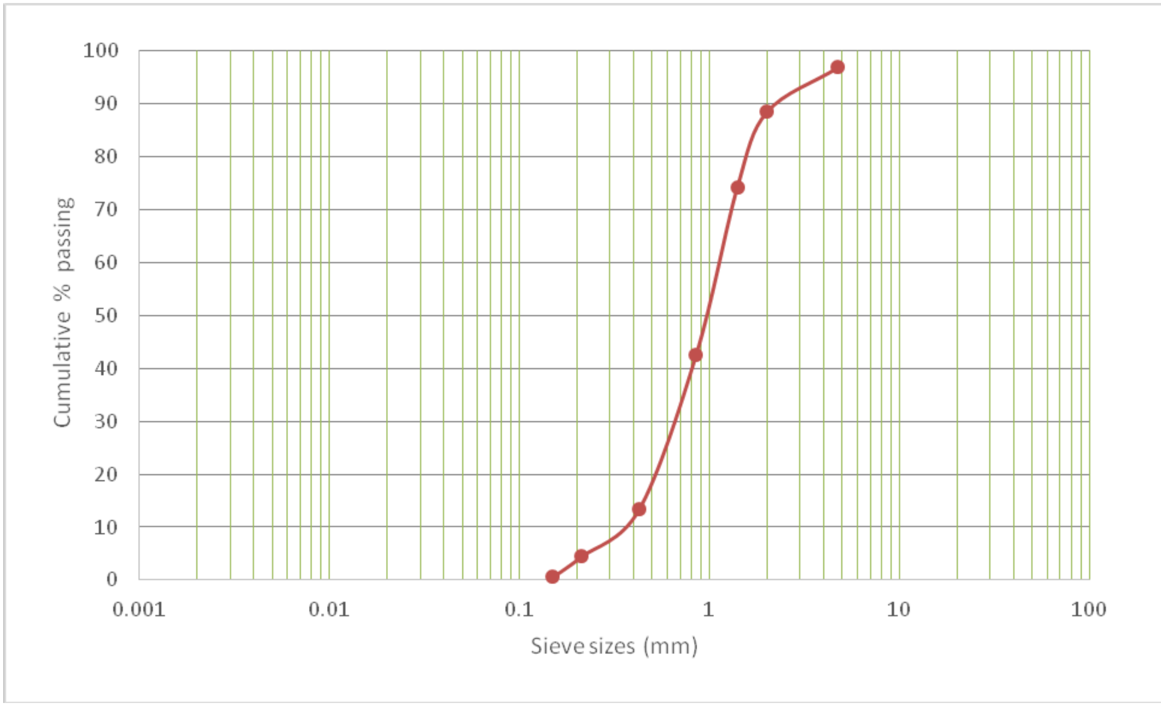

Fig 4.1: Grading curve for Otamiri river sand

From Fig 4.1, $D_{10} = 0.37$; $D_{30} = 0.66$; $D_{60} = 1.2$

From Eqn. 2.2, coefficient of uniformity (Cu) = $\frac{D_{60}}{D_{10}} = \frac{1.2}{0.37} = 3.24$.

From Eqn. 2.3, coefficient of curvature (Cc) = $\frac{(D_{30})^2}{D_{10} X D_{60}} = \frac{0.66^2}{1.2*0.37} = 0.98 \approx 1$

Table 4.2: Grain size distribution of granite chippings

S/No	Seive size (mm)	Mass of sieve (g)	Mass of sieve & sample (g)	Mass of sample retained (g)	Cumulative Mass of sample retained (g)	Mass of sample passing (g)	% passing
1.	22.4	511.60	511.60	0	0	1000.00	100.00
2.	19.00	465.60	585.72	120.12	120.12	879.88	87.988
3.	14.00	426.51	1087.29	660.78	780.9	219.10	21.910
4.	13.20	445.42	545.54	100.12	881.02	118.98	11.898
5.	10.00	414.87	485.04	70.17	951.19	48.81	4.881
6.	9.50	441.33	470.45	29.12	980.31	19.69	1.969
7.	6.70	467.06	480.23	13.17	993.48	6.52	0.652
8	2.80	422.15	425.91	3.76	997.24	2.76	0.276
9.	Pan	370.72	373.48	2.76	1000.00	0	0

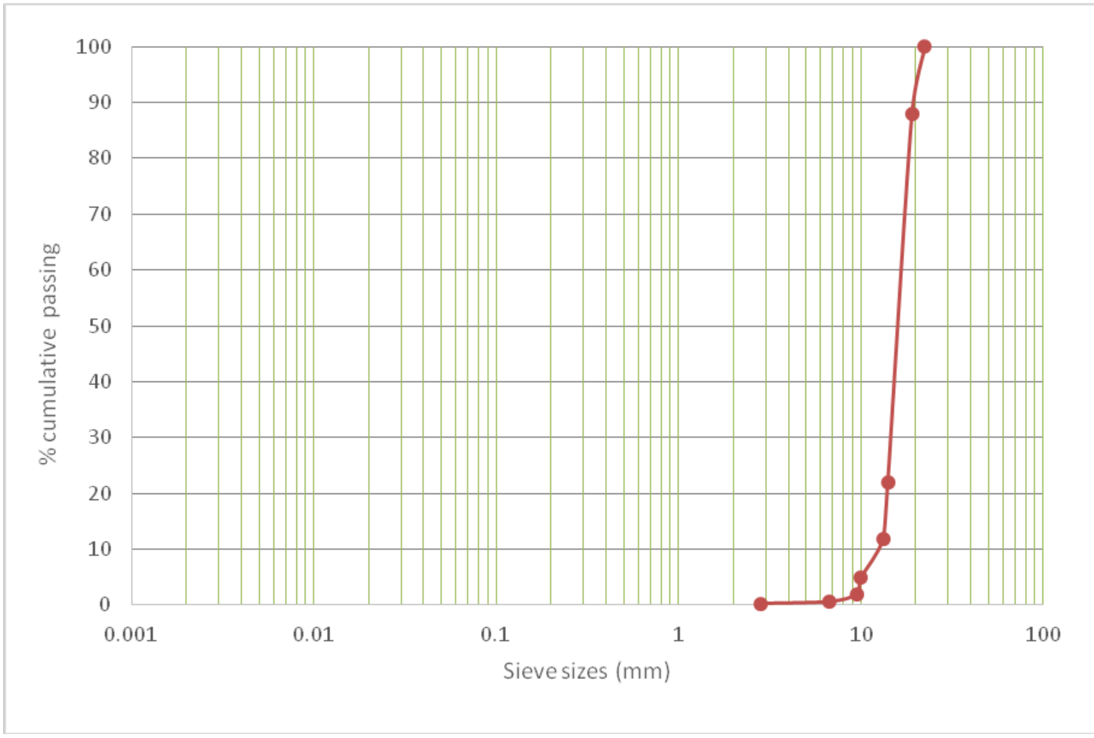

Fig 4.2: Grading curve for the granite chippings

From Fig 4.2, $D_{10} = 11$; $D_{30} = 13$; $D_{60} = 15$

From Eqn. 2.2, coefficient of uniformity (Cu) = $\frac{D_{60}}{D_{10}} = \frac{15}{11} = 1.4$

From Eqn. 2.3, coefficient of curvature (Cc) = $\frac{(D_{30})^2}{D_{10} X D_{60}} = \frac{13^2}{11 * 15} = 1.02$

4.1.1.2 Bulk density of aggregates.

Bulk density test for the fine and coarse aggregates were carried out and the results obtained are presented in Table 4.3 and Table 4.4 respectively.

Table 4.3: Bulk density of river sand

Property	Content (Sample A)	Content (Sample B)
Mass of cutter (kg) and wet sample (kg)	1.7500	1.700
Mass of cutter alone (kg)	0.0756	0.0756
Mass of sample (kg)	1.6744	1.6244
Volume of sample (m^3)	0.000996	0.000996
Bulk density = (mass of sample) / (vol. of sample) = (Kg/m^3)	1681.12	1630.92
Average bulk density (Kg/m^3)	1656.022	

Table 4.4: Bulk density of granite chippings

Property	Content (Sample A)	Content (Sample B)
Mass of cutter (kg) and wet sample (kg)	1.750	1.80
Mass of cutter alone (kg)	0.0756	0.0756
Mass of sample (kg)	1.6744	1.7244
Volume of sample (m^3)	0.00096	0.000996
Bulk density = (mass of sample) / (vol. of sample) = (Kg/m^3)	1681.124	1731.325
Average bulk density (Kg/m^3)	1706.225	

4.1.1.3 Workability test on concrete mixes

Workability test in the form of slump test was carried out on the fresh concrete and the results obtained are presented in Table 4.5.

Table 4.5: Workability test results of concrete mixes

S/No.	Sample No.	Mix ratio	Water-cement ratio.	Slump (cm)			Type of slump
				Sample A	Sample B	Average	
1	N1	0.9 : 0.1 : 3 : 6	0.600	0.00	1.00	1.00	Very low
2	N2	0.85 : 0.15 : 2 : 4	0.570	14.00	15.50	14.75	High
3	N3	0.8 : 0.2 : 2.5: 5	0.550	3.70	0.00	3.70	Low
4	N4	0.7 : 0.3 : 1.5 : 3	0.530	11.50	16.50	14.00	High
5	N5	0.6 : 0.4 : 1 : 2	0.500	18.50	19.50	19.00	High
6	N12	0.875 : 0.125 : 2.5 : 5	0.585	3.20	4.00	3.60	Low
7	N13	0.85 : 0.15 : 2.75 : 5.5	0.575	1.00	1.30	1.15	Very low
8	N14	0.8 : 0.2 : 2.25 : 4.5	0.565	3.50	2.50	3.00	Low
9	N15	0.75 : 0.25 : 2 : 4	0.550	7.00	5.00	6.00	Medium
10	N23	0.825 : 0.175 : 2.25 : 4.5	0.560	3.00	2.50	2.75	Low
11	N24	0.775 : 0.225 : 1.75 : 3.5	0.550	8.70	8.30	8.50	Medium
12	N25	0.725 : 0.275 : 1.5 : 3	0.535	19.00	14.00	16.50	High
13	N34	0.75 : 0.25 : 2 : 4	0.540	7.00	8.00	7.50	Medium
14	N35	0.70 : 0.30 : 1.75 : 3.5	0.525	9.20	12.00	10.50	High
15	N45	0.65 : 0.35 : 1.25 : 2.5	0.515	16.30	17.50	16.90	High
16	C1	0.875 : 0.125 : 2.55 : 5	0.586	3.40	3.50	3.30	Low
17	C2	0.85 : 0.15 : 2.75 : 5.55	0.575	1.00	0.00	1.00	Very low
18	C3	0.775 : 0.225 : 1.75 : 3.55	0.550	8.20	8.50	8.35	Medium
19	C4	0.70 : 0.30 : 1.75 : 3.55	0.525	11.50	9.00	10.25	High
20	C5	0.65 : 0.35 : 1.25 : 2.5	0.517	17.10	18.50	17.80	High
21	C6	0.8625 : 0.1375 : 2.625 : 5.25	0.580	2.50	0.00	2.50	Low
22	C7	0.7625 : 0.2375 : 1.875 : 3.75	0.550	13.50	12.30	12.90	High
23	C8	0.8125 : 0.187 : 2.25 : 4.5	0.5625	4.20	3.80	4.00	Low
24	C9	0.732 : 0.268 : 1.825 : 3.65	0.5429	12.50	11.00	11.75	High
25	C10	0.799 : 0.201 : 2.325 : 4.33	0.5597	3.30	4.50	3.90	Low
26	C11	0.817 : 0.183 : 2.1625 : 4.33	0.5667	8.60	9.60	9.10	Medium
27	C12	0.79 : 0.21 : 2.15 : 4.3	0.557	11.70	8.00	9.85	Medium
28	C13	0.775: 0.225 : 2.1 : 4.2	0.553	2.00	1.40	1.70	Very low
29	C14	0.8125 : 0.1875 : 2.225 : 4.45	0.562	1.20	1.50	1.35	Low
30	C15	0.79 : 0.21 : 2.1 : 4.2	0.560	9.10	7.20	8.15	Medium

4.1.1.4 Setting time test

Results of the initial and final setting time test for the portland cement paste and hydrated lime paste are presented in Table 4.6

Table 4.6: Setting time test for the portland cement paste and hydrated lime paste

Paste	Initial setting time (minutes.)	Final setting time (minutes.)
Cement	60	435
Hydrated lime	2880	4320

4.1.1.5 Chemical property test for the hydrated lime and the portland cement

Chemical property test on the hydrated lime was carried out, and results obtained are presented in Table 4.7. Also, results of chemical property test conducted on the portland cement are presented in Table 4.8

Table 4.7: Chemical properties of hydrated lime

S/NO	Chemical properties	Percentage composition
1	Calcium Oxide (CaO)	93.0%
2	Moisture (H_2O)	0.58%
4	Silicon Oxide(SiO_2)	2.38%
5	Aluminum Oxide(AL_2O_3)	2.04%
6	Magnesium Oxide(MgO)	2.0%
7	pH	8.6

Table 4.8: Chemical properties of portland cement

S/NO	Chemical properties	Content in mass fraction
1	Calcium Oxide (CaO)	67.62
2	Moisture (H_2O)	0.003
3	Silicon Oxide(SiO_2)	20.39
4	Aluminum Oxide(AL_2O_3)	6.03
5	Iron Oxide	2.29
6	Magnesium Oxide(MgO)	1.31
7	Potassium oxide (K_2O)	0.54
8	Titanium oxide (TiO_2)	0.20
9	Loss on ignition	2.80
7	pH	9.2

Source: (Awodiji, 2012, p. 60)

4.1.2 Structural characteristics test results on the hardened lime cement concrete.

The structural characteristics test results were determined and calculated using the equations given under section 3.2.2. They are presented in Table A1 to Table A56 of Appendix A. The summary of these results are as shown on Table 4.9 to Table 4.15.

Table 4.9: Summary of compressive strength results for the lime cement concrete

S/No	Mix no.	Portland cement (PC)	Hydrated lime	Sand	Granite chipping	Water cement ratio	Density Kg/m^3	Compressive Strength (N/mm^2)			
								7th day results	14th day results	21st day results	28th day results
1	N1	0.9000	0.1000	3.0000	6.0000	0.6000	2449	5.60	11.24	14.72	15.12
2	N2	0.8500	0.1500	2.0000	4.0000	0.5700	2514	8.68	16.24	18.30	18.50
3	N3	0.8000	0.2000	2.5000	5.0000	0.5500	2489	7.37	14.61	16.06	17.86
4	N4	0.7000	0.3000	1.5000	3.0000	0.5300	2499	5.67	19.34	21.68	22.00
5	N5	0.6000	0.4000	1.0000	2.0000	0.5000	2558	4.55	14.35	15.78	19.56
6	N12	0.8750	0.1250	2.5000	5.0000	0.5850	2521	9.78	19.18	20.02	20.85
7	N13	0.8500	0.1500	2.7500	5.5000	0.5750	2539	10.29	19.17	22.30	22.70
8	N14	0.8000	0.2000	2.2500	4.5000	0.5650	2558	7.59	18.72	22.30	22.17
9	N15	0.7500	0.2500	2.0000	4.0000	0.5500	2504	7.76	15.87	21.43	21.56
10	N23	0.8250	0.1750	2.2500	4.5000	0.5600	2616	7.03	19.32	25.26	23.81
11	N24	0.7750	0.2250	1.7500	3.5000	0.5500	2568	8.63	18.76	22.56	23.34
12	N25	0.7250	0.2750	1.5000	3.0000	0.5350	2464	7.48	18.32	20.65	21.33
13	N34	0.7500	0.2500	2.0000	4.0000	0.5400	2499	8.71	11.93	16.00	16.22
14	N35	0.7000	0.3000	1.7500	3.5000	0.5250	2499	9.08	10.78	15.35	16.16
15	N45	0.6500	0.3500	1.2500	2.5000	0.5150	2449	6.61	10.90	17.23	19.00
16	C1	0.8750	0.1250	2.5500	5.0000	0.5860	2578	9.62	19.15	20.10	20.85
17	C2	0.8500	0.1500	2.7500	5.5500	0.5750	2578	10.47	19.21	22.27	22.45
18	C3	0.7750	0.2250	1.7500	3.5500	0.5500	2509	11.09	20.67	26.37	26.68
19	C4	0.7000	0.3000	1.7500	3.5500	0.5250	2469	8.92	10.72	16.11	16.20
20	C5	0.6500	0.3500	1.2500	2.5000	0.5170	2471	6.80	10.43	17.48	19.15
21	C6	0.8625	0.1375	2.6250	5.2500	0.5800	2607	10.97	14.90	23.11	23.56
22	C7	0.7625	0.2375	1.8750	3.7500	0.5500	2528	8.81	20.01	23.55	23.87
23	C8	0.8125	0.1870	2.2500	4.5000	0.5625	2529	12.31	22.02	28.00	28.50
24	C9	0.7320	0.2680	1.8250	3.6500	0.5429	2548	8.65	20.03	23.56	23.94
25	C10	0.7990	0.2010	2.3250	4.3300	0.5597	2517	9.10	24.91	29.33	29.85
26	C11	0.8170	0.1830	2.1625	4.3300	0.5667	2528	13.24	20.92	27.33	27.80
27	C12	0.7900	0.2100	2.1500	4.3000	0.5570	2509	11.06	19.13	24.22	24.58
28	C13	0.7750	0.2250	2.1000	4.2000	0.5530	2509	12.26	18.91	28.42	28.90
29	C14	0.8125	0.1875	2.2250	4.4500	0.5620	2548	6.68	24.01	30.23	30.83
30	C15	0.7900	0.2100	2.1000	4.2000	0.5600	2460	12.90	19.34	21.00	21.45

Table 4.10: Summary of flexural strength results for the lime cement concrete

S/No	Mix No.	PC	Hydrated lime	Sand	Granite chippings	Water cement ratio	Density Kg/m^3	Flexural Strength (N/mm^2)			
								7th day results	14th day results	21st day results	28th day results
1	N1	0.900	0.100	3.000	6.000	0.6000	2657	1.480	1.720	2.160	2.280
2	N2	0.850	0.150	2.000	4.000	0.5700	2580	1.750	2.350	3.560	3.860
3	N3	0.800	0.200	2.500	5.000	0.5500	2642	1.630	2.160	3.390	3.620
4	N4	0.700	0.300	1.500	3.000	0.5300	2652	1.600	3.000	3.330	3.490
5	N5	0.600	0.400	1.000	2.000	0.5000	2511	1.740	1.950	2.630	2.960
6	N12	0.875	0.125	2.500	5.000	0.5850	2590	2.300	2.860	4.200	4.370
7	N13	0.850	0.150	2.750	5.500	0.5750	2625	2.450	2.840	3.410	3.910
8	N14	0.800	0.200	2.250	4.500	0.5650	2608	1.930	2.650	3.420	3.980
9	N15	0.750	0.250	2.000	4.000	0.5500	2701	1.820	2.220	3.020	3.230
10	N23	0.825	0.175	2.250	4.500	0.5600	2590	1.650	2.890	4.270	4.390
11	N24	0.775	0.225	1.750	3.500	0.5500	2696	2.250	2.780	4.080	4.260
12	N25	0.725	0.275	1.500	3.000	0.5350	2583	2.170	2.540	3.400	3.580
13	N34	0.750	0.250	2.000	4.000	0.5400	2546	1.620	1.800	2.600	2.770
14	N35	0.700	0.300	1.750	3.500	0.5250	2558	1.470	1.630	2.890	2.940
15	N45	0.650	0.350	1.250	2.500	0.5150	2556	1.580	1.680	2.520	2.670
16	C1	0.875	0.125	2.550	5.000	0.5860	2629	2.430	2.960	4.380	4.510
17	C2	0.850	0.150	2.750	5.550	0.5750	2617	2.250	2.560	3.040	3.270
18	C3	0.775	0.225	1.750	3.550	0.5500	2592	2.140	3.580	3.840	4.020
19	C4	0.700	0.300	1.750	3.550	0.5250	2501	1.400	1.660	2.360	2.820
20	C5	0.650	0.350	1.250	2.500	0.5170	2558	1.510	1.740	2.700	2.700
21	C6	0.863	0.138	2.625	5.250	0.5800	2733	2.220	3.510	4.910	5.030
22	C7	0.763	0.238	1.875	3.750	0.5500	2590	3.080	3.330	3.730	3.850
23	C8	0.813	0.187	2.250	4.500	0.5625	2439	1.640	2.990	4.200	4.360
24	C9	0.732	0.268	1.825	3.650	0.5429	2464	2.320	2.670	3.480	3.670
25	C10	0.799	0.201	2.325	4.330	0.5597	2560	1.670	3.120	4.060	4.150
26	C11	0.817	0.183	2.163	4.330	0.5667	2627	2.030	3.250	4.120	4.280
27	C12	0.790	0.210	2.150	4.300	0.5570	2676	1.960	3.260	3.900	4.100
28	C13	0.775	0.225	2.100	4.200	0.5530	2565	2.270	2.630	2.930	3.020
29	C14	0.813	0.188	2.225	4.450	0.5620	2617	1.640	3.100	4.460	4.520
30	C15	0.790	0.210	2.100	4.200	0.5600	2509	1.830	3.160	4.020	4.160

Table 4.11: Summary of splitting tensile strength results for the lime cement concrete

S/No	Mix No.	Portland cement	Hydrated lime	Sand	Granite chippings	Water cement ratio	Density Kg/m^3	Splitting tensile strength (N/mm^2)			
								7th day results	14th day results	21st day results	28th day results
1	N1	0.900	0.100	3.000	6.000	0.6000	2426	1.300	1.540	1.980	2.100
2	N2	0.850	0.150	2.000	4.000	0.5700	2572	0.800	1.400	2.605	2.905
3	N3	0.800	0.200	2.500	5.000	0.5500	2578	0.710	1.240	2.470	2.700
4	N4	0.700	0.300	1.500	3.000	0.5300	2490	0.690	2.095	2.425	2.585
5	N5	0.600	0.400	1.000	2.000	0.5000	2578	1.130	1.340	2.020	2.250
6	N12	0.875	0.125	2.500	5.000	0.5850	2578	1.360	1.770	3.110	3.280
7	N13	0.850	0.150	2.750	5.500	0.5750	2697	1.225	1.785	2.335	2.835
8	N14	0.800	0.200	2.250	4.500	0.5650	2628	0.490	1.210	2.350	2.540
9	N15	0.750	0.250	2.000	4.000	0.5500	2647	1.015	1.415	2.215	2.425
10	N23	0.825	0.175	2.250	4.500	0.5600	2672	0.610	1.850	3.230	3.350
11	N24	0.775	0.225	1.750	3.500	0.5500	2609	1.190	1.720	3.020	3.200
12	N25	0.725	0.275	1.500	3.000	0.5350	2546	1.240	1.610	2.470	2.650
13	N34	0.750	0.250	2.000	4.000	0.5400	2603	0.930	1.110	1.910	2.080
14	N35	0.700	0.300	1.750	3.500	0.5250	2641	0.735	0.895	2.155	2.205
15	N45	0.650	0.350	1.250	2.500	0.5150	2603	0.910	1.010	1.850	2.000
16	C1	0.875	0.125	2.550	5.000	0.5860	2647	1.300	1.830	3.250	3.380
17	C2	0.850	0.150	2.750	5.550	0.5750	2672	1.430	1.740	2.220	2.450
18	C3	0.775	0.225	1.750	3.550	0.5500	2641	1.135	1.575	2.835	3.015
19	C4	0.700	0.300	1.750	3.550	0.5250	2641	0.700	0.820	2.050	2.115
20	C5	0.650	0.350	1.250	2.500	0.5170	2515	0.835	1.065	1.875	2.025
21	C6	0.863	0.138	2.625	5.250	0.5800	2641	0.915	2.205	3.605	3.725
22	C7	0.763	0.238	1.875	3.750	0.5500	2653	1.565	2.350	2.720	2.850
23	C8	0.813	0.187	2.250	4.500	0.5625	2609	0.550	1.900	3.110	3.270
24	C9	0.732	0.268	1.825	3.650	0.5429	2609	1.400	1.750	2.560	2.750
25	C10	0.799	0.201	2.325	4.330	0.5597	2653	0.630	2.080	3.025	3.115
26	C11	0.817	0.183	2.163	4.330	0.5667	2685	0.960	2.180	3.050	3.210
27	C12	0.790	0.210	2.150	4.300	0.5570	2641	0.940	2.235	2.875	3.075
28	C13	0.775	0.225	2.100	4.200	0.5530	2635	1.500	1.860	2.160	2.250
29	C14	0.813	0.188	2.225	4.450	0.5620	2660	0.520	1.980	3.340	3.400
30	C15	0.790	0.210	2.100	4.200	0.5600	2609	0.770	2.150	2.950	3.120

Table 4.12: Summary of the shear strength results for the lime cement concrete

S/No	Mix **No.**	**Portland cement**	Hydrated **lime**	Sand	Granite **chippings**	Water **cement ratio**	Shear Strength (N/mm^2)			
							7th day results	**14th day results**	**21st day results**	**28th day results**
1	N1	0.9000	0.1000	3.00	6.00	0.6000	0.369	0.430	0.535	0.569
2	N2	0.8500	0.1500	2.00	4.00	0.5700	0.437	0.587	0.889	0.965
3	N3	0.8000	0.2000	2.50	5.00	0.5500	0.408	0.540	0.848	0.906
4	N4	0.7000	0.3000	1.50	3.00	0.5300	0.400	0.751	0.837	0.873
5	N5	0.6000	0.4000	1.00	2.00	0.5000	0.434	0.488	0.657	0.741
6	N12	0.8750	0.1250	2.50	5.00	0.5850	0.575	0.715	1.049	1.093
7	N13	0.8500	0.1500	2.75	5.50	0.5750	0.613	0.710	0.852	0.978
8	N14	0.8000	0.2000	2.25	4.50	0.5650	0.483	0.663	0.855	0.996
9	N15	0.7500	0.2500	2.00	4.00	0.5500	0.455	0.555	0.754	0.807
10	N23	0.8250	0.1750	2.25	4.50	0.5600	0.412	0.723	1.068	1.098
11	N24	0.7750	0.2250	1.75	3.50	0.5500	0.563	0.723	1.021	1.065
12	N25	0.7250	0.2750	1.50	3.00	0.5350	0.543	0.635	0.850	0.946
13	N34	0.7500	0.2500	2.00	4.00	0.5400	0.404	0.450	0.650	0.693
14	N35	0.7000	0.3000	1.75	3.50	0.5250	0.367	0.408	0.684	0.759
15	N45	0.6500	0.3500	1.25	2.50	0.5150	0.394	0.420	0.629	0.668
16	C1	0.8750	0.1250	2.55	5.00	0.5860	0.608	0.741	1.095	1.128
17	C2	0.8500	0.1500	2.75	5.55	0.5750	0.562	0.640	0.760	0.818
18	C3	0.7750	0.2250	1.75	3.55	0.5500	0.536	0.895	0.959	1.006
19	C4	0.7000	0.3000	1.75	3.55	0.5250	0.349	0.416	0.590	0.704
20	C5	0.6500	0.3500	1.25	2.50	0.5170	0.377	0.435	0.674	0.674
21	C6	0.8625	0.1375	2.63	5.25	0.5800	0.554	0.877	1.227	1.257
22	C7	0.7625	0.2375	1.88	3.75	0.5500	0.771	0.833	0.933	0.963
23	C8	0.8125	0.1870	2.25	4.50	0.5625	0.410	0.744	1.050	1.090
24	C9	0.7320	0.2680	1.83	3.65	0.5429	0.579	0.703	0.870	0.917
25	C10	0.7990	0.2010	2.33	4.33	0.5597	0.409	0.779	1.015	1.037
26	C11	0.8170	0.1830	2.16	4.33	0.5667	0.507	0.812	1.030	1.070
27	C12	0.7900	0.2100	2.15	4.30	0.5570	0.490	0.814	0.975	1.026
28	C13	0.7750	0.2250	2.10	4.20	0.5530	0.568	0.657	0.733	0.755
29	C14	0.8125	0.1875	2.23	4.45	0.5620	0.409	0.775	1.115	1.130
30	C15	0.7900	0.2100	2.10	4.20	0.5600	0.457	0.790	1.005	1.040

Table 4.13: Summary of the poisson ratio results for the lime cement concrete

S/No	Mix No.	Portland cement	Hydrated lime	Sand	Granite chippings	Water cement ratio	Poisson Ratio			
							7th day results	14th day results	21st day results	28th day results
1	N1	0.9000	0.1000	3.000	6.000	0.6000	0.264	0.154	0.145	0.151
2	N2	0.8500	0.1500	2.000	4.000	0.5700	0.202	0.145	0.195	0.209
3	N3	0.8000	0.2000	2.500	5.000	0.5500	0.221	0.148	0.213	0.203
4	N4	0.7000	0.3000	1.500	3.000	0.5300	0.283	0.156	0.154	0.159
5	N5	0.6000	0.4000	1.000	2.000	0.5000	0.382	0.136	0.167	0.140
/6	N12	0.8750	0.1250	2.500	5.000	0.5850	0.235	0.149	0.211	0.210
7	N13	0.8500	0.1500	2.750	5.500	0.5750	0.239	0.148	0.153	0.172
8	N14	0.8000	0.2000	2.250	4.500	0.5650	0.255	0.142	0.155	0.181
9	N15	0.7500	0.2500	2.000	4.000	0.5500	0.235	0.140	0.142	0.150
10	N23	0.8250	0.1750	2.250	4.500	0.5600	0.234	0.150	0.170	0.164
11	N24	0.7750	0.2250	1.750	3.500	0.5500	0.261	0.150	0.181	0.183
12	N25	0.7250	0.2750	1.500	3.000	0.5350	0.290	0.140	0.165	0.168
13	N34	0.7500	0.2500	2.000	4.000	0.5400	0.186	0.151	0.165	0.173
14	N35	0.7000	0.3000	1.750	3.500	0.5250	0.162	0.152	0.178	0.183
15	N45	0.6500	0.3500	1.250	2.500	0.5150	0.239	0.155	0.148	0.141
16	C1	0.8750	0.1250	2.550	5.000	0.5860	0.253	0.154	0.218	0.216
17	C2	0.8500	0.1500	2.750	5.550	0.5750	0.215	0.133	0.137	0.146
18	C3	0.7750	0.2250	1.750	3.550	0.5500	0.193	0.173	0.145	0.151
19	C4	0.7000	0.3000	1.750	3.550	0.5250	0.157	0.155	0.147	0.174
20	C5	0.6500	0.3500	1.250	2.500	0.5170	0.222	0.167	0.154	0.141
21	C6	0.8625	0.1375	2.625	5.250	0.5800	0.203	0.237	0.215	0.214
22	C7	0.7625	0.2375	1.875	3.750	0.5500	0.350	0.167	0.159	0.161
23	C8	0.8125	0.1870	2.250	4.500	0.5625	0.133	0.136	0.150	0.153
24	C9	0.7320	0.2680	1.825	3.650	0.5429	0.268	0.140	0.148	0.153
25	C10	0.7990	0.2010	2.325	4.330	0.5597	0.184	0.125	0.139	0.139
26	C11	0.8170	0.1830	2.163	4.330	0.5667	0.153	0.155	0.151	0.154
27	C12	0.7900	0.2100	2.150	4.300	0.5570	0.178	0.171	0.161	0.167
28	C13	0.7750	0.2250	2.100	4.200	0.5530	0.185	0.139	0.103	0.105
29	C14	0.8125	0.1875	2.225	4.450	0.5620	0.246	0.129	0.148	0.147
30	C15	0.7900	0.2100	2.100	4.200	0.5600	0.142	0.164	0.192	0.194

Table 4.14: Summary of the modulus of elasticity results for the lime cement concrete

S/No	Mix No	Portland cement	Hydrated lime	Sand	Granite chippings	Water cement ratio	Modulus of Elasticity ($10^3N/mm^2$) 7th day results	14th day results	21st day results	28th day results
1	N1	0.9000	0.1000	3.000	6.000	0.600	12.332	17.472	19.994	20.264
2	N2	0.8500	0.1500	2.000	4.000	0.570	15.969	21.843	23.187	23.313
3	N3	0.8000	0.2000	2.500	5.000	0.550	14.496	20.409	21.398	22.566
4	N4	0.7000	0.3000	1.500	3.000	0.530	12.791	23.624	25.012	25.196
5	N5	0.6000	0.4000	1.000	2.000	0.500	11.867	21.074	22.099	24.604
6	N12	0.8750	0.1250	2.500	5.000	0.585	17.021	23.837	24.353	24.853
7	N13	0.8500	0.1500	2.750	5.500	0.575	17.647	24.086	25.979	26.211
8	N14	0.8000	0.2000	2.250	4.500	0.565	15.326	24.070	26.153	26.194
9	N15	0.7500	0.2500	2.000	4.000	0.550	15.009	21.464	24.942	25.018
10	N23	0.8250	0.1750	2.250	4.500	0.560	15.255	25.289	28.916	28.074
11	N24	0.7750	0.2250	1.750	3.500	0.550	16.439	24.237	26.579	27.034
12	N25	0.7250	0.2750	1.500	3.000	0.535	14.384	22.511	23.900	24.290
13	N34	0.7500	0.2500	2.000	4.000	0.540	15.854	18.554	21.487	21.634
14	N35	0.7000	0.3000	1.750	3.500	0.525	16.187	17.637	21.046	21.594
15	N45	0.6500	0.3500	1.250	2.500	0.515	13.398	17.205	21.632	22.716
16	C1	0.8750	0.1250	2.550	5.000	0.586	17.457	24.631	19.994	25.701
17	C2	0.8500	0.1500	2.750	5.550	0.575	18.212	24.669	23.187	26.669
18	C3	0.7750	0.2250	1.750	3.550	0.550	17.996	24.569	21.398	27.913
19	C4	0.7000	0.3000	1.750	3.550	0.525	15.756	17.272	25.012	21.233
20	C5	0.6500	0.3500	1.250	2.500	0.517	13.773	17.058	22.099	23.113
21	C6	0.8625	0.1375	2.625	5.250	0.580	18.958	22.094	24.353	27.782
22	C7	0.7625	0.2375	1.875	3.750	0.550	16.223	24.449	25.979	26.703
23	C8	0.8125	0.1870	2.250	4.500	0.563	19.188	25.663	26.153	29.195
24	C9	0.7320	0.2680	1.825	3.650	0.543	16.266	24.752	24.942	27.060
25	C10	0.7990	0.2010	2.325	4.330	0.560	16.380	27.101	28.916	29.666
26	C11	0.8170	0.1830	2.163	4.330	0.567	19.887	24.999	26.579	28.818
27	C12	0.7900	0.2100	2.150	4.300	0.557	17.972	23.636	23.900	26.792
28	C13	0.7750	0.2250	2.100	4.200	0.553	18.922	23.500	21.487	29.051
29	C14	0.8125	0.1875	2.225	4.450	0.562	14.294	27.100	21.046	30.708
30	C15	0.7900	0.2100	2.100	4.200	0.560	18.844	23.073	21.632	24.299

Table 4.15: Summary of the modulus of rigidity results for the lime cement concrete

S/No	Mix No.	Portland cement	Hydrated lime	Sand	Granite chippings	Water cement ratio	Modulus of Rigidity ($10^3 N/mm^2$)			
							7th day results	14th day results	21st day results	28th day results
1	N1	0.9000	0.1000	3.000	6.000	0.6000	4.878	7.570	8.731	8.803
2	N2	0.8500	0.1500	2.000	4.000	0.5700	6.643	9.538	9.702	9.641
3	N3	0.8000	0.2000	2.500	5.000	0.5500	5.936	8.889	8.820	9.379
4	N4	0.7000	0.3000	1.500	3.000	0.5300	4.985	10.218	10.837	10.870
5	N5	0.6000	0.4000	1.000	2.000	0.5000	4.293	9.276	9.468	10.791
6	N12	0.8750	0.1250	2.500	5.000	0.5850	6.891	10.373	10.055	10.270
7	N13	0.8500	0.1500	2.750	5.500	0.5750	7.121	10.490	11.266	11.182
8	N14	0.8000	0.2000	2.250	4.500	0.5650	6.106	10.539	11.322	11.090
9	N15	0.7500	0.2500	2.000	4.000	0.5500	6.077	9.414	10.920	10.877
10	N23	0.8250	0.1750	2.250	4.500	0.5600	6.181	10.995	12.357	12.059
11	N24	0.7750	0.2250	1.750	3.500	0.5500	6.518	10.538	11.253	11.426
12	N25	0.7250	0.2750	1.500	3.000	0.5350	5.575	9.873	10.258	10.398
13	N34	0.7500	0.2500	2.000	4.000	0.5400	6.684	8.060	9.222	9.222
14	N35	0.7000	0.3000	1.750	3.500	0.5250	6.965	7.655	8.933	9.127
15	N45	0.6500	0.3500	1.250	2.500	0.5150	5.407	7.448	9.422	9.954
16	C1	0.8750	0.1250	2.550	5.000	0.5860	6.966	10.672	10.359	10.568
17	C2	0.8500	0.1500	2.750	5.550	0.5750	7.495	10.887	11.681	11.636
18	C3	0.7750	0.2250	1.750	3.550	0.5500	7.542	10.473	12.118	12.126
19	C4	0.7000	0.3000	1.750	3.550	0.5250	6.809	7.477	9.230	9.043
20	C5	0.6500	0.3500	1.250	2.500	0.5170	5.635	7.308	9.568	10.128
21	C6	0.8625	0.1375	2.625	5.250	0.5800	7.879	8.930	11.323	11.442
22	C7	0.7625	0.2375	1.875	3.750	0.5500	6.009	10.475	11.442	11.500
23	C8	0.8125	0.1870	2.250	4.500	0.5625	8.468	11.295	12.582	12.660
24	C9	0.7320	0.2680	1.825	3.650	0.5429	6.414	10.856	11.692	11.735
25	C10	0.7990	0.2010	2.325	4.330	0.5597	6.917	12.045	12.909	13.023
26	C11	0.8170	0.1830	2.163	4.330	0.5667	8.624	10.822	12.412	12.486
27	C12	0.7900	0.2100	2.150	4.300	0.5570	7.628	10.092	11.453	11.479
28	C13	0.7750	0.2250	2.100	4.200	0.5530	7.984	10.316	13.059	13.145
29	C14	0.8125	0.1875	2.225	4.450	0.5620	5.736	12.002	13.242	13.386
30	C15	0.7900	0.2100	2.100	4.200	0.5600	8.250	9.911	10.085	10.175

Results of the 28th day compressive strengths and slump values, for the first five trial mixes were obtained. These were used to make comparison with the mixes having some percentage replacement of portland cement with hydrated lime as shown in Table C1 to Table C3 of Appendix C. Bar charts, representing Table C2 and C3 are presented in Fig 4.3 and Fig 4.4.

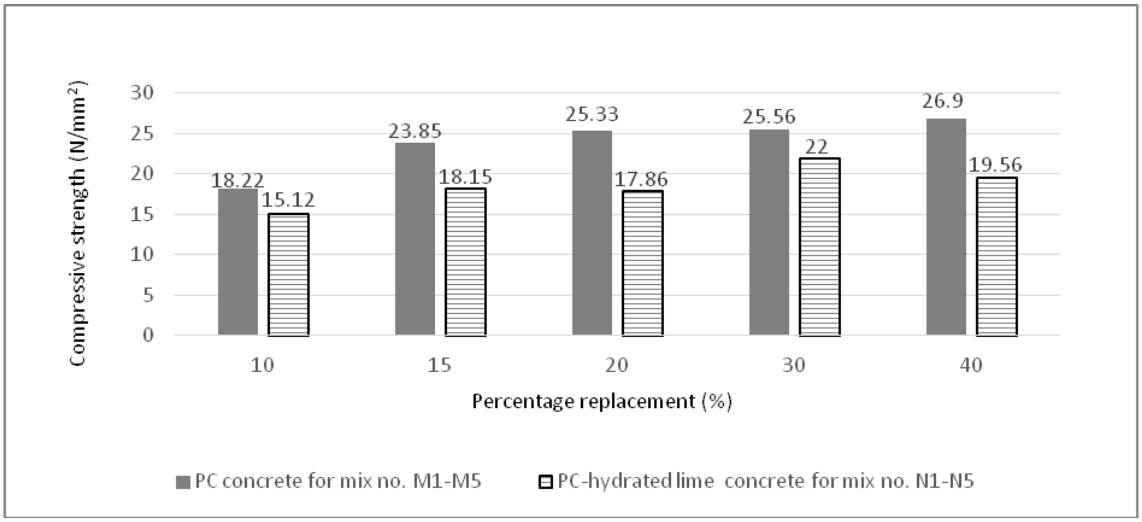

Fig 4.3: Compressive strength (N/mm^2) against percentage replacement (%)

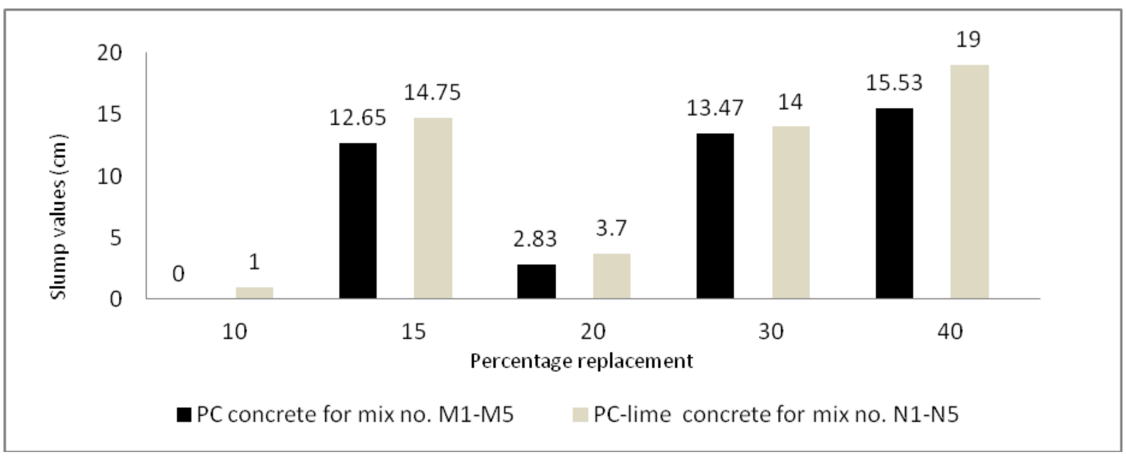

Fig 4.4: Bar chart of slump value (cm) against percentage replacement

Fig 4.5 to Fig 4.11 present the relationships between the various 28 days structural characteristics of the lime cement concrete with respect to water cement ratio.

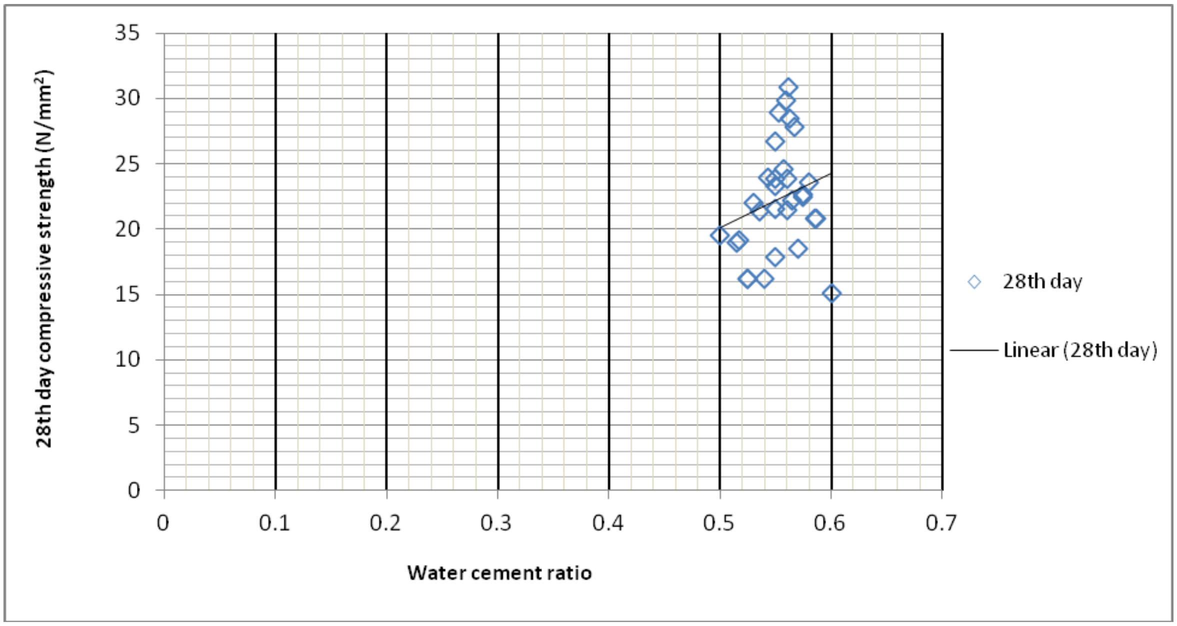

Fig 4.5: Relationship between compressive strength (N/mm^2) against water cement ratio at 28th day curing age

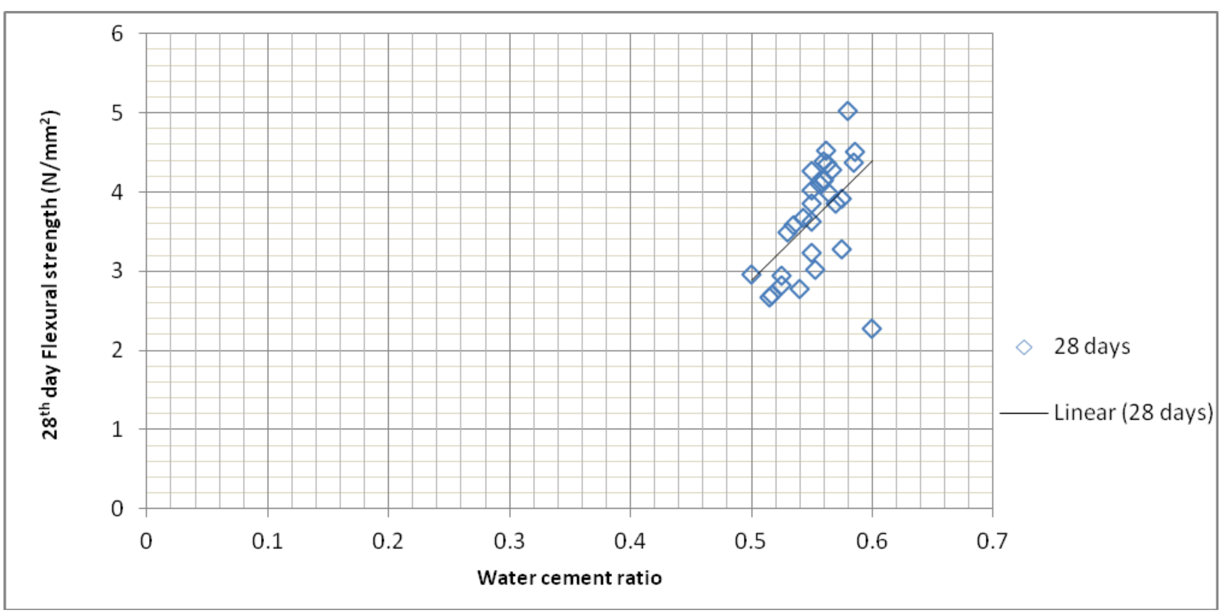

Fig 4.6: Relationship between flexural strength (N/mm^2) against water cement ratio at 28th day curing age.

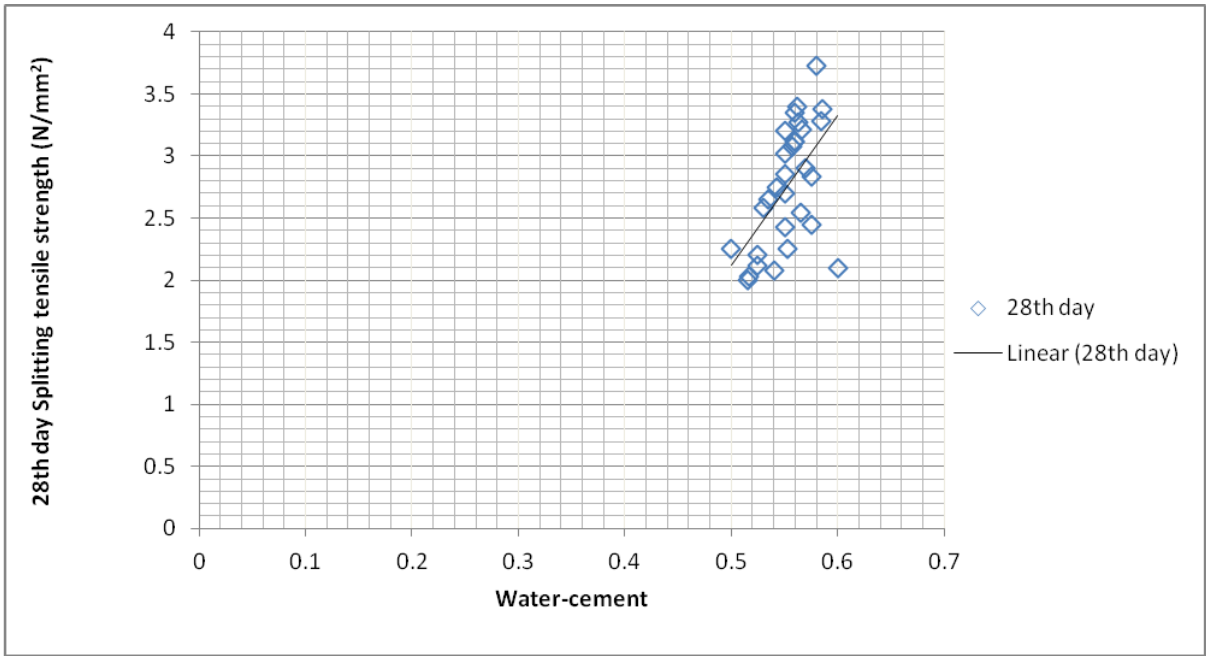

Fig 4.7: Relationship between splitting tensile strength (N/mm^2) and water-cement ratio at 28th day curing age.

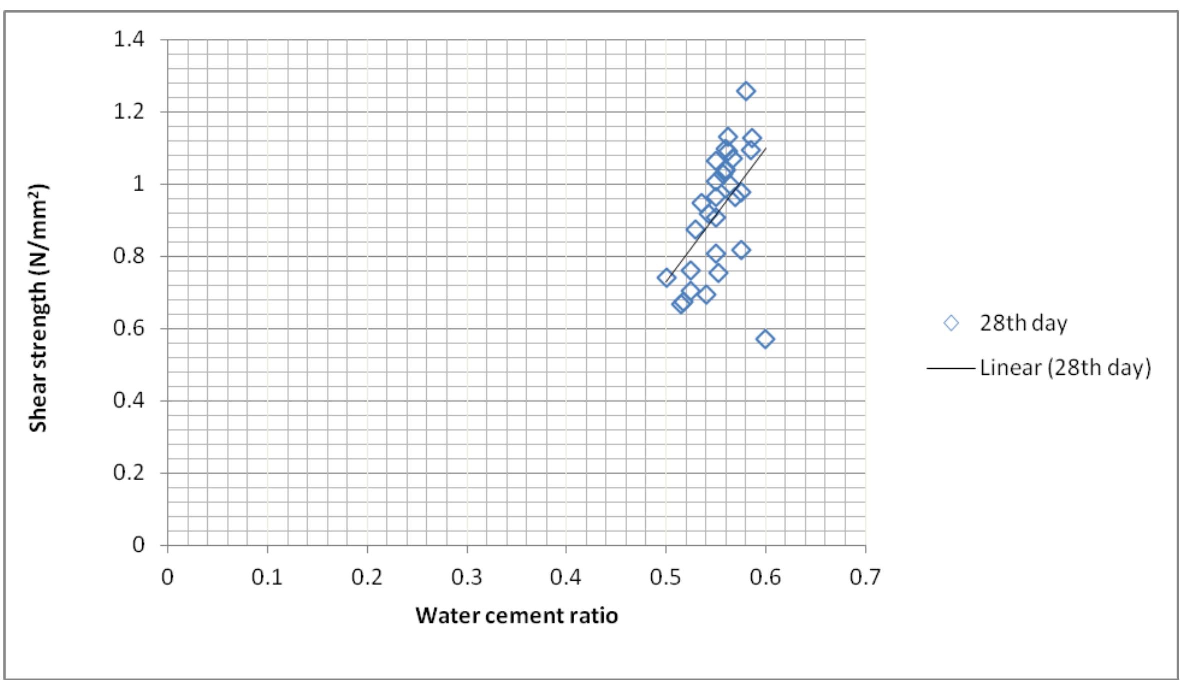

Fig 4.8: Relationship between shear strength (N/mm^2) and water cement ratio at 28th day curing age.

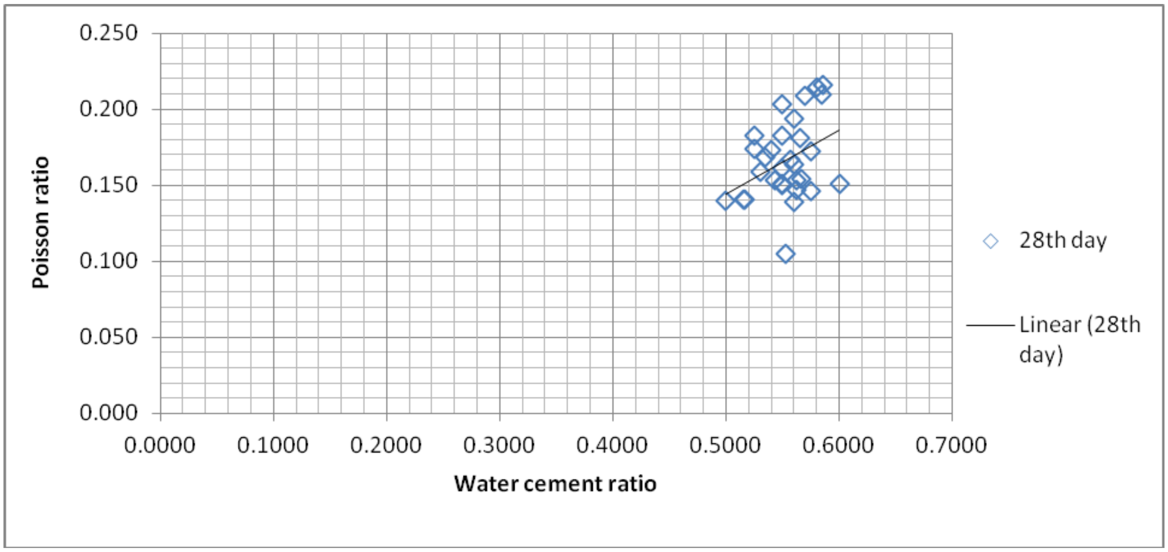

Fig 4.9: Relationship between poisson ratio and water cement ratio at 28th day curing age

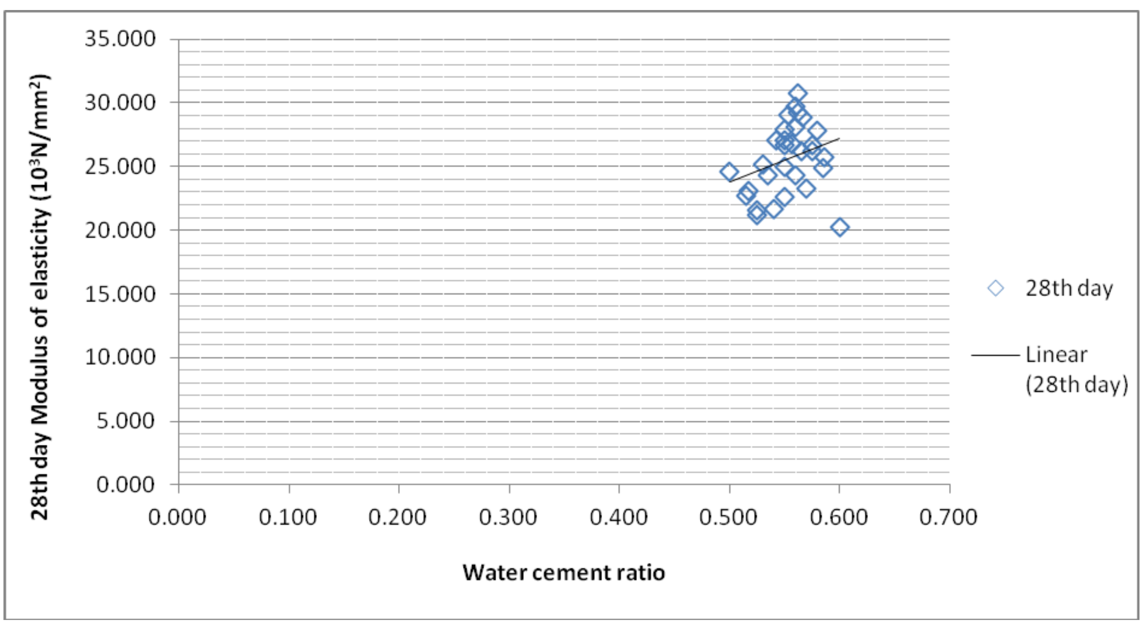

Fig 4.10: Relationship between modulus of elasticity ($10^3 N/mm^2$) and water cement ratio at 28th day curing age

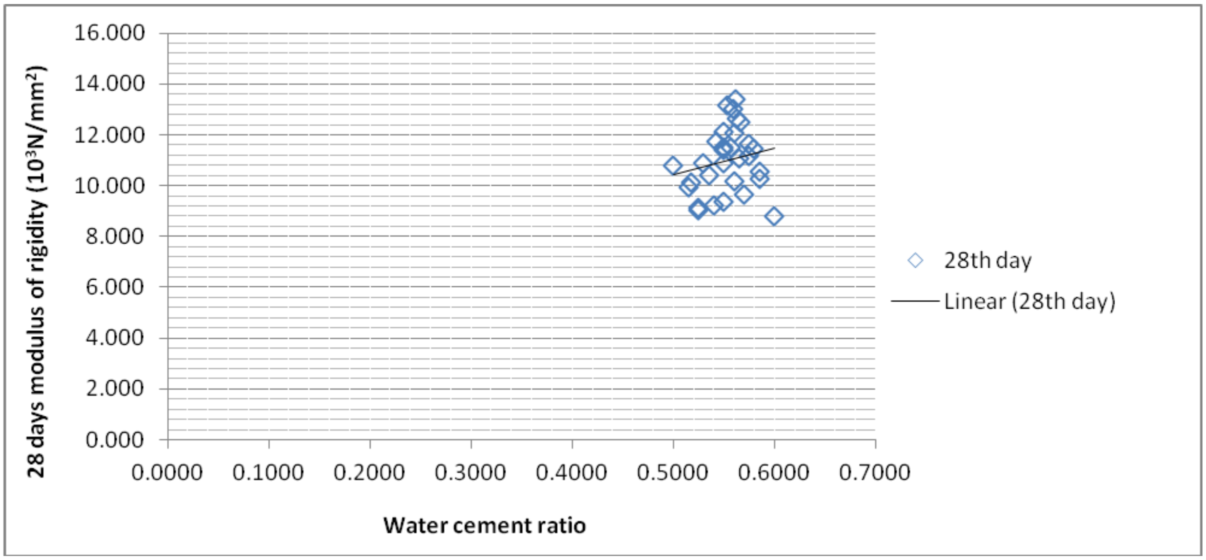

Fig 4.11: Relationship between modulus of rigidity (10^3N/mm^2) and water cement ratio at 28th day curing

4.1.3 Formulation of the artificial neural network models

The results of the structural characteristics of lime cement concrete shown on Table 4.9 to Table 4.15, were used to develop seven artificial neural networks for predicting the structural characteristics of lime cement concrete. The mix proportions of water-cement ratio, portland cement (PC), hydrated lime, river sand, granite chippings and curing age represent the input vectors used for the training of the networks, while their corresponding values of structural characteristic represents the output vector. Fig 4.12 shows the general structure of all the seven neural networks developed. They have 6 input neurons, 20 hidden layer neurons and one output neuron respectively.

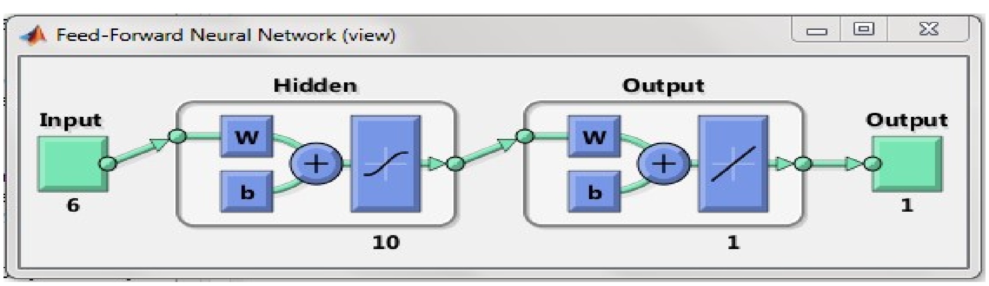

Fig 4.12: General structure for the seven neural networks

The architecture of the neural networks formulated, is presented in Fig 4.13.This was selected by trial and error, in other to minimize the error and obtain speedy convergence of the networks. The networks used for training consist of an input layer, a hidden layer and an output layer. The input layer consist of six (6) neurons, representing the input parameter which are; water cement ratio, portland cement, hydrated lime, river sand, granite chippings and curing age. The output layer had one neuron for each of the seven networks developed. As shown in Table 4.16, these outputs represent the compressive strength, flexural strength, splitting tensile strength, shear strength, possion ratio, modulus of elasticity and modulus of rigidity of the lime cement concrete respectively. The hidden layer consist of twenty (20) neurons, and the tangent sigmoid transfer function was used as activation function. This activation function was selected to allow the network vectors, learn the non-linear relationship between inputs and output as shown in Table 4.17.

Table 4.16: Artificial neural network information

No.	ANN information	Database
1.	The number of data used to create the network	114 data was presented for each network.
2.	Data no. used for training	80
3.	Data no. used for verifying	17
4.	Data no. used for testing	17
5.	Input data	Water cement ratio, portland cement, hydrated lime, river sand, granite chippings and curing age.
6.	Outputs	Compressive strength, flexural strength, split tensile strength, shear strength, poisson ratio, modulus of elasticity, modulus of rigidity.

Table 4.17: Artificial neural network modeling data for each network developed

Training Algorithm	Function	Network Architecture	Training Data	Validating Data	Testing Data
Levenber-Marquardt Back-propagation	TANSIG	6 – 20 – 1 (respectively)	80	17	17

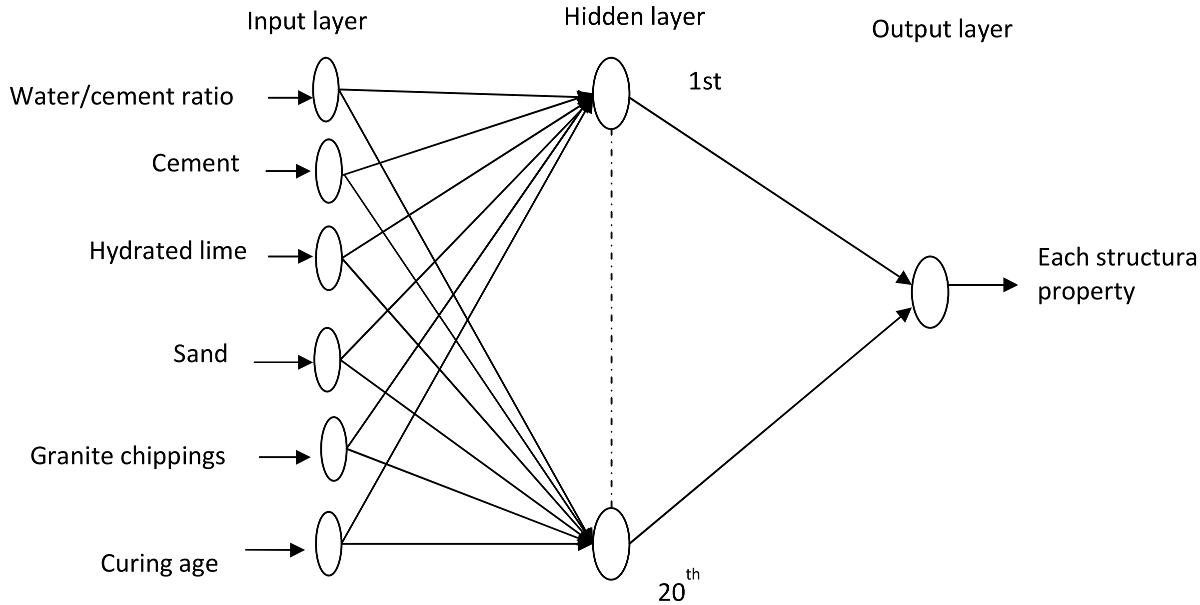

Fig 4.13: Architecture of the neural networks developed

4.1.3.1 Selection of training data

This is a very important step in training a neural network. In preparing the training data set, it was important that the data covered the range of inputs for which the networks will be used. Increasing the number of training data set increased the potential level of accuracy that the networks could achieve but a large number of training patterns can sometimes overwhelm the training algorithm. In the present study, a total of a hundred and fourteen (114) training data set were presented to the networks respectively. Eighty (80) of these were used for training the network, seventeen (17) were used for validation, and another seventeen (17) were used for testing the network's performance. This division was achieved by the use of the 'dividerand' function and the network objects.

4.1.4 Validation of network performance

Validation of the various artificial neural networks (ANNs) were carried out, to see how well the networks were performing during training.

(a) Performance validation on the ANN used for predicting compressive strength of lime cement concrete.

Fig 4.14 to Fig 4.18 present the various results of the performance validation carried out on the ANN developed for predicting the compressive strength of lime cement concrete, given the curing age.

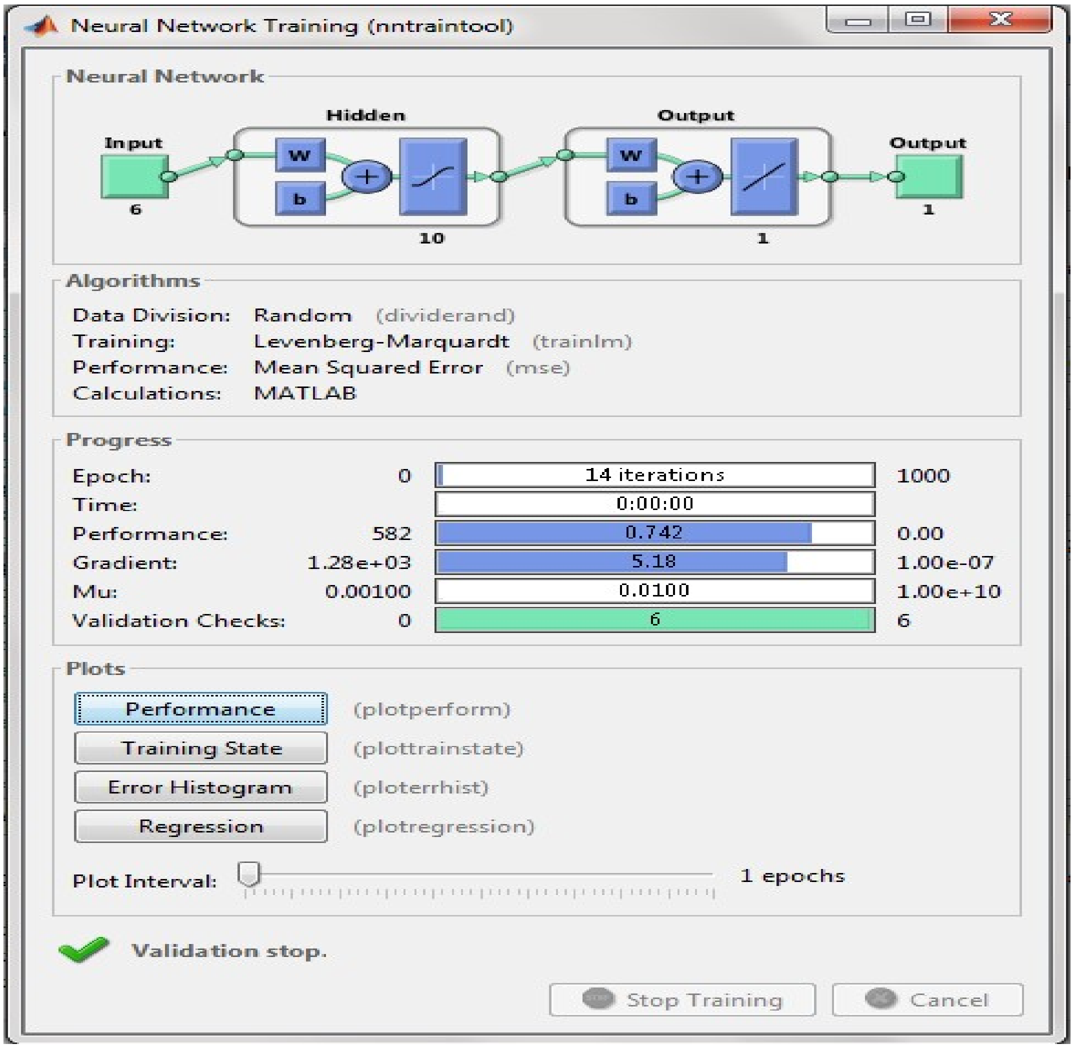

Fig 4.14: Compressive strength ANN training details

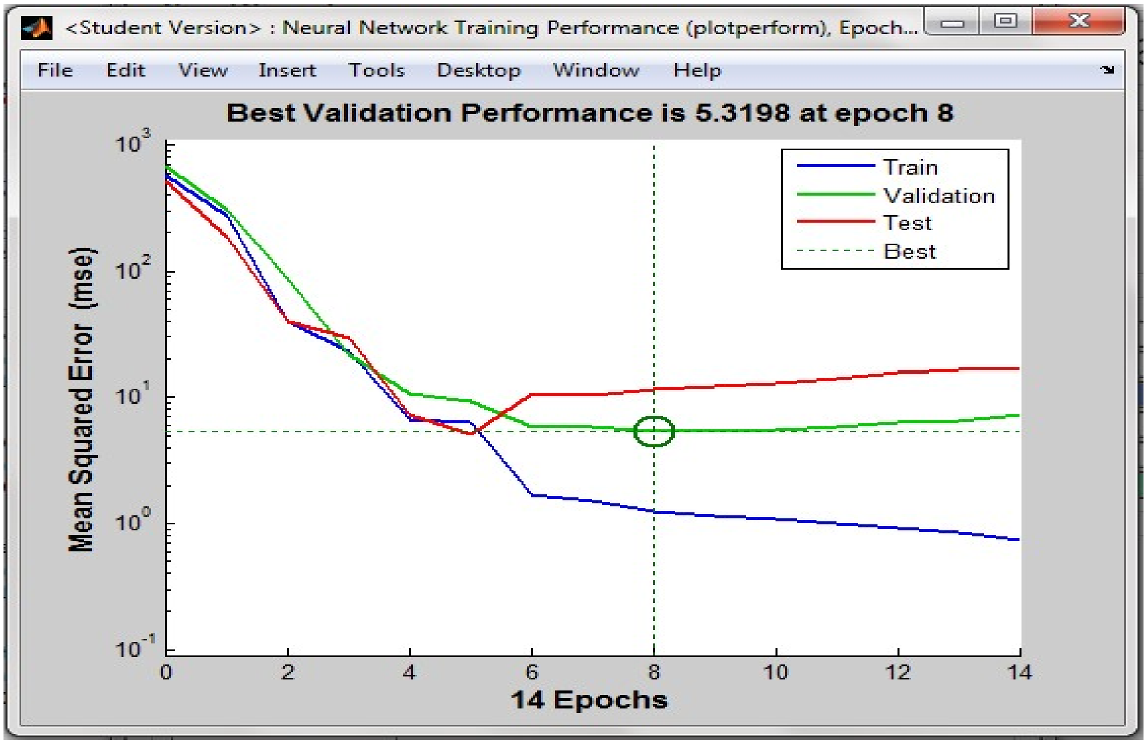

Fig 4.15: Training performance graph for compressive strength neural network (NN)

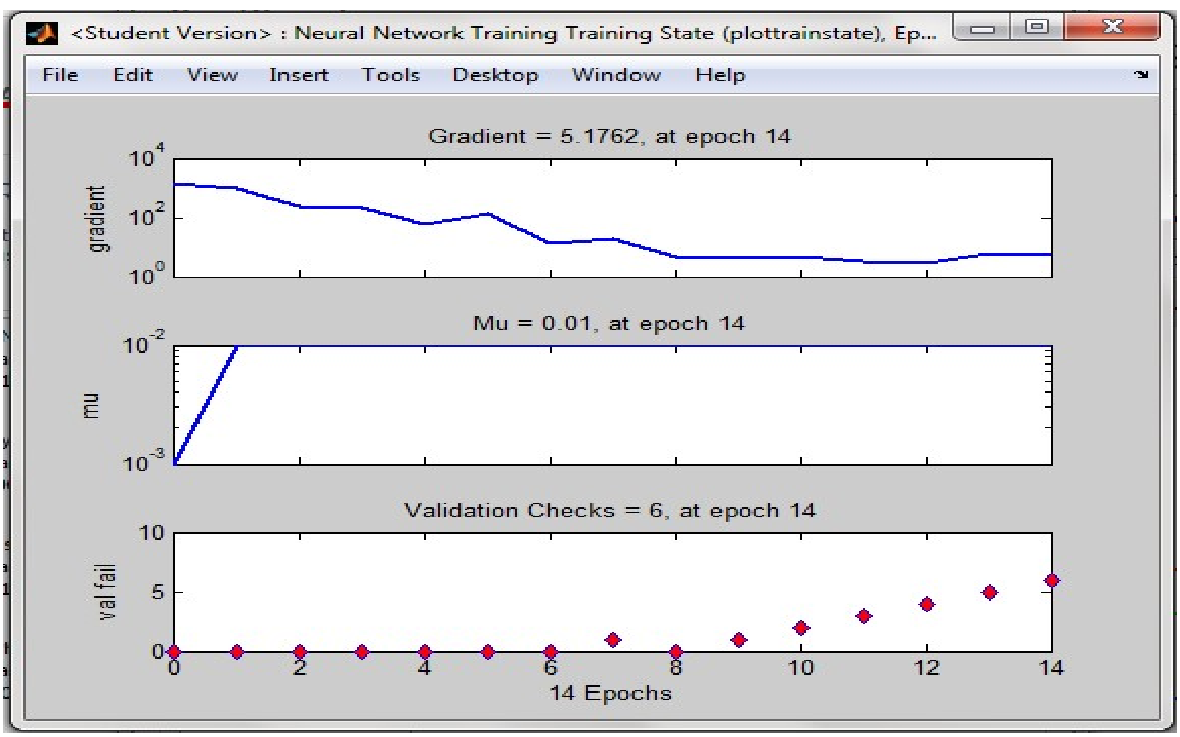

Fig 4.16: Compressive strength NN training state

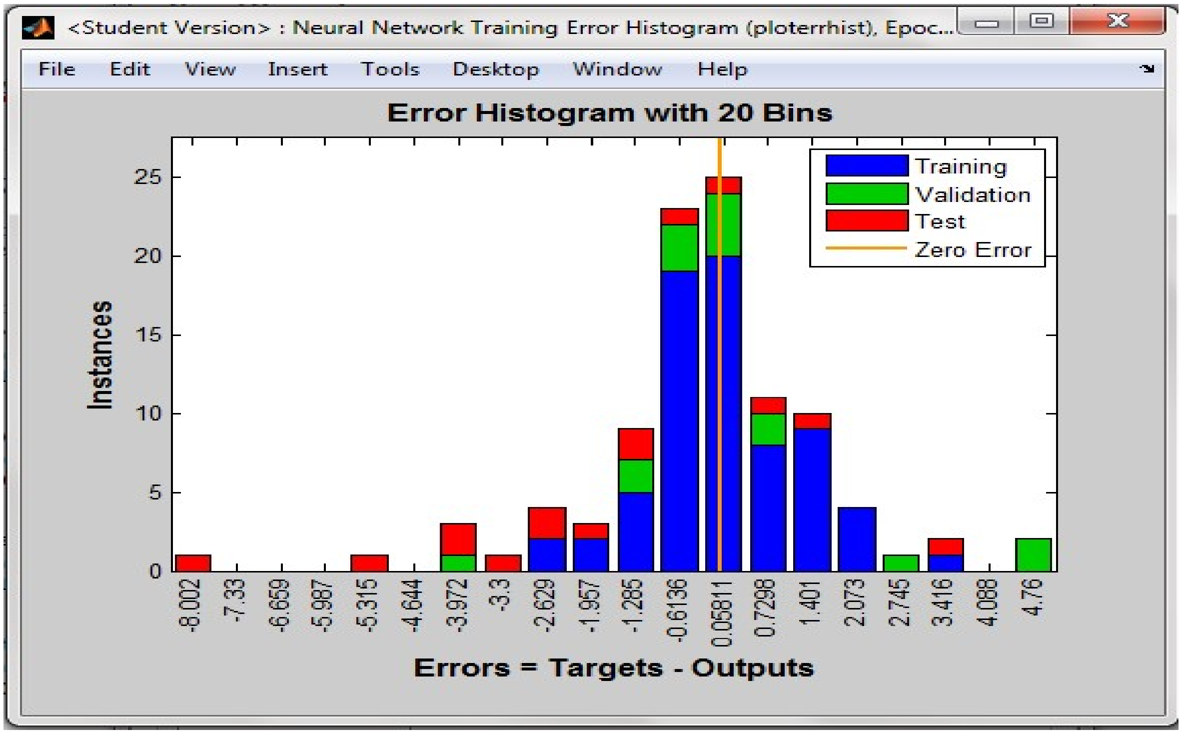

Fig 4.17: Error histogram of compressive strength NN

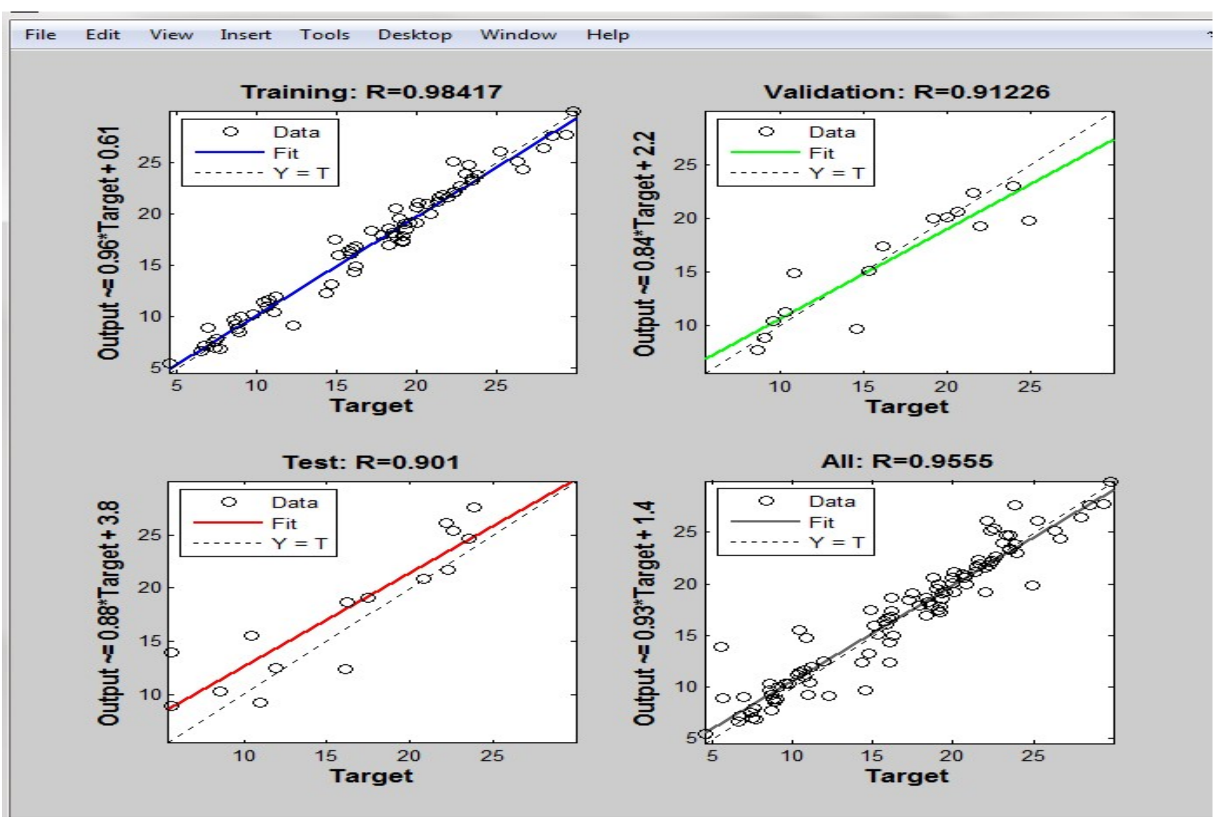

Fig 4.18: Regression curve for the compressive strength NN

(b) Performance validation on the ANN used for predicting flexural strength of lime cement concrete.

Fig 4.19 to Fig 4.23 present the various results of the performance validation carried out on the ANN developed for predicting the flexural strength of lime cement concrete, given the curing age.

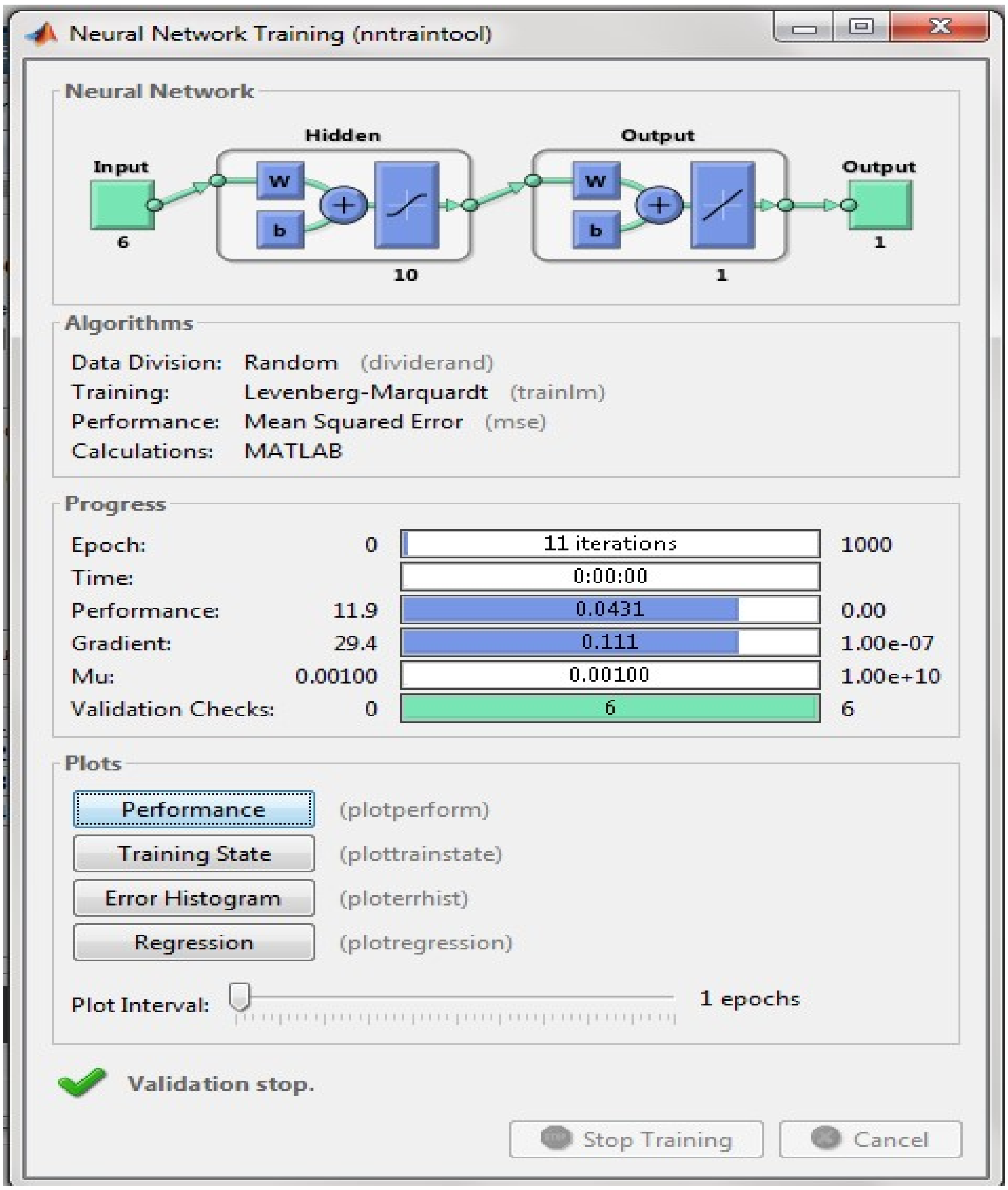

Fig 4.19: Flexural strength ANN training details

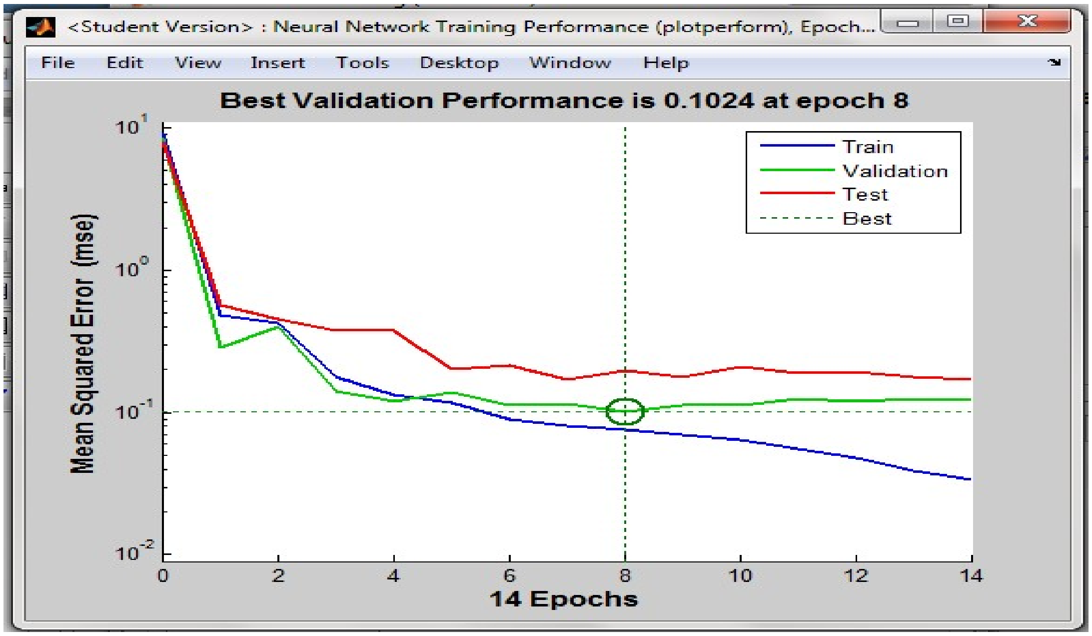

Fig 4.20: Training performance graph for flexural strength NN

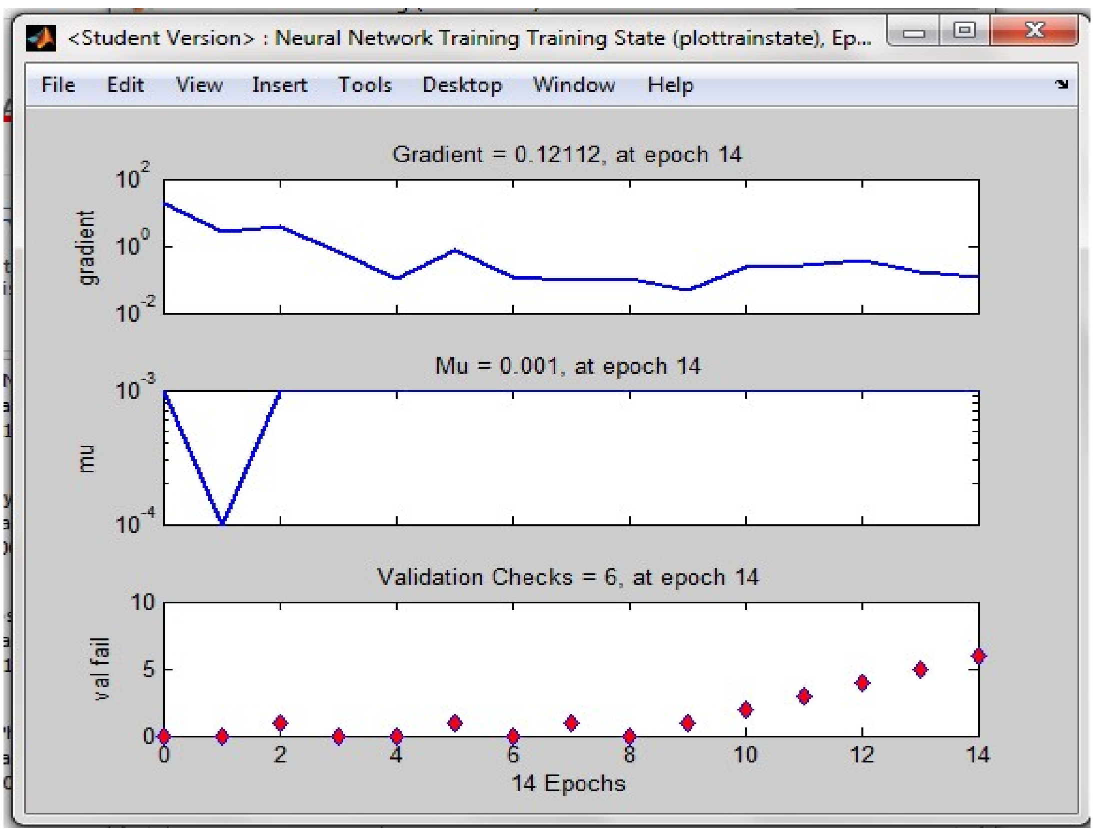

Fig 4.21: Flexural strength NN training state

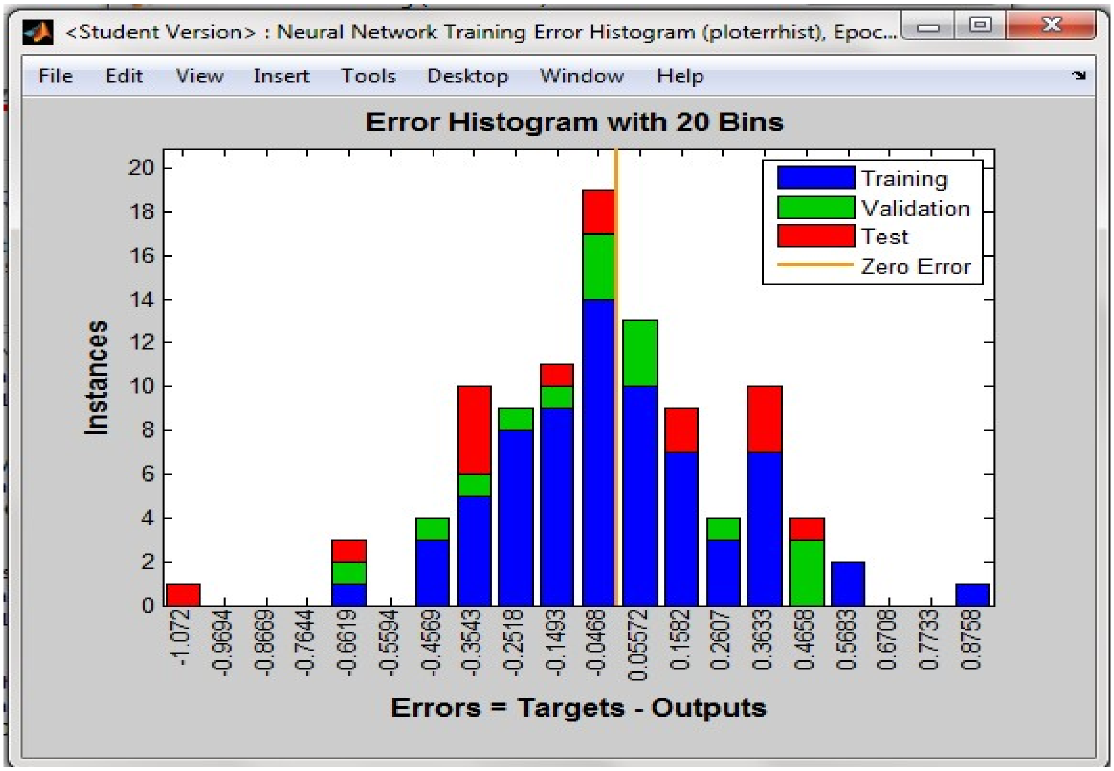

Fig 4.22: Error histogram of flexural strength NN

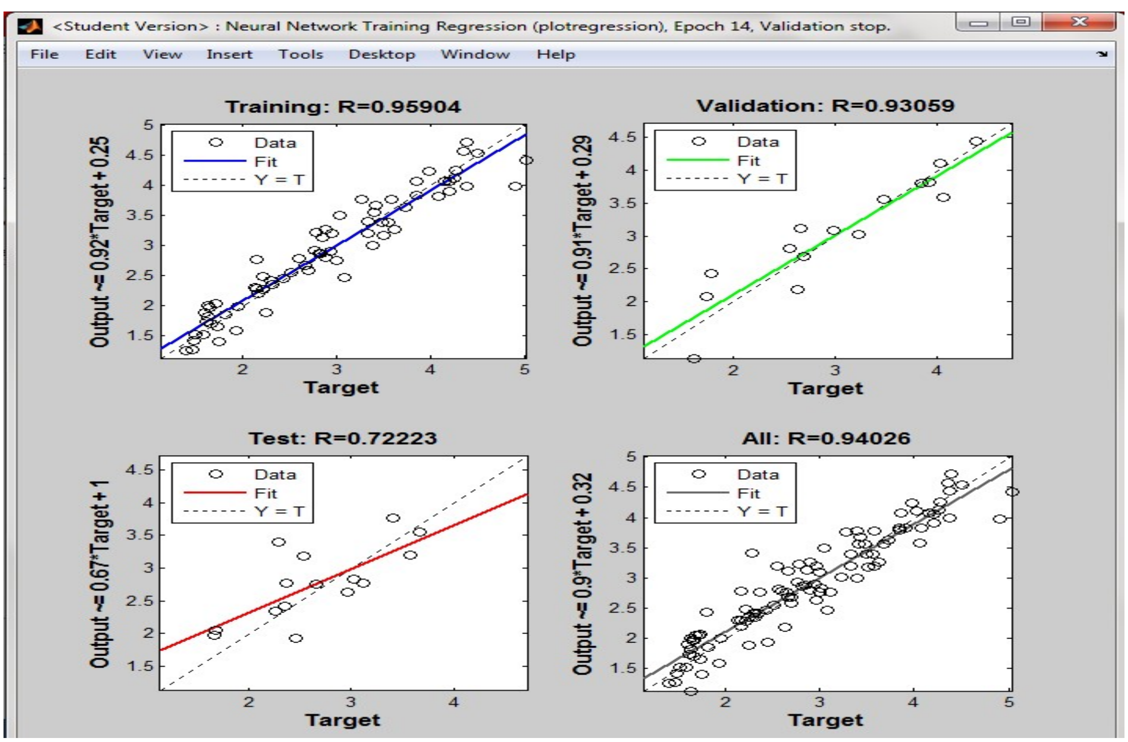

Fig 4.23: Regression curve for the flexural strength NN

(c) Performance validation on the ANN used for predicting split tensile strength of lime cement concrete.

Fig 4.24 to Fig 4.28 present the various results of the performance validation carried out on the (artificial neural network) ANN developed for predicting the split tensile strength of lime cement concrete, given the curing age.

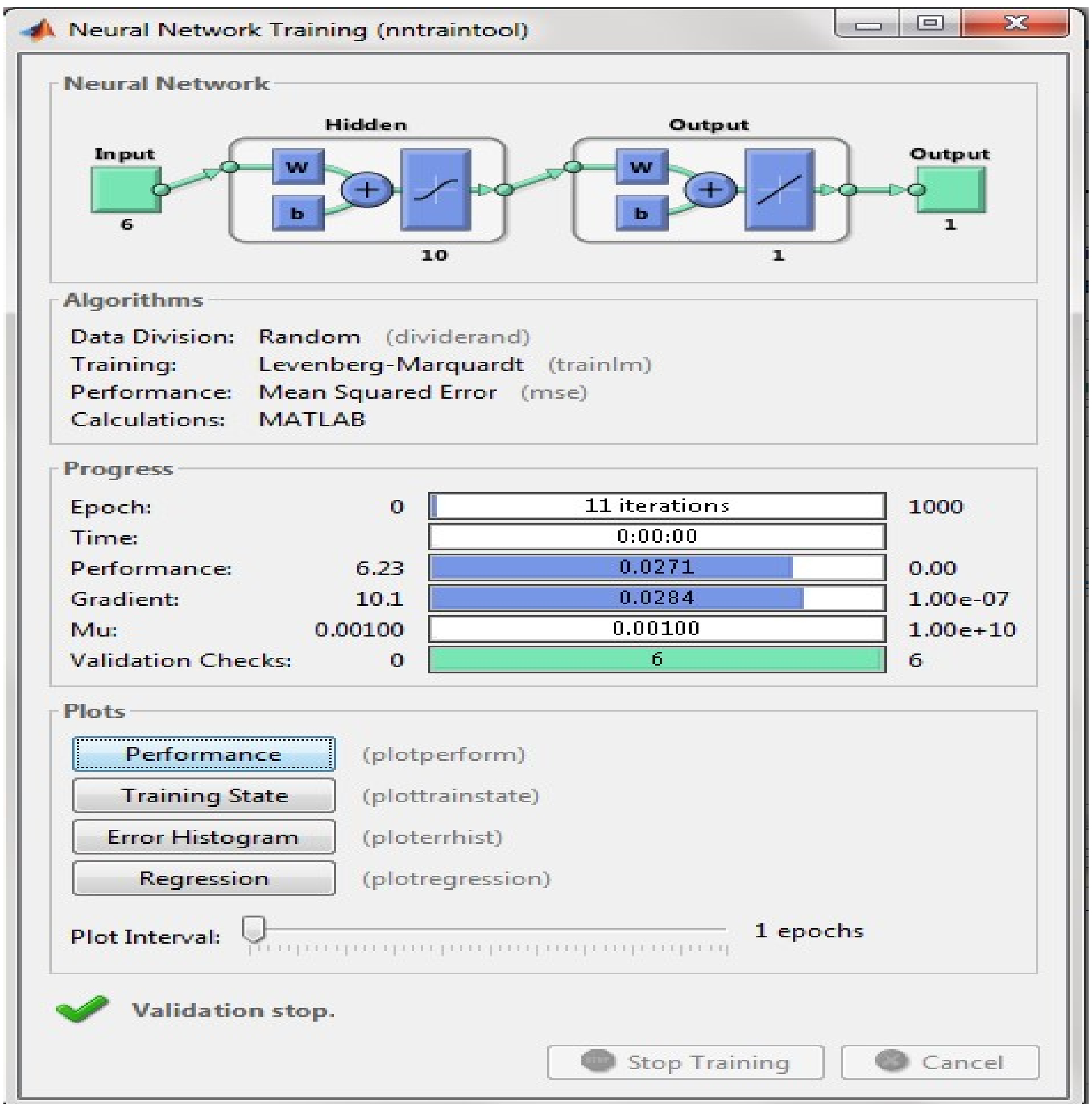

Fig 4.24: Split tensile strength ANN training details

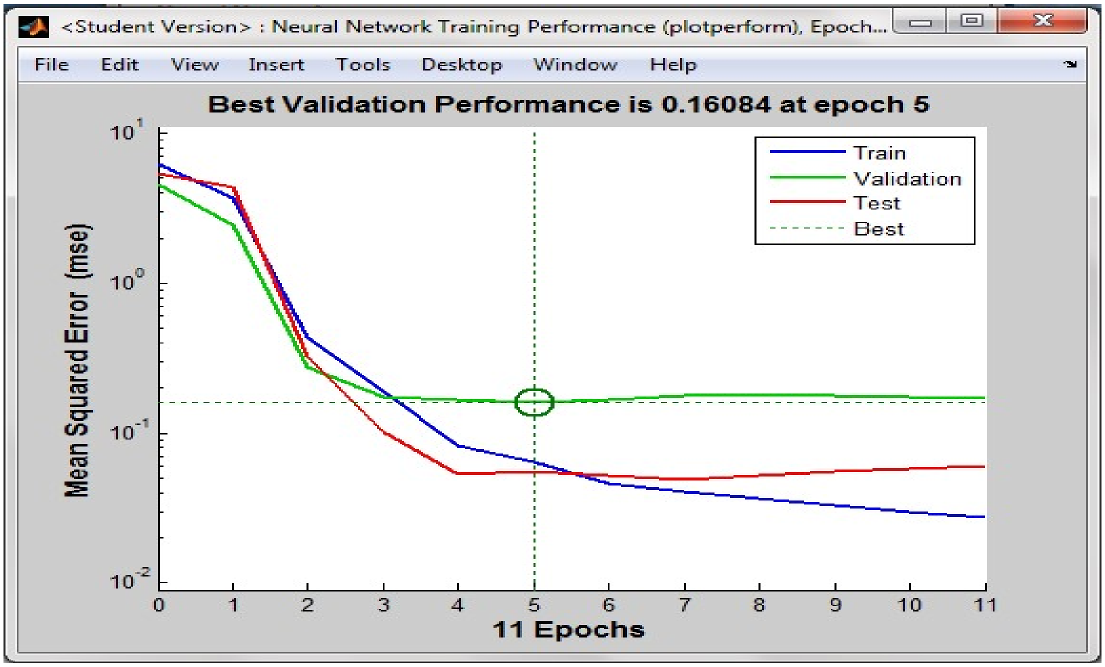

Fig 4.25: Training performance graph for split tensile strength NN

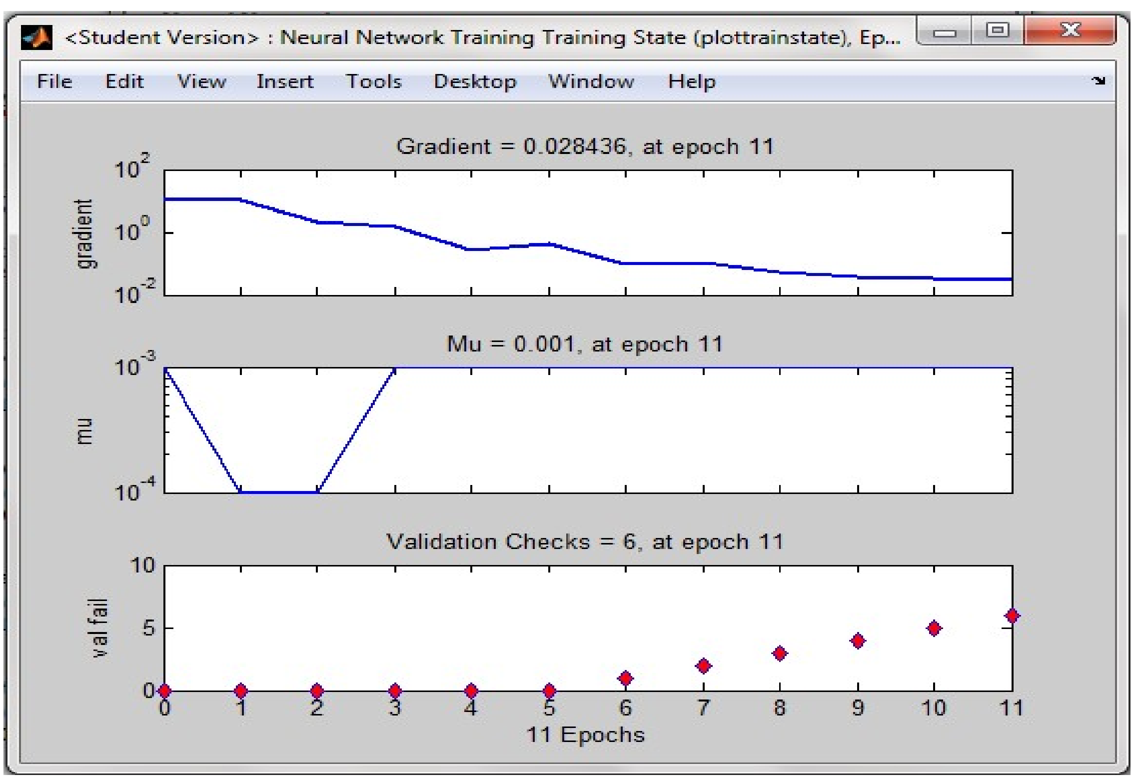

Fig 4.26: Split tensile strength NN training state

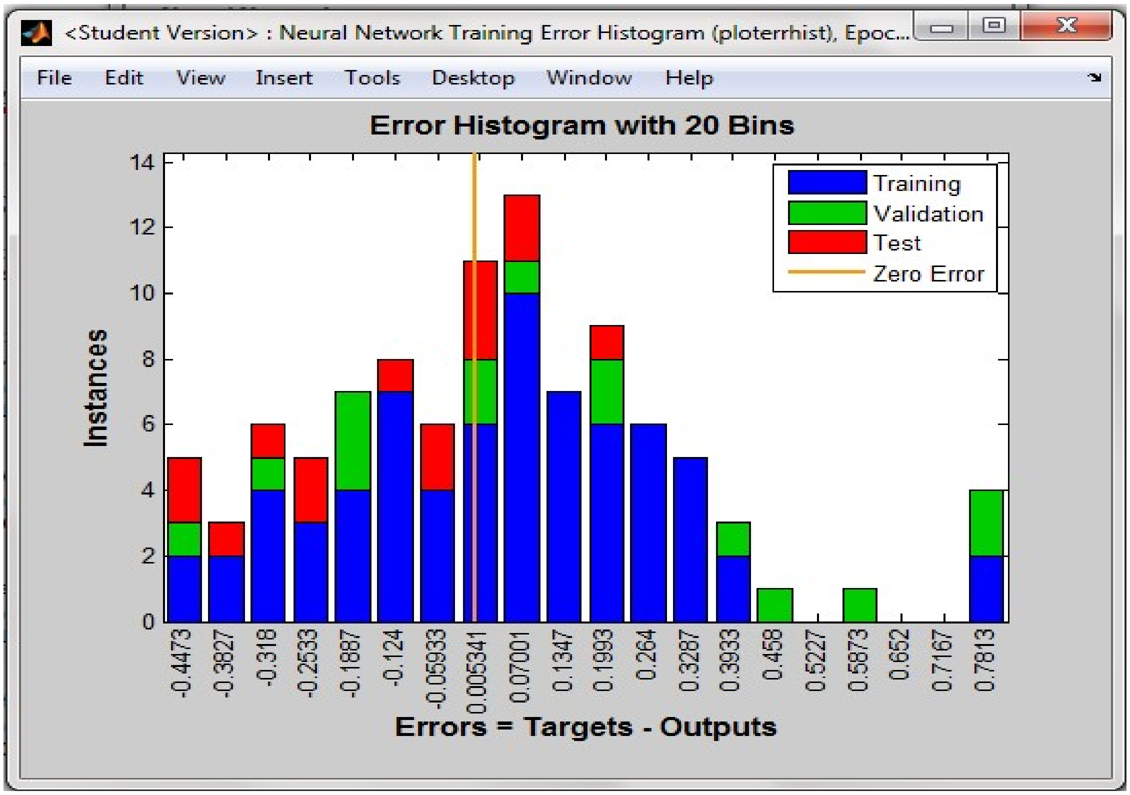

Fig 4.27: Error histogram of split tensile strength NN

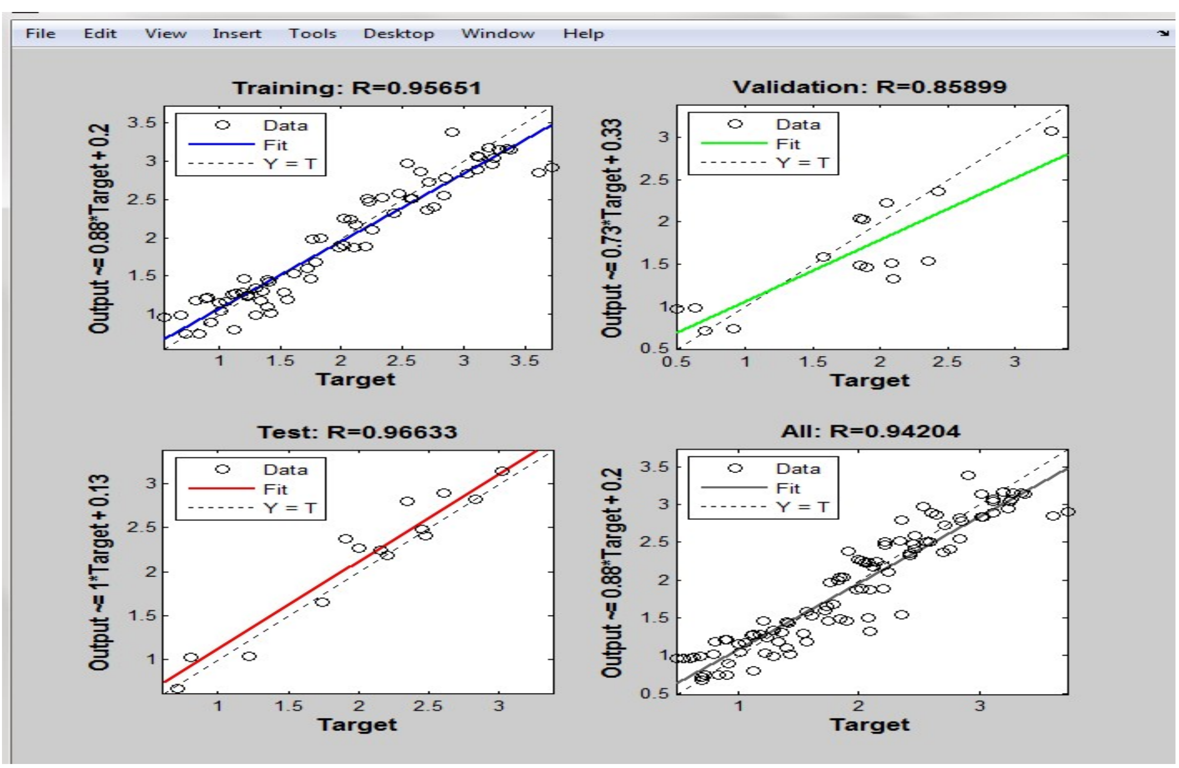

Fig 4.28: Regression curve for the split tensile strength NN

(d) Performance validation on the ANN used for predicting shear strength of lime cement concrete.

Fig 4.29 to Fig 4.33 present the various results of the performance validation carried out on the ANN developed for predicting the shear strength of lime cement concrete, given the curing age.

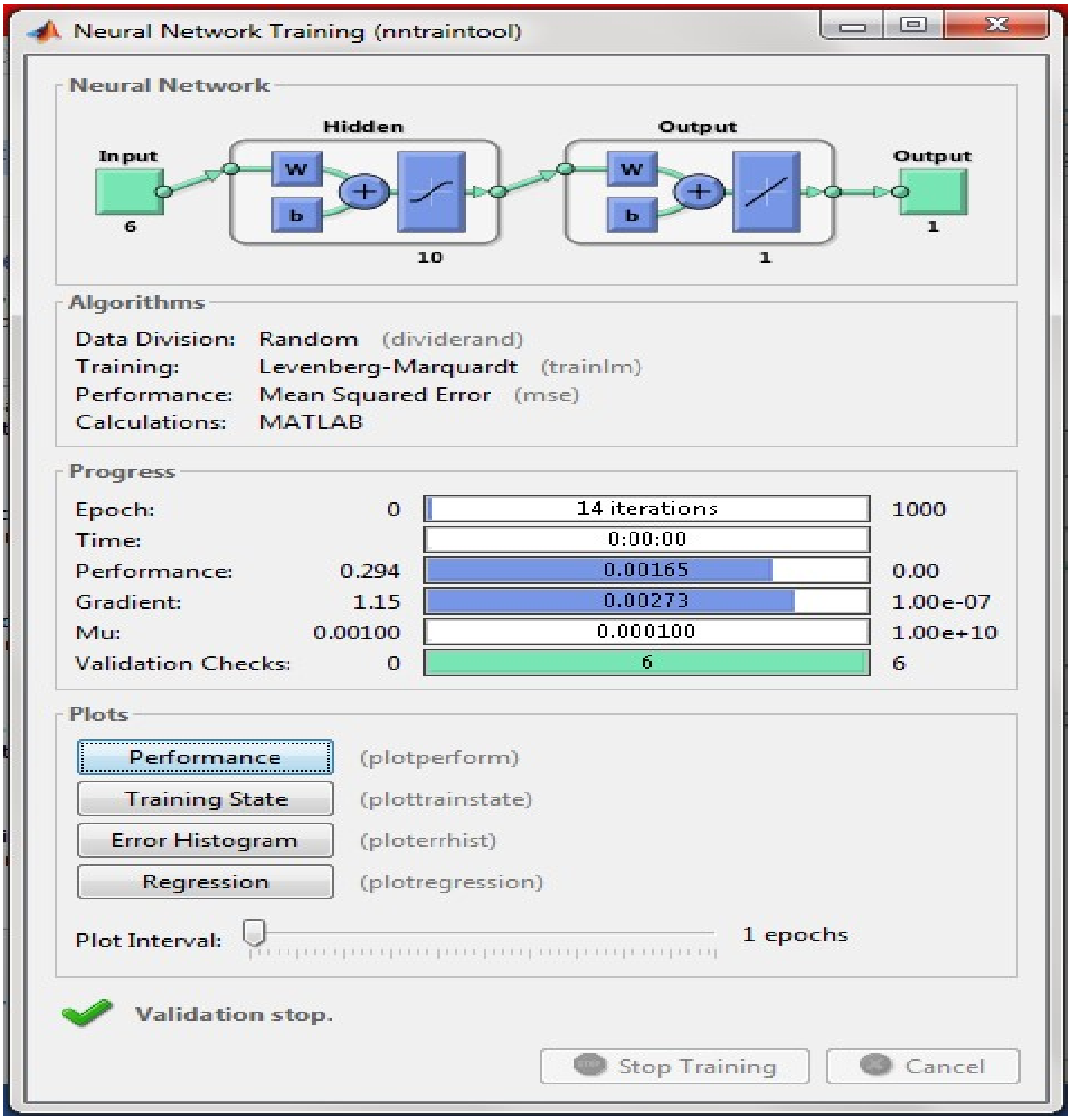

Fig 4.29: Shear strength ANN training details

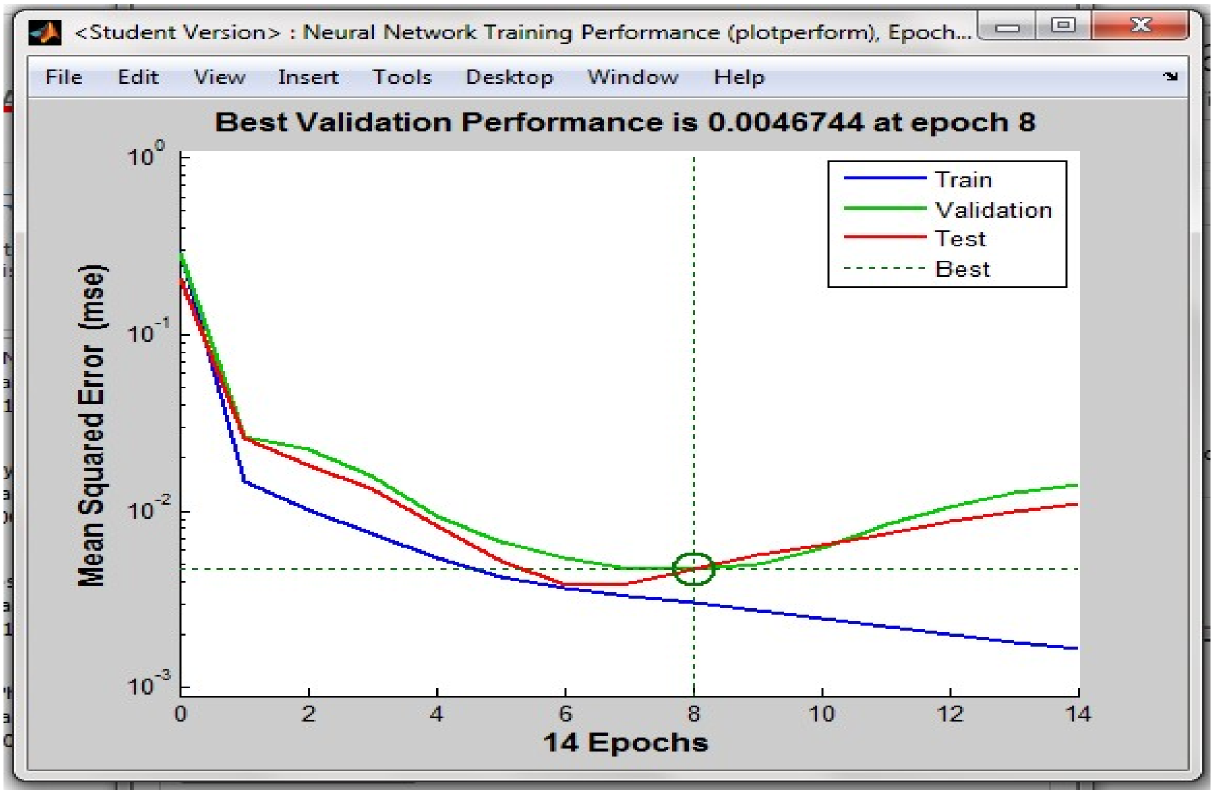

Fig 4.30: Training performance graph for shear strength NN

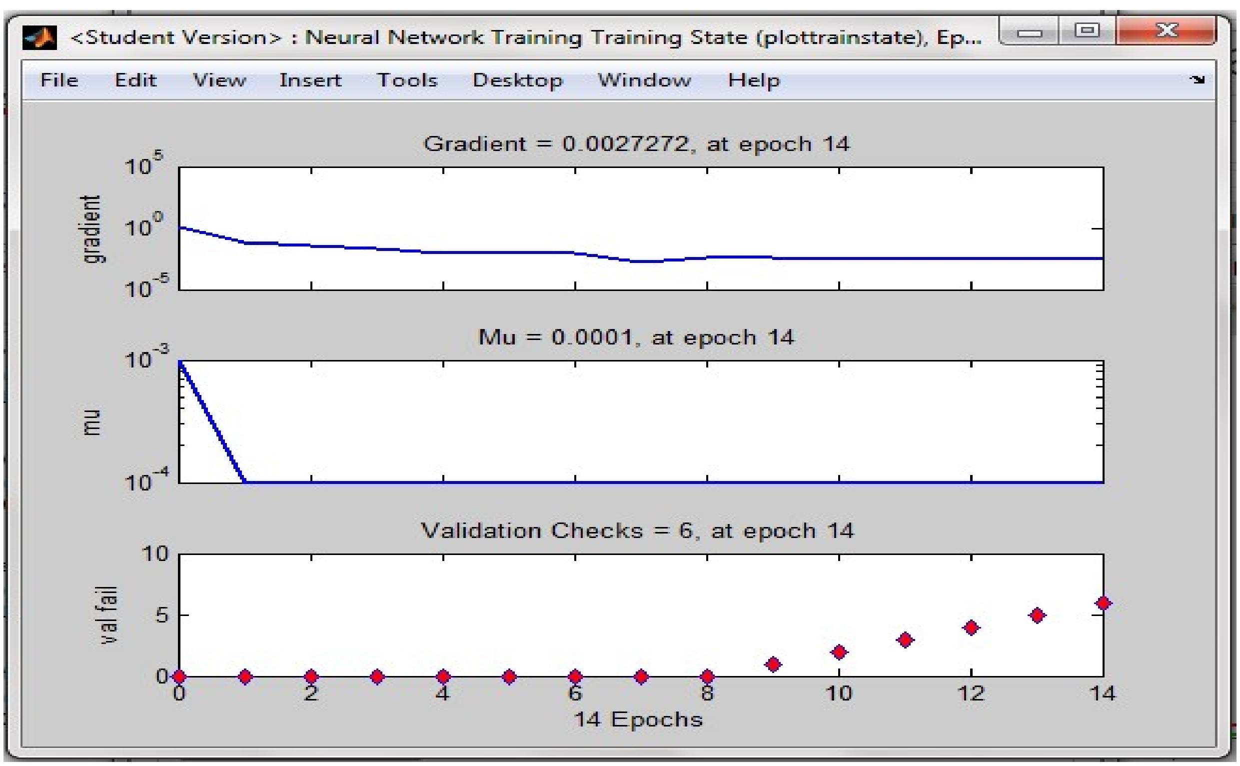

Fig 4.31: Shear strength NN training state

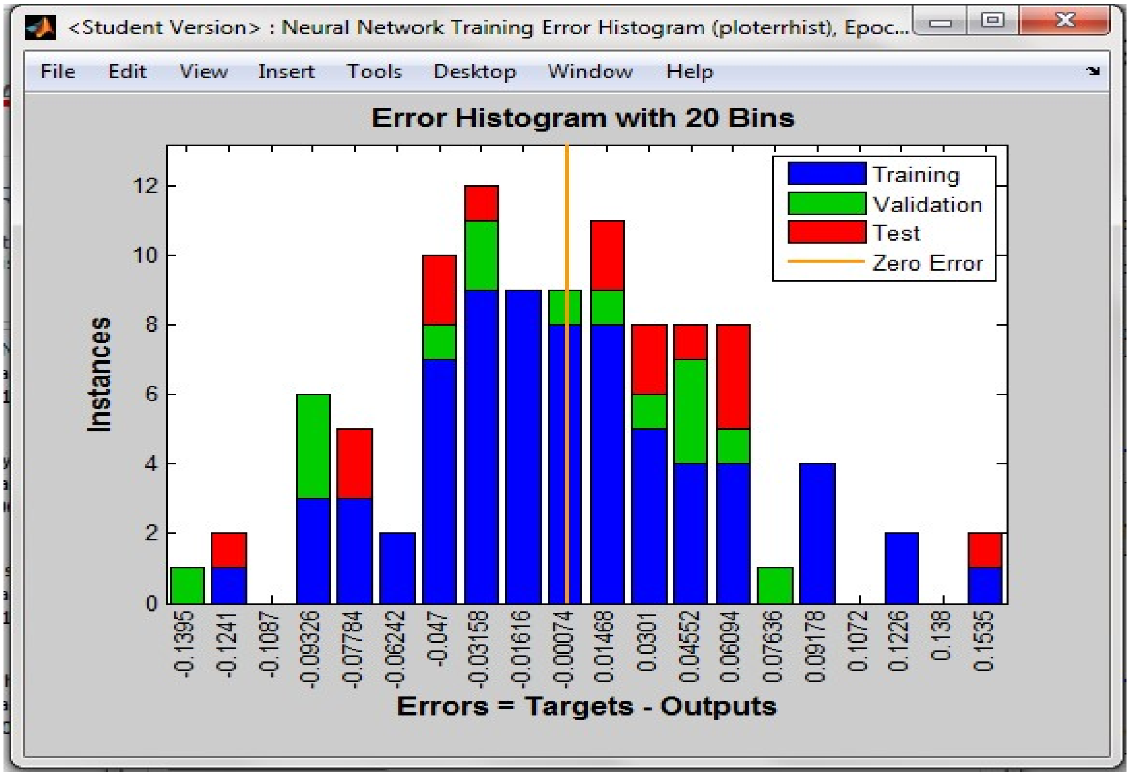

Fig 4.32: Error histogram of shear strength NN

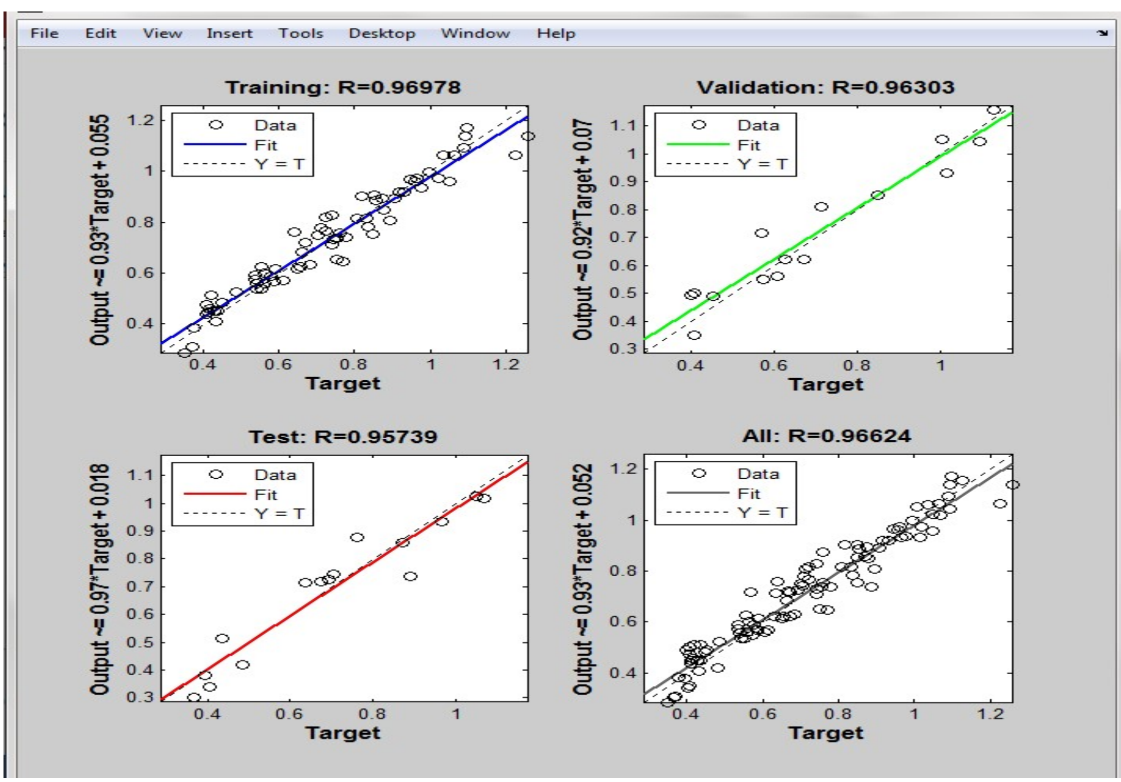

Fig 4.33: Regression curve for the shear strength NN

(e) Performance validation on the ANN used for predicting poisson ratio of lime cement concrete.

Fig 4.34 to Fig 4.38 present the various results of the performance validation carried out on the ANN developed for predicting the poisson ratio of lime cement concrete, given the curing age.

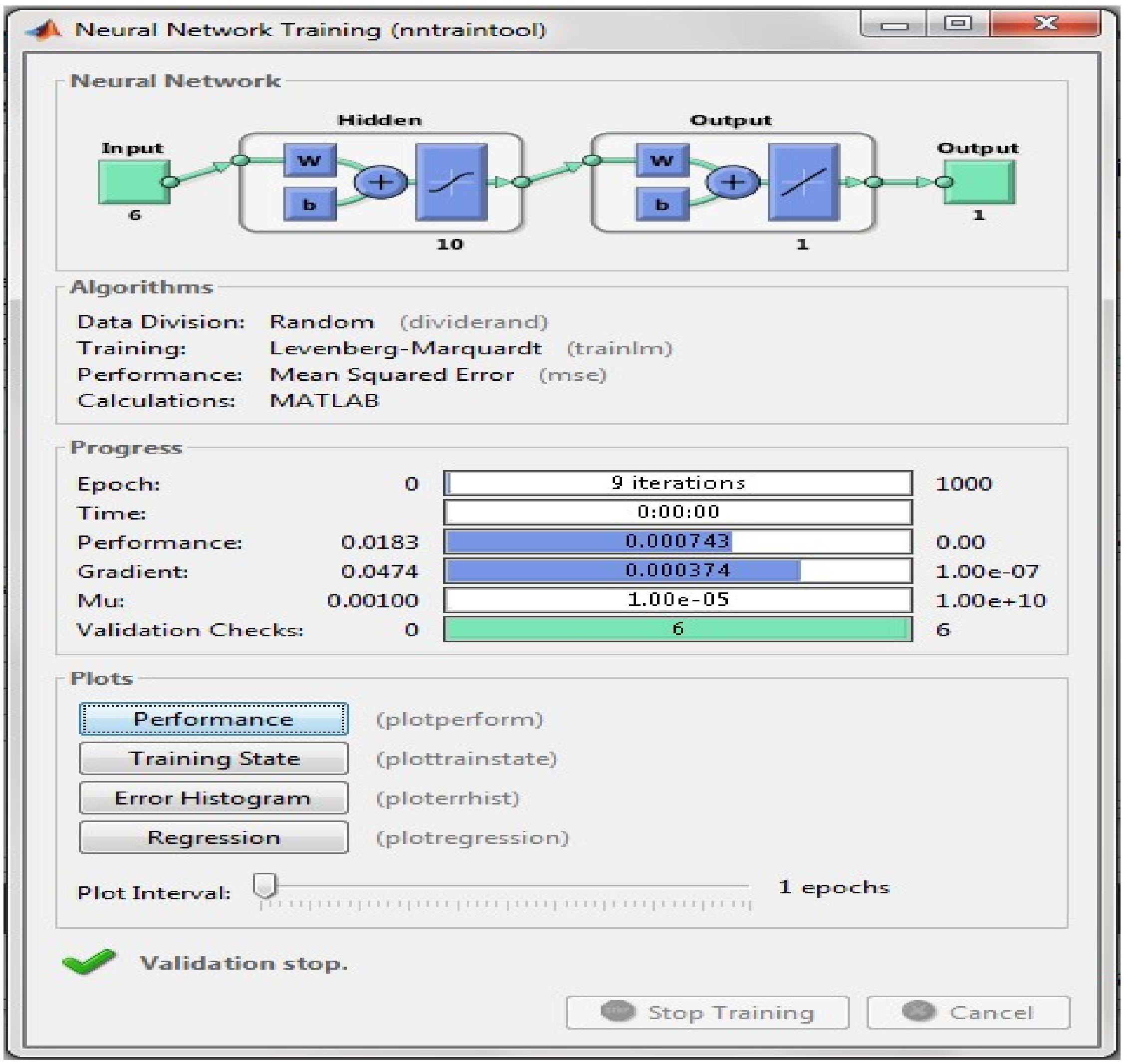

Fig 4.34: Poisson ratio ANN training details

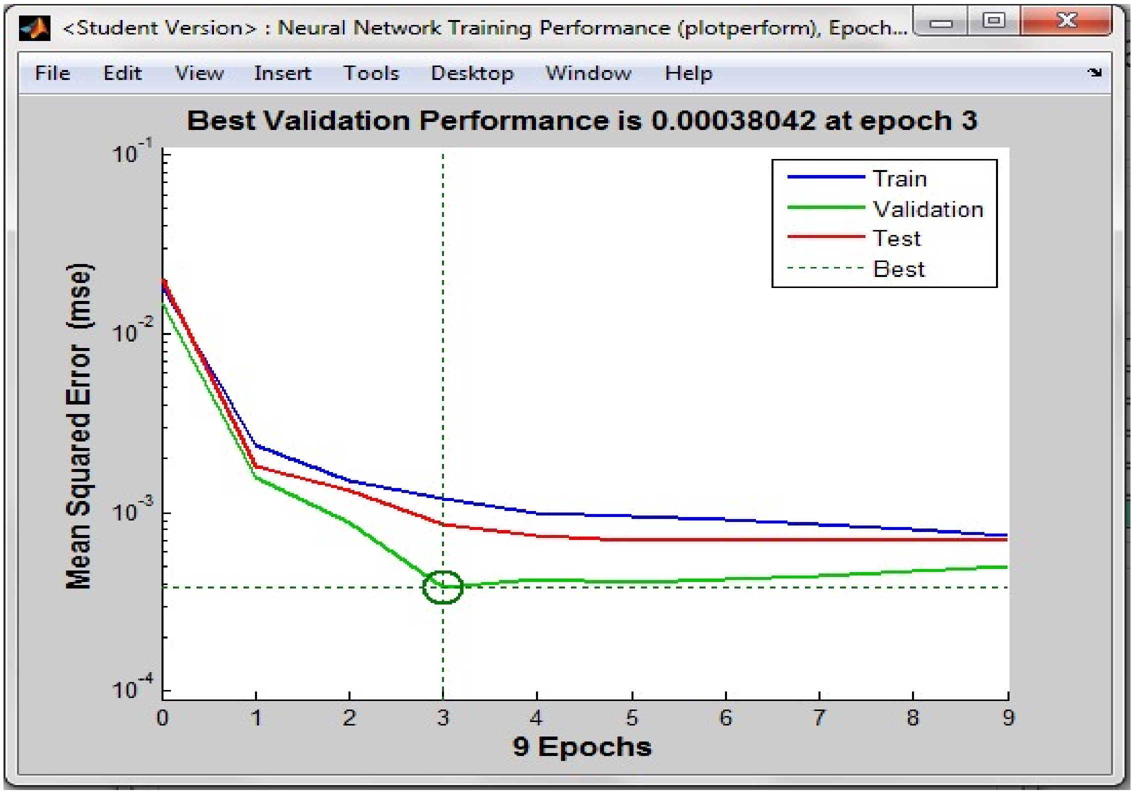

Fig 4.35: Training performance graph for poisson ratio NN

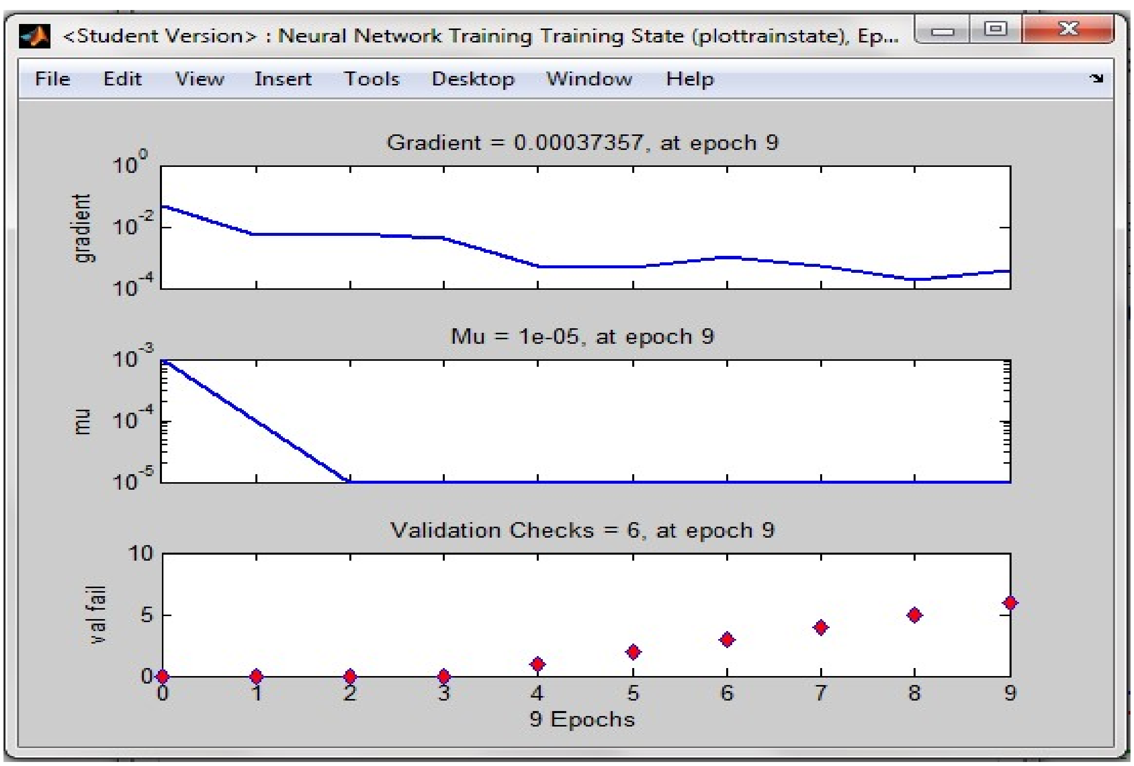

Fig 4.36: Poisson ratio NN training state

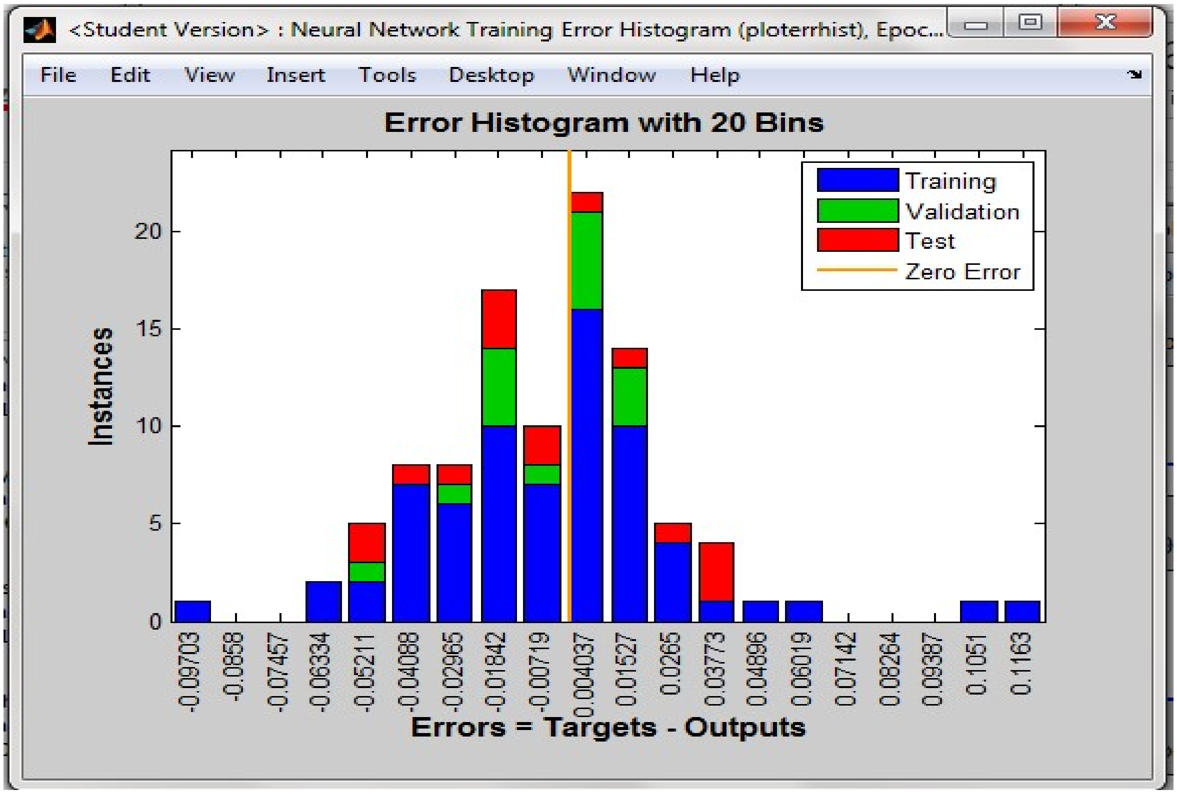

Fig 4.37: Error histogram of poisson ratio NN

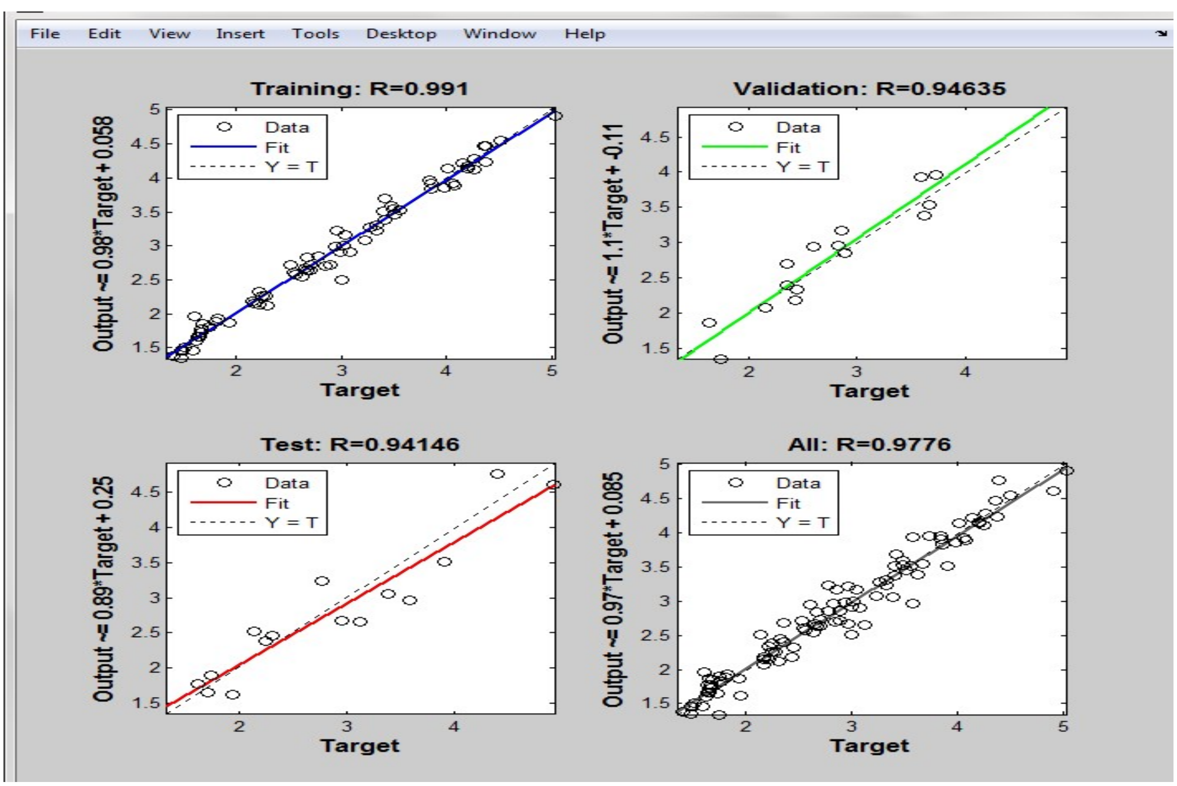

Fig 4.38: Regression curve for the poisson ratio NN

(f) Performance validation on the ANN used for predicting modulus of elasticity of lime cement concrete.

Fig 4.39to Fig 4.43 present the various results of the performance validation carried out on the ANN developed for predicting the modulus of elasticity of lime cement concrete, given the curing age.

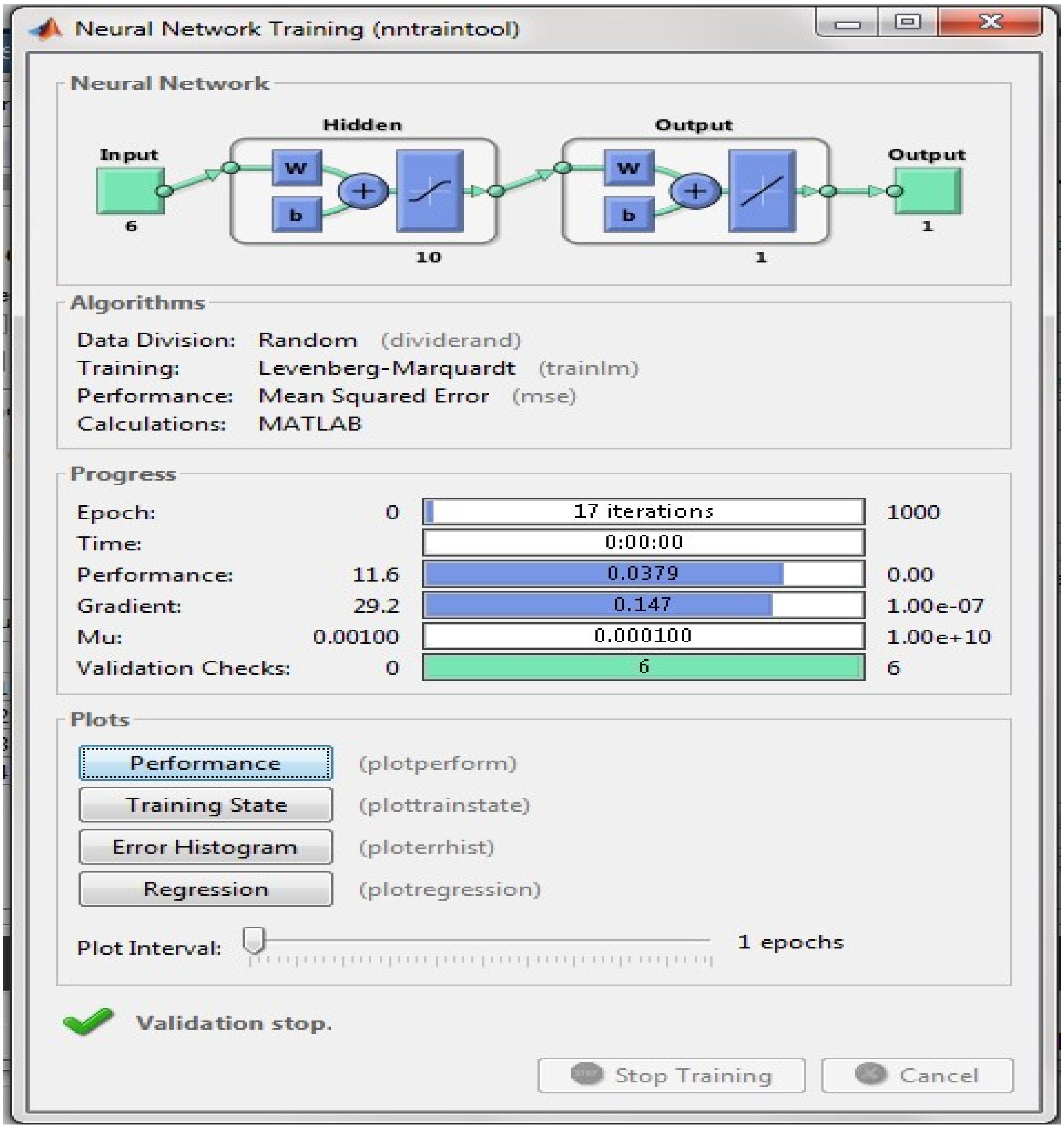

Fig 4.39: Modulus of elasticity ANN training details

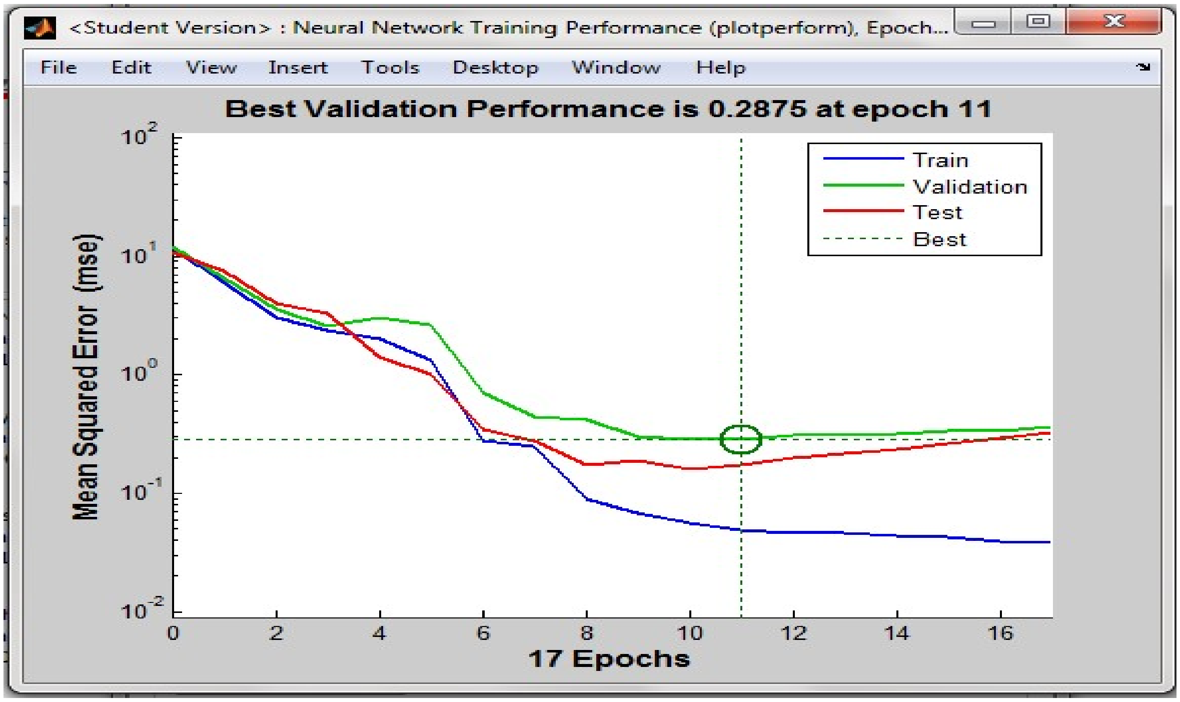

Fig 4.40: Training performance graph for modulus of elasticity NN

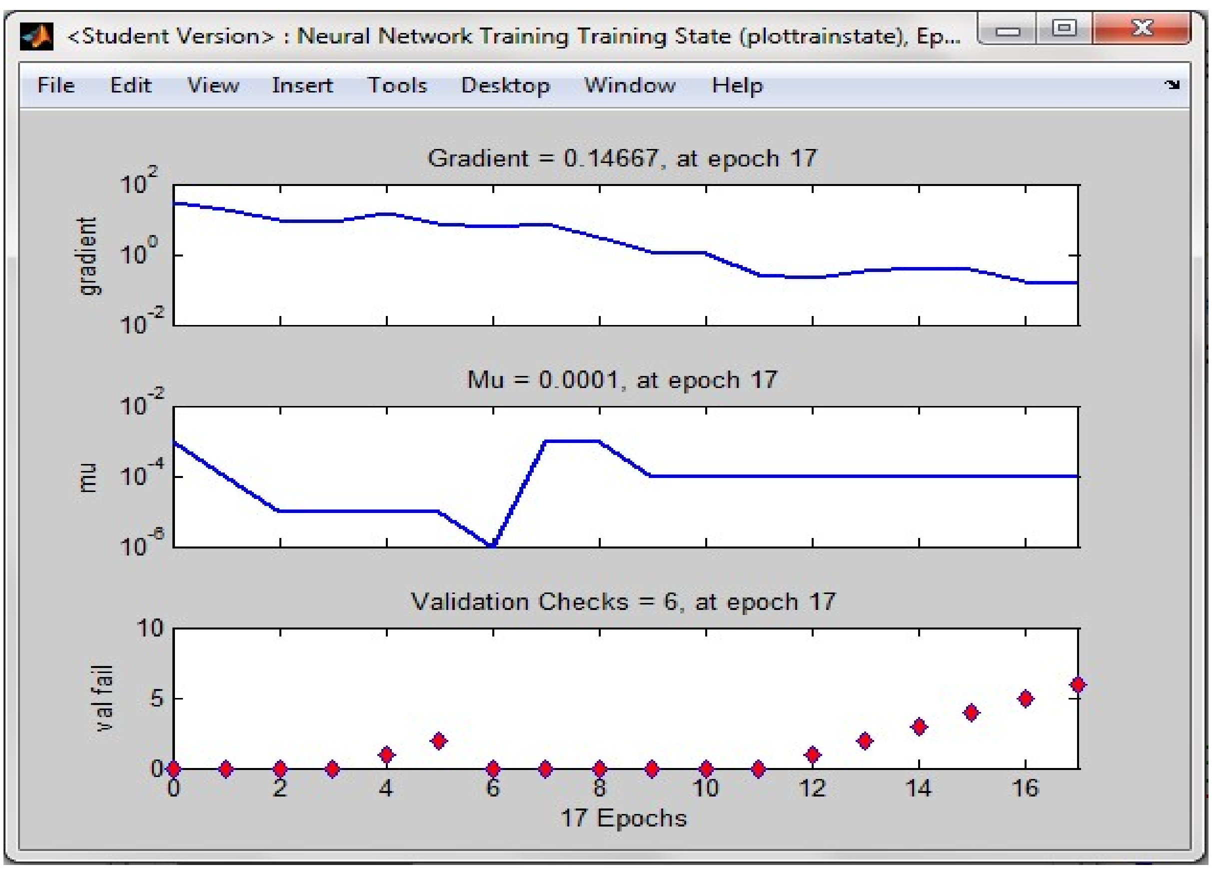

Fig 4.41: Modulus of elasticity NN training state

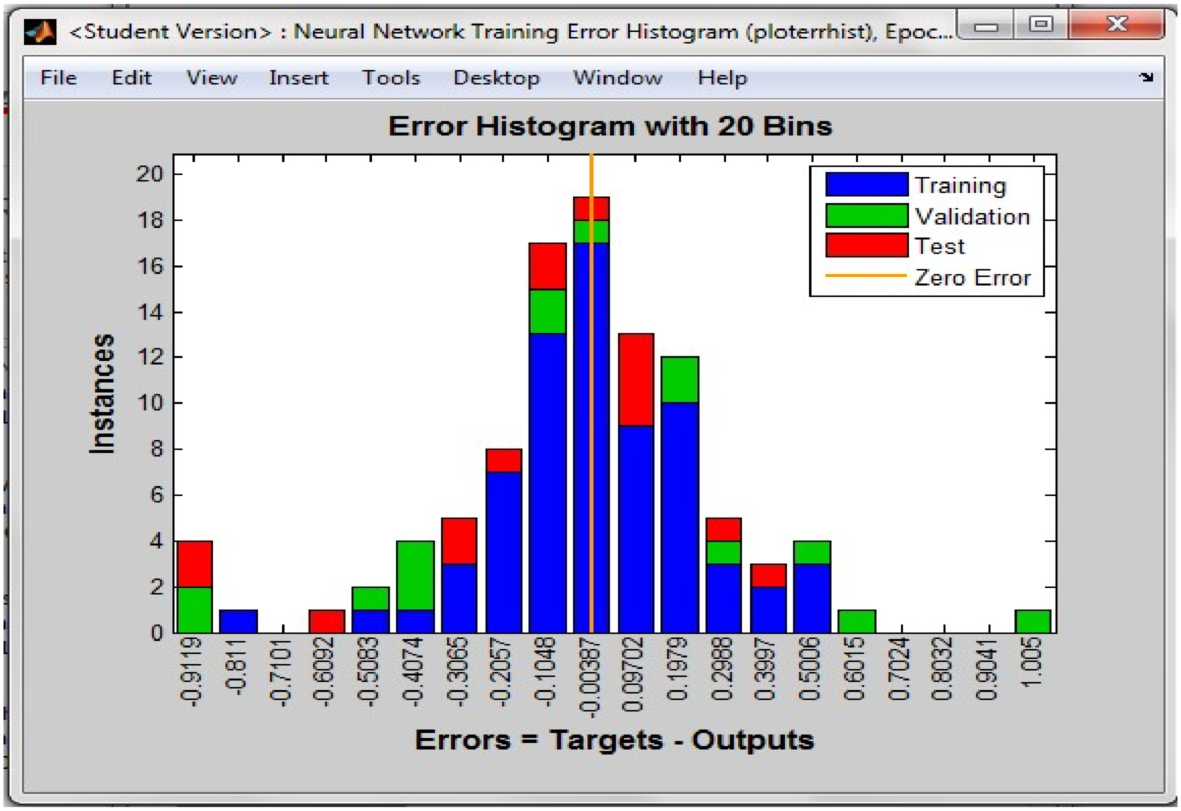

Fig 4.42: Error histogram of modulus of elasticity NN

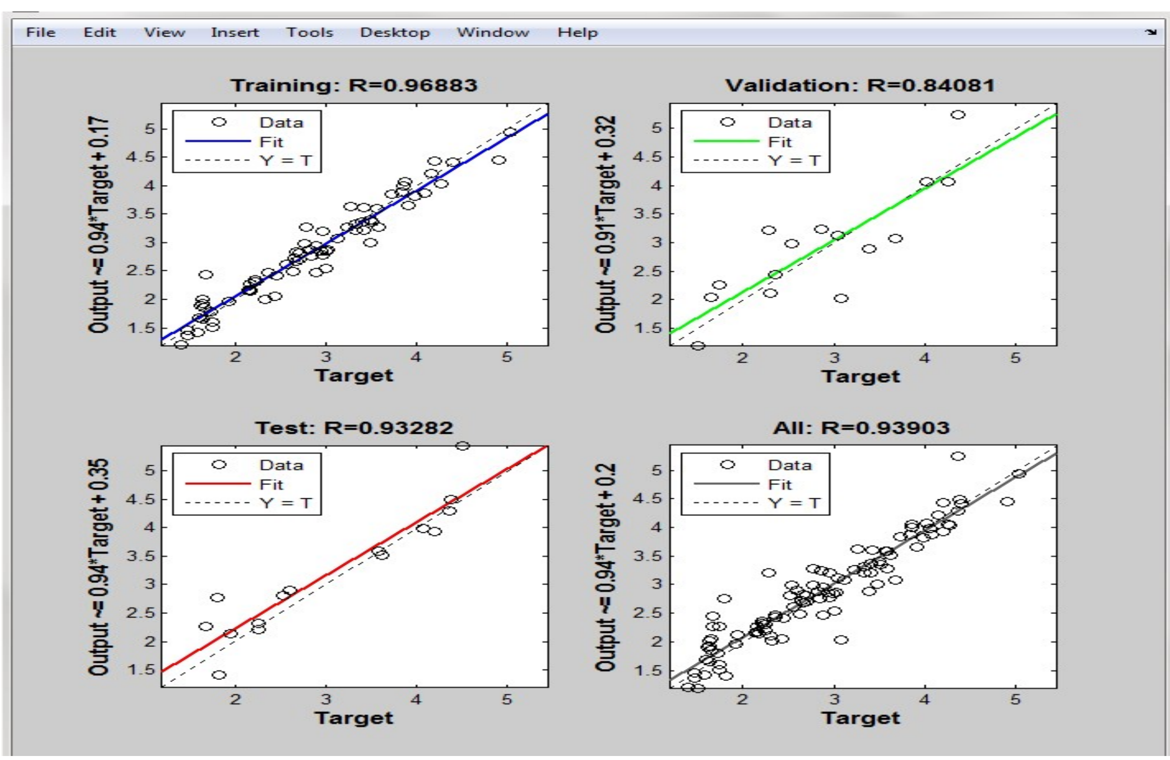

Fig 4.43: Regression curve for the modulus of elasticity NN

(g) Performance validation on the ANN used for predicting modulus of rigidity of lime cement concrete.

Fig 4.44 to Fig 4.48 present the various results of the performance validation carried out on the ANN developed for predicting the modulus of rigidity of lime cement concrete, given the curing age.

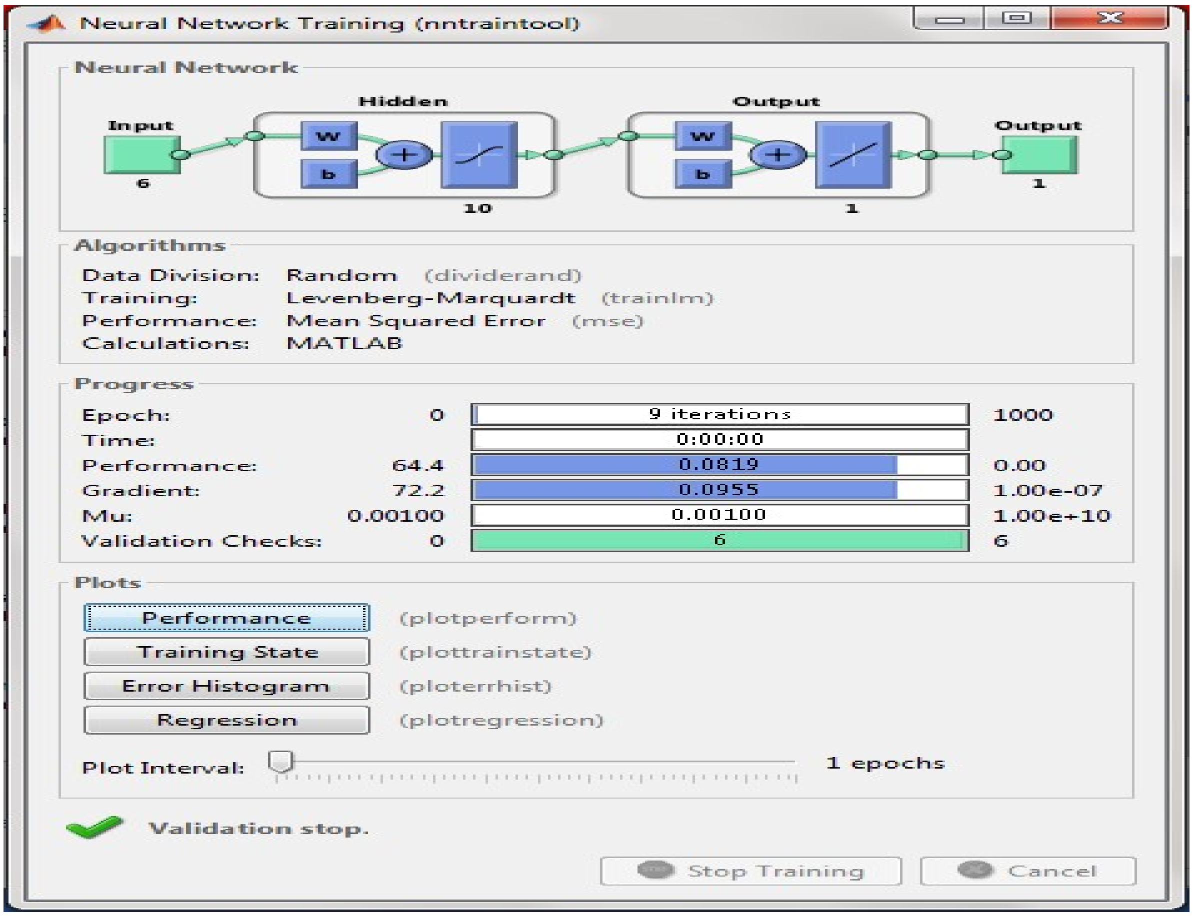

Fig 4.44: Modulus of rigidity ANN training details

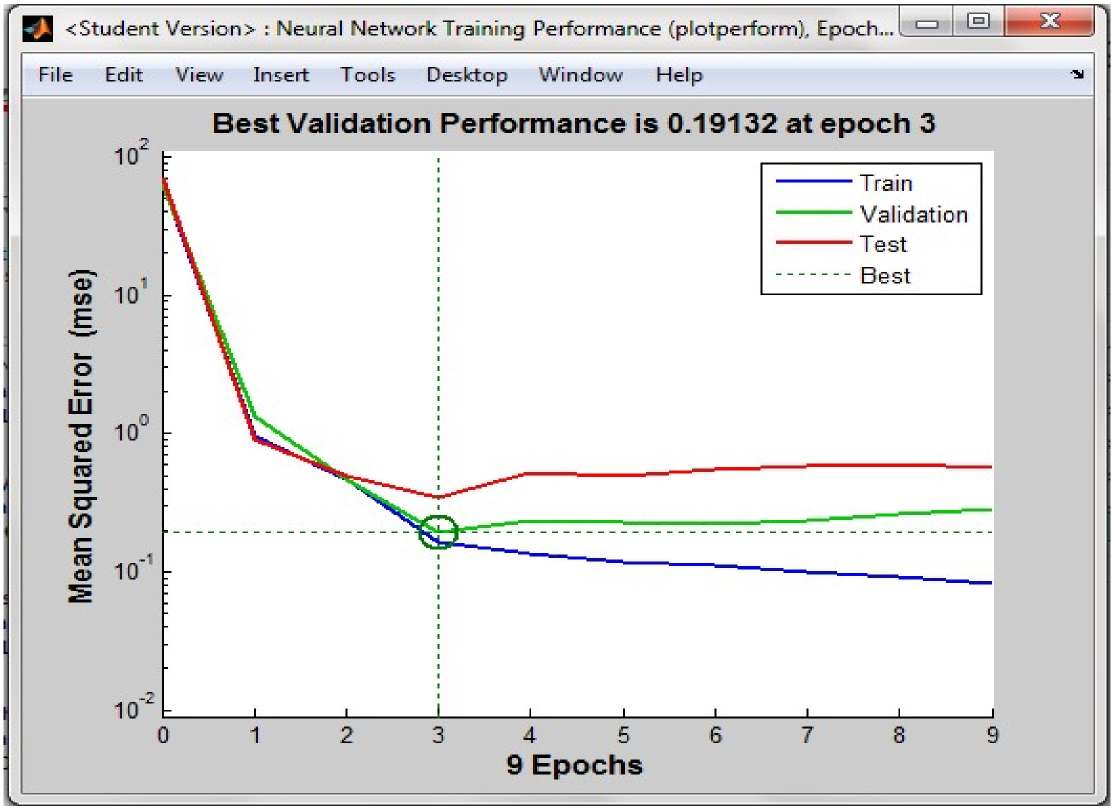

Fig 4.45: Training performance graph for modulus of rigidity NN

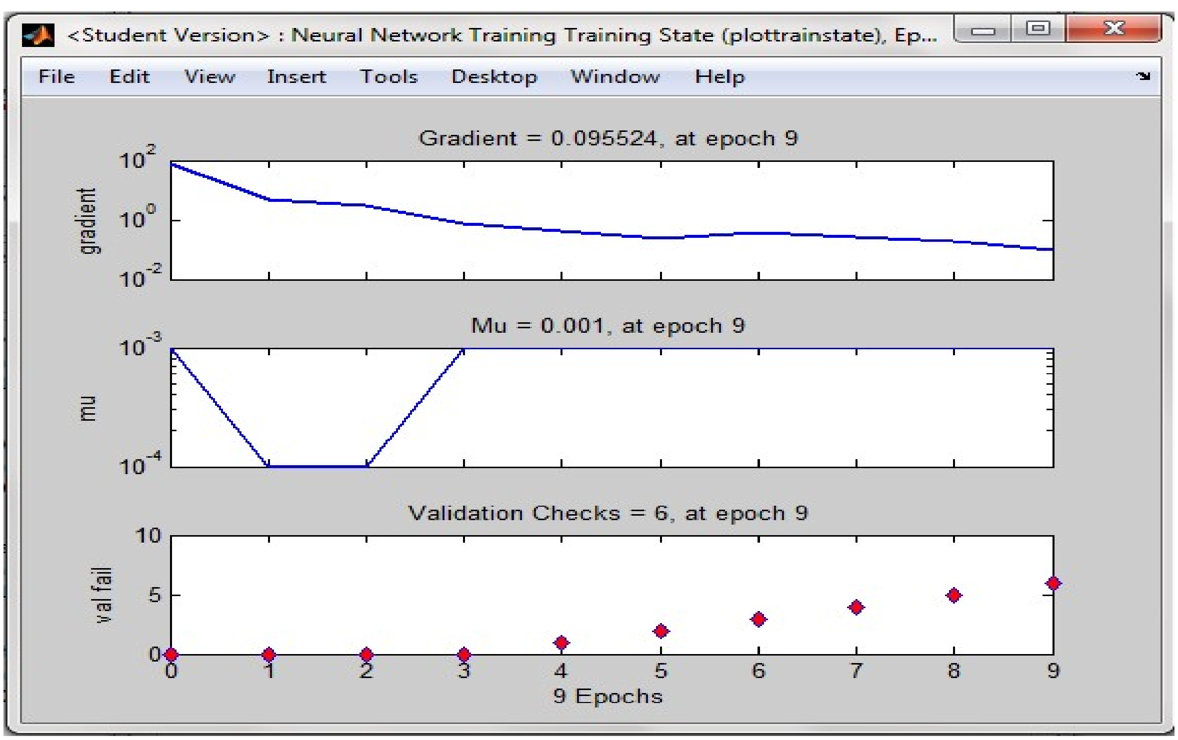

Fig 4.46: Modulus of rigidity NN training state

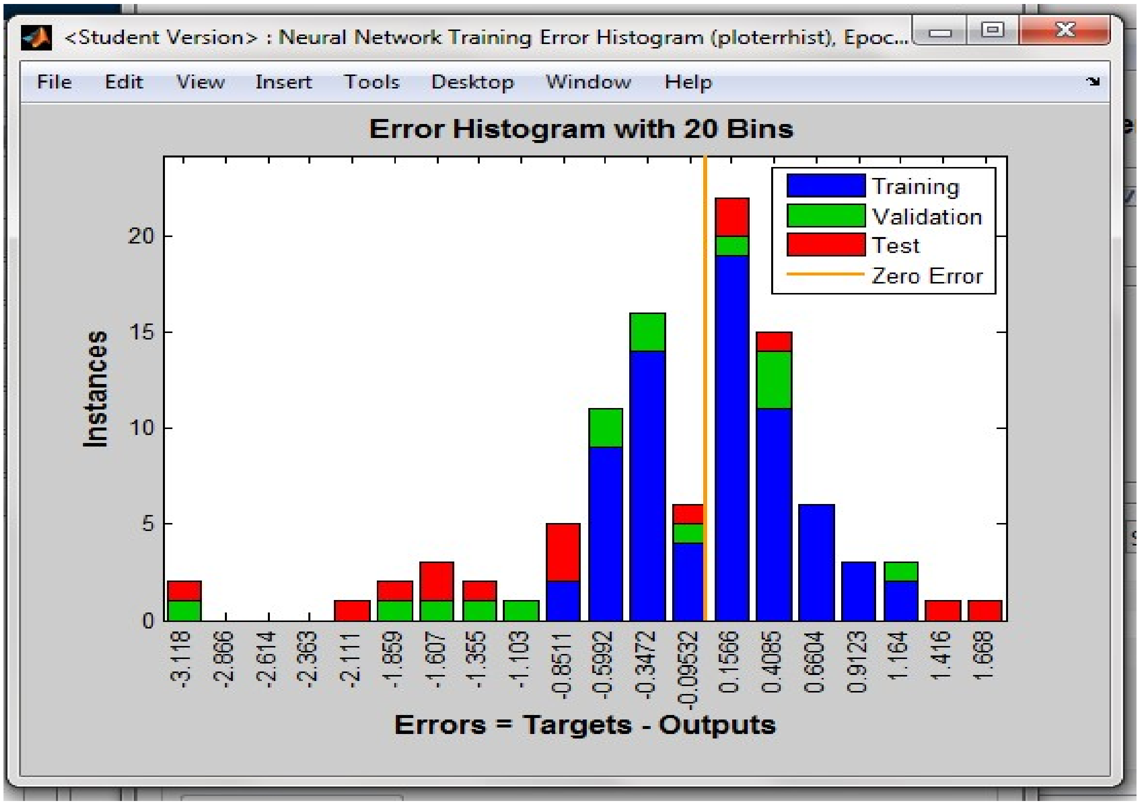

Fig 4.47: Error histogram of modulus of rigidity NN

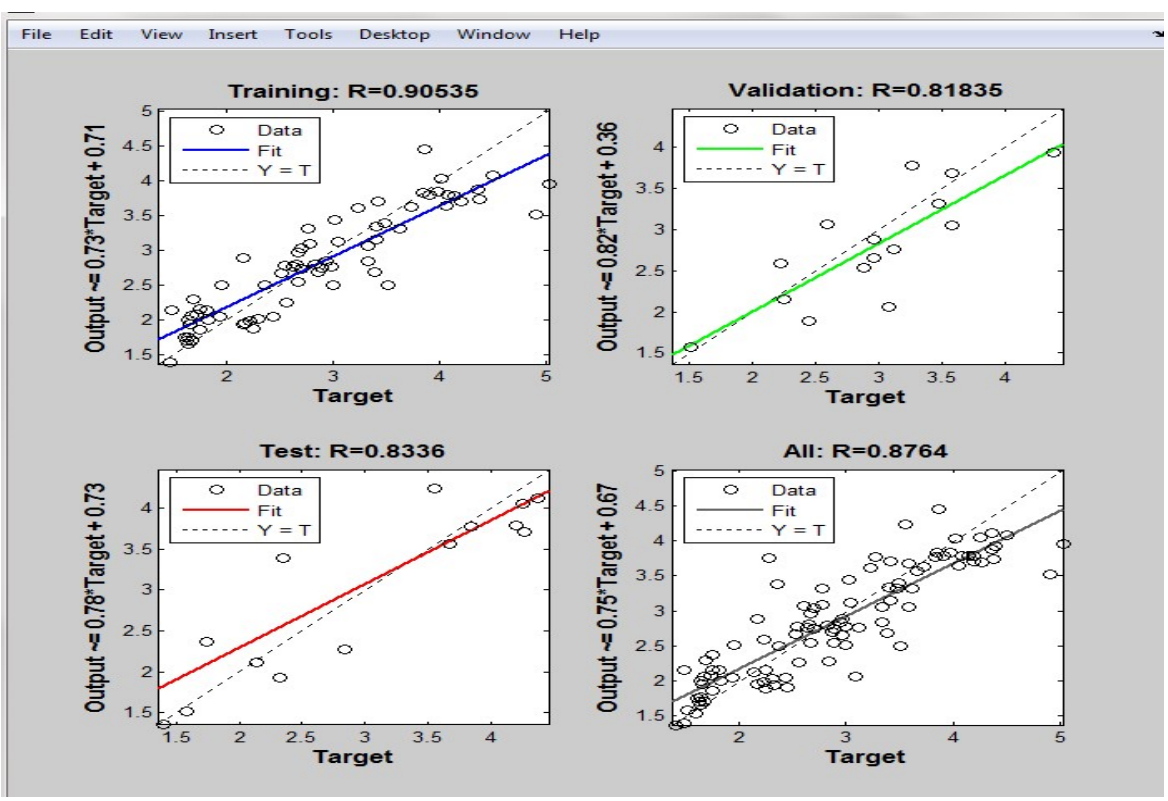

Fig 4.48: Regression curve for the modulus of rigidity NN

4.1.5 Test of adequacy of the neural network predictions with the experimental values

Predictions from the seven neural networks developed were tested for adequacy against their experimental values using the student's t-test. Table 4.18 to Table 4.24 presents the various results obtained from the test.

Table 4.18: Student's t-test of neural network compressive strength

S/NO.	MIX LABEL	CURING AGE	YE	YM	Di = YE - YM	$D_A = (\sum Di)/N$	DA - Di	$(D_A - Di)^2$
1	C10	7	9.10	10.0704	-0.9704	0.1479625	1.1184	1.250735
2	C11	7	13.24	13.2549	-0.0149	0.1479625	0.1629	0.026524
3	C12	7	11.06	11.0248	0.0352	0.1479625	0.1128	0.012715
4	C13	7	12.26	12.1836	0.0764	0.1479625	0.0716	0.005121
5	C14	7	6.68	6.6690	0.0110	0.1479625	0.1370	0.018759
6	C15	7	12.90	11.9903	0.9097	0.1479625	-0.7617	0.580244
7	C10	14	24.91	24.9732	-0.0632	0.1479625	0.2112	0.04459
8	C11	14	20.92	19.9601	0.9599	0.1479625	-0.8119	0.659243
9	C12	14	19.13	18.5780	0.5520	0.1479625	-0.4040	0.163246
10	C13	14	18.91	17.8796	1.0304	0.1479625	-0.8824	0.778696
11	C14	14	24.01	24.7682	-0.7582	0.1479625	0.9062	0.82113
12	C15	14	19.34	19.2900	0.0500	0.1479625	0.0980	0.009597
13	C10	21	29.33	29.1770	0.1530	0.1479625	-0.0050	2.54E-05
14	C11	21	27.33	27.2665	0.0635	0.1479625	0.0845	0.007134
15	C12	21	24.22	24.1784	0.0416	0.1479625	0.1064	0.011313
16	C13	21	28.42	28.6914	-0.2714	0.1479625	0.4194	0.175865
17	C14	21	30.23	29.6406	0.5894	0.1479625	-0.4414	0.194867
18	C15	21	21.00	21.4936	-0.4936	0.1479625	0.6416	0.411602
19	C10	28	29.85	29.4931	0.3569	0.1479625	-0.2089	0.043655
20	C11	28	27.80	27.2217	0.5783	0.1479625	-0.4303	0.18519
21	C12	28	24.58	23.9001	0.6799	0.1479625	-0.5319	0.282958
22	C13	28	28.90	28.8671	0.0329	0.1479625	0.1151	0.013239
23	C14	28	30.83	31.0664	-0.2364	0.1479625	0.3844	0.147735
24	C15	28	21.45	21.2109	0.2391	0.1479625	-0.0911	0.008306
				$\sum Di =$	3.5511		$\sum(D_A - Di)^2 =$	5.852489
						$S^2 = [\sum(D_A - Di)^2]/(N-1) =$	0.254456	
						$S = \sqrt{S^2} =$	0.504436	
						$D_A * \sqrt{N} =$	0.724865	
						$T = [D_A*\sqrt{N}]/S =$	1.436981	

Table 4.19: Student's t-test of neural network flexural strength

S/NO.	MIX LABEL	CURING AGE	YE	YM	Di = YE - YM	$D_A = (\sum Di)/N$	D_A - Di	$(D_A - Di)^2$
1	C10	7	1.670	1.9471	-0.2771	0.003330833	0.2804	0.078641
2	C11	7	2.030	2.0622	-0.0322	0.003330833	0.0355	0.00126
3	C12	7	1.960	2.0617	-0.1017	0.003330833	0.1050	0.011031
4	C13	7	2.270	2.1329	0.1371	0.003330833	-0.1338	0.017894
5	C14	7	1.640	1.5269	0.1131	0.003330833	-0.1098	0.012049
6	C15	7	1.830	2.0029	-0.1729	0.003330833	0.1762	0.031057
7	C10	14	3.120	3.0504	0.0696	0.003330833	-0.0663	0.004392
8	C11	14	3.250	3.1569	0.0931	0.003330833	-0.0898	0.008059
9	C12	14	3.260	3.1392	0.1208	0.003330833	-0.1175	0.013799
10	C13	14	2.630	2.6570	-0.0270	0.003330833	0.0303	0.00092
11	C14	14	3.100	3.1143	-0.0143	0.003330833	0.0176	0.000311
12	C15	14	3.160	3.2276	-0.0676	0.003330833	0.0709	0.005031
13	C10	21	4.060	3.9970	0.0630	0.003330833	-0.0597	0.00356
14	C11	21	4.120	4.0625	0.0575	0.003330833	-0.0542	0.002934
15	C12	21	3.900	3.9088	-0.0088	0.003330833	0.0121	0.000147
16	C13	21	2.930	2.7303	0.1997	0.003330833	-0.1964	0.038561
17	C14	21	4.460	4.4189	0.0411	0.003330833	-0.0378	0.001427
18	C15	21	4.020	3.9900	0.0300	0.003330833	-0.0267	0.000711
19	C10	28	4.150	4.1807	-0.0307	0.003330833	0.0340	0.001158
20	C11	28	4.280	4.3019	-0.0219	0.003330833	0.0252	0.000637
21	C12	28	4.100	4.0867	0.0133	0.003330833	-0.0100	9.94E-05
22	C13	28	3.020	3.0876	-0.0676	0.003330833	0.0709	0.005031
23	C14	28	4.520	4.5498	-0.0298	0.003330833	0.0331	0.001098
24	C15	28	4.160	4.1668	-0.0068	0.003330833	0.0101	0.000103
				$\sum Di$ =	0.0799		$\sum(D_A - Di)^2$ =	0.23991
						$S^2 = [\sum(D_A - Di)^2]/(N-1)$ =	0.010431	
						$S = \sqrt{S^2}$ =	0.102132	
						$D_A * \sqrt{N}$ =	0.016318	
						$T = [D_A * \sqrt{N}]/S$ =	0.159771	

Table 4.20: Student's t-test of neural network split tensile strength

S/NO.	MIX LABEL	CURING AGE	YE	YM	Di = YE - YM	$D_A = (\sum Di)/N$	D_A - Di	$(D_A - Di)^2$
1	C10	7	0.630	0.6343	-0.0043	0.023075417	0.0274	0.000749
2	C11	7	0.960	0.9639	-0.0039	0.023075417	0.0270	0.000728
3	C12	7	0.940	1.5715	-0.6315	0.023075417	0.6546	0.428469
4	C13	7	1.500	0.7963	0.7037	0.023075417	-0.6806	0.46325
5	C14	7	0.520	0.7592	-0.2392	0.023075417	0.2623	0.068788
6	C15	7	0.770	0.7095	0.0605	0.023075417	-0.0374	0.001401
7	C10	14	2.080	1.9503	0.1297	0.023075417	-0.1066	0.011369
8	C11	14	2.180	2.3157	-0.1357	0.023075417	0.1588	0.025206
9	C12	14	2.235	2.1154	0.1196	0.023075417	-0.0965	0.009317
10	C13	14	1.860	1.8281	0.0319	0.023075417	-0.0088	7.79E-05
11	C14	14	1.980	1.4504	0.5296	0.023075417	-0.5065	0.256567
12	C15	14	2.150	2.2727	-0.1227	0.023075417	0.1458	0.02125
13	C10	21	3.025	3.0244	0.0006	0.023075417	0.0225	0.000505
14	C11	21	3.050	2.9995	0.0505	0.023075417	-0.0274	0.000752
15	C12	21	2.875	2.7273	0.1477	0.023075417	-0.1246	0.015531
16	C13	21	2.160	2.1367	0.0233	0.023075417	-0.0002	5.04E-08
17	C14	21	3.340	3.2116	0.1284	0.023075417	-0.1053	0.011093
18	C15	21	2.950	2.8629	0.0871	0.023075417	-0.0640	0.004099
19	C10	28	3.115	3.3086	-0.1936	0.023075417	0.2167	0.046948
20	C11	28	3.210	3.2081	0.0019	0.023075417	0.0212	0.000448
21	C12	28	3.075	3.0602	0.0148	0.023075417	0.0083	6.85E-05
22	C13	28	2.250	2.3375	-0.0875	0.023075417	0.1106	0.012227
23	C14	28	3.400	3.4110	-0.0110	0.023075417	0.0341	0.001161
24	C15	28	3.120	3.1661	-0.0461	0.023075417	0.0692	0.004785
				$\sum Di$ =	0.5538		$\sum(D_A - Di)^2$ =	1.384792
						$S^2 = [\sum(D_A - Di)^2]/(N-1)$ =	0.060208	
						$S = \sqrt{S^2}$ =	0.245374	
						$D_A * \sqrt{N}$ =	0.113046	
						$T = [D_A*\sqrt{N}]/S$ =	0.460709	

Table 4.21: Student's t-test of neural network shear strength

S/NO.	MIX LABEL	CURING AGE	YE	YM	Di = YE - YM	$D_A = (\sum Di)/N$	D_A - Di	$(D_A - Di)^2$
1	C10	7	0.4090	0.4009	0.0081	0.013058333	0.0050	2.46E-05
2	C11	7	0.5070	0.4918	0.0152	0.013058333	-0.0021	4.59E-06
3	C12	7	0.4900	0.5030	-0.0130	0.013058333	0.0261	0.000679
4	C13	7	0.5680	0.5097	0.0583	0.013058333	-0.0452	0.002047
5	C14	7	0.4090	0.4331	-0.0241	0.013058333	0.0372	0.001381
6	C15	7	0.4570	0.4703	-0.0133	0.013058333	0.0264	0.000695
7	C10	14	0.7790	0.7386	0.0404	0.013058333	-0.0273	0.000748
8	C11	14	0.8120	0.8114	0.0006	0.013058333	0.0125	0.000155
9	C12	14	0.8140	0.8050	0.0090	0.013058333	0.0041	1.65E-05
10	C13	14	0.6570	0.6019	0.0551	0.013058333	-0.0420	0.001768
11	C14	14	0.7750	0.7663	0.0087	0.013058333	0.0044	1.9E-05
12	C15	14	0.7900	0.7966	-0.0066	0.013058333	0.0197	0.000386
13	C10	21	1.0150	0.9926	0.0224	0.013058333	-0.0093	8.73E-05
14	C11	21	1.0300	0.9981	0.0319	0.013058333	-0.0188	0.000355
15	C12	21	0.9750	0.8930	0.0820	0.013058333	-0.0689	0.004753
16	C13	21	0.7330	0.7648	-0.0318	0.013058333	0.0449	0.002012
17	C14	21	1.1150	1.0551	0.0599	0.013058333	-0.0468	0.002194
18	C15	21	1.0050	1.0110	-0.0060	0.013058333	0.0191	0.000363
19	C10	28	1.0370	1.0421	-0.0051	0.013058333	0.0182	0.00033
20	C11	28	1.0700	1.0861	-0.0161	0.013058333	0.0292	0.00085
21	C12	28	1.0260	0.9590	0.0670	0.013058333	-0.0539	0.00291
22	C13	28	0.7550	0.8811	-0.1261	0.013058333	0.1392	0.019365
23	C14	28	1.1300	1.0929	0.0371	0.013058333	-0.0240	0.000578
24	C15	28	1.0400	0.9802	0.0598	0.013058333	-0.0467	0.002185
				$\sum Di$ =	0.3134		$\sum(D_A - Di)^2$ =	0.043905
						$S^2 = [\sum(D_A - Di)^2]/(N-1)$ =	0.001909	
						$S = \sqrt{S^2}$ =	0.043691	
						$D_A * \sqrt{N}$ =	0.063973	
						$T = [D_A*\sqrt{N}]/S$ =	1.464199	

Table 4.22: Student's t-test of neural network poisson ratio

S/NO.	MIX LABEL	CURING AGE	YE	YM	Di = YE - YM	D_A = (∑Di)/N	D_A - Di	$(D_A - Di)^2$
1	C10	7	0.184	0.1875	-0.0035	-0.002429167	0.0011	1.15E-06
2	C11	7	0.153	0.2000	-0.0470	-0.002429167	0.0446	0.001987
3	C12	7	0.178	0.1787	-0.0007	-0.002429167	-0.0017	2.99E-06
4	C13	7	0.185	0.2053	-0.0203	-0.002429167	0.0179	0.000319
5	C14	7	0.246	0.2310	0.0150	-0.002429167	-0.0174	0.000304
6	C15	7	0.142	0.1421	-0.0001	-0.002429167	-0.0023	5.43E-06
7	C10	14	0.125	0.1271	-0.0021	-0.002429167	-0.0003	1.08E-07
8	C11	14	0.155	0.1551	-0.0001	-0.002429167	-0.0023	5.43E-06
9	C12	14	0.171	0.1800	-0.0090	-0.002429167	0.0066	4.32E-05
10	C13	14	0.139	0.1383	0.0007	-0.002429167	-0.0031	9.79E-06
11	C14	14	0.129	0.1300	-0.0010	-0.002429167	-0.0014	2.04E-06
12	C15	14	0.164	0.1636	0.0004	-0.002429167	-0.0028	8E-06
13	C10	21	0.139	0.1435	-0.0045	-0.002429167	0.0021	4.29E-06
14	C11	21	0.151	0.1500	0.0010	-0.002429167	-0.0034	1.18E-05
15	C12	21	0.161	0.1557	0.0053	-0.002429167	-0.0077	5.97E-05
16	C13	21	0.103	0.1030	0.0000	-0.002429167	-0.0024	5.9E-06
17	C14	21	0.148	0.1481	-0.0001	-0.002429167	-0.0023	5.43E-06
18	C15	21	0.192	0.1863	0.0057	-0.002429167	-0.0081	6.61E-05
19	C10	28	0.139	0.1431	-0.0041	-0.002429167	0.0017	2.79E-06
20	C11	28	0.154	0.1514	0.0026	-0.002429167	-0.0050	2.53E-05
21	C12	28	0.167	0.1635	0.0035	-0.002429167	-0.0059	3.52E-05
22	C13	28	0.105	0.1060	-0.0010	-0.002429167	-0.0014	2.04E-06
23	C14	28	0.147	0.1470	0.0000	-0.002429167	-0.0024	5.9E-06
24	C15	28	0.194	0.1930	0.0010	-0.002429167	-0.0034	1.18E-05
				∑Di =	-0.0583		$\sum(D_A - Di)^2$ =	0.002924
						$S^2 = [\sum(D_A - Di)^2]/(N-1)$ =	0.000127	
						$S = \sqrt{S^2}$ =	0.011275	
						$D_A * \sqrt{N}$ =	-0.0119	
						$T = [D_A*\sqrt{N}]/S$ =	-1.05546	

Table 4.23: Student's t-test of neural network modulus of elasticity

S/NO.	MIX LABEL	CURING AGE	YE	YM	Di = YE - YM	$D_A = (\sum Di)/N$	D_A - Di	$(D_A - Di)^2$
1	C10	7	16.3800	16.0606	0.3194	0.022958333	-0.2964	0.087878
2	C11	7	19.8870	19.3908	0.4962	0.022958333	-0.4732	0.223958
3	C12	7	17.9720	17.6393	0.3327	0.022958333	-0.3097	0.09594
4	C13	7	18.9220	18.9936	-0.0716	0.022958333	0.0946	0.008941
5	C14	7	14.2940	14.2947	-0.0007	0.022958333	0.0237	0.00056
6	C15	7	18.8440	18.7639	0.0801	0.022958333	-0.0571	0.003265
7	C10	14	27.1010	27.0540	0.0470	0.022958333	-0.0240	0.000578
8	C11	14	24.9990	24.9008	0.0982	0.022958333	-0.0752	0.005661
9	C12	14	23.6360	24.0008	-0.3648	0.022958333	0.3878	0.150357
10	C13	14	23.5000	23.7198	-0.2198	0.022958333	0.2428	0.058932
11	C14	14	27.1000	27.0029	0.0971	0.022958333	-0.0741	0.005497
12	C15	14	23.0730	23.0680	0.0050	0.022958333	0.0180	0.000323
13	C10	21	28.9160	28.9145	0.0015	0.022958333	0.0215	0.00046
14	C11	21	26.5790	25.9172	0.6618	0.022958333	-0.6388	0.408119
15	C12	21	23.9000	23.8998	0.0002	0.022958333	0.0228	0.000518
16	C13	21	21.4870	21.4292	0.0578	0.022958333	-0.0348	0.001214
17	C14	21	21.0460	21.0484	-0.0024	0.022958333	0.0254	0.000643
18	C15	21	21.6320	21.9350	-0.3030	0.022958333	0.3260	0.106249
19	C10	28	29.6660	29.6620	0.0040	0.022958333	0.0190	0.000359
20	C11	28	28.8180	29.0008	-0.1828	0.022958333	0.2058	0.042336
21	C12	28	26.7920	27.0010	-0.2090	0.022958333	0.2320	0.053805
22	C13	28	29.0510	29.0405	0.0105	0.022958333	0.0125	0.000155
23	C14	28	30.7080	31.0004	-0.2924	0.022958333	0.3154	0.099451
24	C15	28	24.2990	24.3130	-0.0140	0.022958333	0.0370	0.001366
				$\sum Di$ =	0.5510		$\sum(D_A - Di)^2$ =	1.356564
						$S^2 = [\sum(D_A - Di)^2]/(N-1)$ =	0.058981	
						$S = \sqrt{S^2}$ =	0.24286	
						$D_A * \sqrt{N}$ =	0.112472	
						$T = [D_A*\sqrt{N}]/S$ =	0.463116	

Table 4.24: Student's t-test of neural network modulus of rigidity

S/NO.	MIX LABEL	CURING AGE	YE	YM	Di = YE - YM	$D_A = (\sum Di)/N$	D_A - Di	$(D_A - Di)^2$
1	C10	7	6.9170	7.0004	-0.0834	0.112641667	0.1960	0.038432
2	C11	7	8.6240	8.1940	0.4300	0.112641667	-0.3174	0.100716
3	C12	7	7.6280	7.6692	-0.0412	0.112641667	0.1538	0.023667
4	C13	7	7.9840	7.5185	0.4655	0.112641667	-0.3529	0.124509
5	C14	7	5.7360	5.9598	-0.2238	0.112641667	0.3364	0.113193
6	C15	7	8.2500	8.2584	-0.0084	0.112641667	0.1210	0.014651
7	C10	14	12.0450	11.9055	0.1395	0.112641667	-0.0269	0.000721
8	C11	14	10.8220	10.7240	0.0980	0.112641667	0.0146	0.000214
9	C12	14	10.0920	10.5683	-0.4763	0.112641667	0.5889	0.346852
10	C13	14	10.3160	10.3533	-0.0373	0.112641667	0.1499	0.022483
11	C14	14	12.0020	11.8249	0.1771	0.112641667	-0.0645	0.004155
12	C15	14	9.9110	10.0007	-0.0897	0.112641667	0.2023	0.040942
13	C10	21	12.9090	12.8657	0.0433	0.112641667	0.0693	0.004808
14	C11	21	12.4120	11.8890	0.5230	0.112641667	-0.4104	0.168394
15	C12	21	11.4530	11.4279	0.0251	0.112641667	0.0875	0.007664
16	C13	21	13.0590	12.9596	0.0994	0.112641667	0.0132	0.000175
17	C14	21	13.2420	13.1496	0.0924	0.112641667	0.0202	0.00041
18	C15	21	10.0850	10.0730	0.0120	0.112641667	0.1006	0.010129
19	C10	28	13.0230	12.3119	0.7111	0.112641667	-0.5985	0.358152
20	C11	28	12.4860	11.5468	0.9392	0.112641667	-0.8266	0.683199
21	C12	28	11.4790	11.4299	0.0491	0.112641667	0.0635	0.004038
22	C13	28	13.1450	13.4755	-0.3305	0.112641667	0.4431	0.196375
23	C14	28	13.3860	13.0273	0.3587	0.112641667	-0.2461	0.060545
24	C15	28	10.1750	10.3444	-0.1694	0.112641667	0.2820	0.079548
				$\sum Di$ =	2.7034		$\sum(D_A - Di)^2$ =	2.403971
						$S^2 = [\sum(D_A - Di)^2]/(N-1)$ =	0.10452	
						$S = \sqrt{S^2}$ =	0.323296	
						$D_A * \sqrt{N}$ =	0.551829	
						$T = [D_A * \sqrt{N}]/S$ =	1.706884	

4.1.6 Comparison of predicted and experimental values of structural characteristics of lime cement concrete

The comparison of results of the predicted values of the structural characteristics of lime cement concrete and those of their corresponding experimental values are presented in Table 4.25 to Table 4.31. The last six mixes (i.e. C10 to C15) for all properties of lime cement concrete tested, were left out during the training of the various ANNs. After the networks were trained, these mixes were then used to test the networks. The predictions made were then compared with their actual experimental values and their percentage errors were determined.

Table 4.25: Comparison of the experimental results against.neural network predictions against percentage error of the compressive strength of lime cement concrete.

Mix label	Curing age	Experimental results (N/mm^2)	Neural network prediction (N/mm^2)	Error	% Error
C10	7	9.10	10.0704	-0.9704	-10.663736
C11	7	13.24	13.2549	-0.0149	-0.1125378
C12	7	11.06	11.0248	0.0352	0.31826401
C13	7	12.26	12.1836	0.0764	0.62316476
C14	7	6.68	6.6690	0.0110	0.16467066
C15	7	12.90	11.9903	0.9097	7.05193798
C10	14	24.91	24.9732	-0.0632	-0.2537134
C11	14	20.92	19.9601	0.9599	4.58843212
C12	14	19.13	18.5780	0.5520	2.88552013
C13	14	18.91	17.8796	1.0304	5.4489688
C14	14	24.01	24.7682	-0.7582	-3.1578509
C15	14	19.34	19.2900	0.0500	0.25853154
C10	21	29.33	29.1770	0.1530	0.52165019
C11	21	27.33	27.2665	0.0635	0.23234541
C12	21	24.22	24.1784	0.0416	0.17175888
C13	21	28.42	28.6914	-0.2714	-0.9549613
C14	21	30.23	29.6406	0.5894	1.94971882
C15	21	21.00	21.4936	-0.4936	-2.3504762
C10	28	29.85	29.4931	0.3569	1.19564489
C11	28	27.80	27.2217	0.5783	2.08021583
C12	28	24.58	23.9001	0.6799	2.76606998
C13	28	28.90	28.8671	0.0329	0.11384083
C14	28	30.83	31.0664	-0.2364	-0.7667856
C15	28	21.45	21.2109	0.2391	1.11468531

Table 4.26: Comparison of the experimental results against neural network predictions against percentage error of the flexural strength of lime cement concrete.

Mix label	Curing age	Experimental results (N/mm^2)	Neural network prediction (N/mm^2)	Error	% Error
C10	7	1.670	1.9471	-0.2771	-16.592814
C11	7	2.030	2.0622	-0.0322	-1.5842365
C12	7	1.960	2.0617	-0.1017	-5.1887755
C13	7	2.270	2.1329	0.1371	6.03964758
C14	7	1.640	1.5269	0.1131	6.89634146
C15	7	1.830	2.0029	-0.1729	-9.4480874
C10	14	3.120	3.0504	0.0696	2.23076923
C11	14	3.250	3.1569	0.0931	2.86461538
C12	14	3.260	3.1392	0.1208	3.70552147
C13	14	2.630	2.6570	-0.0270	-1.026616
C14	14	3.100	3.1143	-0.0143	-0.4612903
C15	14	3.160	3.2276	-0.0676	-2.1392405
C10	21	4.060	3.9970	0.0630	1.55172414
C11	21	4.120	4.0625	0.0575	1.39563107
C12	21	3.900	3.9088	-0.0088	-0.225641
C13	21	2.930	2.7303	0.1997	6.81569966
C14	21	4.460	4.4189	0.0411	0.92152466
C15	21	4.020	3.9900	0.0300	0.74626866
C10	28	4.150	4.1807	-0.0307	-0.739759
C11	28	4.280	4.3019	-0.0219	-0.5116822
C12	28	4.100	4.0867	0.0133	0.32439024
C13	28	3.020	3.0876	-0.0676	-2.2384106
C14	28	4.520	4.5498	-0.0298	-0.659292
C15	28	4.160	4.1668	-0.0068	-0.1634615

Table 4.27: Comparison of the experimental results against neural network predictions against percentage error of the splitting tensile strength of lime cement concrete.

Mix label	Curing age	Experimental results (N/mm^2)	Neural network prediction (N/mm^2)	Error	% Error
C10	7	0.630	0.6343	-0.00430	-0.68254
C11	7	0.960	0.9639	-0.00390	-0.40625
C12	7	0.940	1.5715	-0.63150	-67.18085
C13	7	1.500	0.7963	0.70370	46.91333
C14	7	0.520	0.7592	-0.23920	-46.00000
C15	7	0.770	0.7095	0.06050	7.85714
C10	14	2.080	1.9503	0.12970	6.23558
C11	14	2.180	2.3157	-0.13569	-6.22431
C12	14	2.235	2.1154	0.11960	5.35123
C13	14	1.860	1.8281	0.03190	1.71505
C14	14	1.980	1.4504	0.52960	26.74747
C15	14	2.150	2.2727	-0.12270	-5.70698
C10	21	3.025	3.0244	0.00060	0.01983
C11	21	3.050	2.9995	0.05050	1.65574
C12	21	2.875	2.7273	0.14770	5.13739
C13	21	2.160	2.1367	0.02330	1.07870
C14	21	3.340	3.2116	0.12840	3.84431
C15	21	2.950	2.8629	0.08710	2.95254
C10	28	3.115	3.3086	-0.19360	-6.21509
C11	28	3.210	3.2081	0.00190	0.05919
C12	28	3.075	3.0602	0.01480	0.48130
C13	28	2.250	2.3375	-0.08750	-3.88889
C14	28	3.400	3.4110	-0.01100	-0.32353
C15	28	3.120	3.1661	-0.04610	-1.47756

Table 4.28: Comparison of the experimental results against neural network predictions against percentage error of the shear strength of lime cement concrete.

Mix label	Curing age	Experimental results (N/mm^2)	Neural network prediction (N/mm^2)	Error	% Error
C10	7.0000	0.4090	0.4009	0.0081	1.9804
C11	7.0000	0.5070	0.4918	0.0152	2.9980
C12	7.0000	0.4900	0.5030	-0.0130	-2.6531
C13	7.0000	0.5680	0.5097	0.0583	10.2641
C14	7.0000	0.4090	0.4331	-0.0241	-5.8924
C15	7.0000	0.4570	0.4703	-0.0133	-2.9103
C10	14.0000	0.7790	0.7386	0.0404	5.1861
C11	14.0000	0.8120	0.8114	0.0006	0.0739
C12	14.0000	0.8140	0.8050	0.0090	1.1057
C13	14.0000	0.6570	0.6019	0.0551	8.3866
C14	14.0000	0.7750	0.7663	0.0087	1.1226
C15	14.0000	0.7900	0.7966	-0.0066	-0.8354
C10	21.0000	1.0150	0.9926	0.0224	2.2069
C11	21.0000	1.0300	0.9981	0.0319	3.0971
C12	21.0000	0.9750	0.8930	0.0820	8.4103
C13	21.0000	0.7330	0.7648	-0.0318	-4.3383
C14	21.0000	1.1150	1.0551	0.0599	5.3722
C15	21.0000	1.0050	1.0110	-0.0060	-0.5970
C10	28.0000	1.0370	1.0421	-0.0051	-0.4918
C11	28.0000	1.0700	1.0861	-0.0161	-1.5047
C12	28.0000	1.0260	0.9590	0.0670	6.5302
C13	28.0000	0.7550	0.8811	-0.1261	-16.7020
C14	28.0000	1.1300	1.0929	0.0371	3.2832
C15	28.0000	1.0400	0.9802	0.0598	5.7500

Table 4.29: Comparison of the experimental results against neural network predictions against percentage error of the poisson ratio of lime cement concrete.

Mix label	Curing age	Experimental results ($10^3N/mm^2$)	Neural network prediction ($10^3N/mm^2$)	Error	% Error
C10	7	0.184	0.1875	-0.0035	-1.9022
C11	7	0.153	0.2000	-0.0470	-30.7190
C12	7	0.178	0.1787	-0.0007	-0.3933
C13	7	0.185	0.2053	-0.0203	-10.9730
C14	7	0.246	0.2310	0.0150	6.0976
C15	7	0.142	0.1421	-0.0001	-0.0704
C10	14	0.125	0.1271	-0.0021	-1.6800
C11	14	0.155	0.1551	-0.0001	-0.0645
C12	14	0.171	0.1800	-0.0090	-5.2632
C13	14	0.139	0.1383	0.0007	0.5036
C14	14	0.129	0.1300	-0.0010	-0.7752
C15	14	0.164	0.1636	0.0004	0.2439
C10	21	0.139	0.1435	-0.0045	-3.2374
C11	21	0.151	0.1500	0.0010	0.6623
C12	21	0.161	0.1557	0.0053	3.2919
C13	21	0.103	0.1030	0.0000	0.0000
C14	21	0.148	0.1481	-0.0001	-0.0676
C15	21	0.192	0.1863	0.0057	2.9688
C10	28	0.139	0.1431	-0.0041	-2.9496
C11	28	0.154	0.1514	0.0026	1.6883
C12	28	0.167	0.1635	0.0035	2.0958
C13	28	0.105	0.1060	-0.0010	-0.9524
C14	28	0.147	0.1470	0.0000	0.0000
C15	28	0.194	0.1930	0.0010	0.5155

Table 4.30: Comparison of the experimental results against neural network predictions against percentage error of the modulus of elasticity of lime cement concrete.

Mix label	Curing age	Experimental results ($10^3 N/mm^2$)	Neural network prediction ($10^3 N/mm^2$)	Error	% Error
C10	7	16.3800	16.0606	0.3194	1.9499
C11	7	19.8870	19.3908	0.4962	2.4951
C12	7	17.9720	17.6393	0.3327	1.8512
C13	7	18.9220	18.9936	-0.0716	-0.3784
C14	7	14.2940	14.2947	-0.0007	-0.0049
C15	7	18.8440	18.7639	0.0801	0.4251
C10	14	27.1010	27.0540	0.0470	0.1734
C11	14	24.9990	24.9008	0.0982	0.3928
C12	14	23.6360	24.0008	-0.3648	-1.5434
C13	14	23.5000	23.7198	-0.2198	-0.9353
C14	14	27.1000	27.0029	0.0971	0.3583
C15	14	23.0730	23.0680	0.0050	0.0217
C10	21	28.9160	28.9145	0.0015	0.0052
C11	21	26.5790	25.9172	0.6618	2.4899
C12	21	23.9000	23.8998	0.0002	0.0008
C13	21	21.4870	21.4292	0.0578	0.2690
C14	21	21.0460	21.0484	-0.0024	-0.0114
C15	21	21.6320	21.9350	-0.3030	-1.4007
C10	28	29.6660	29.6620	0.0040	0.0135
C11	28	28.8180	29.0008	-0.1828	-0.6343
C12	28	26.7920	27.0010	-0.2090	-0.7801
C13	28	29.0510	29.0405	0.0105	0.0361
C14	28	30.7080	31.0004	-0.2924	-0.9522
C15	28	24.2990	24.3130	-0.0140	-0.0576

Table 4.31: Comparison of the experimental results against neural network predictions against percentage error of the modulus of rigidity of lime cement concrete.

Mix label	Curing age	Experimental results ($10^3 N/mm^2$)	Neural network prediction ($10^3 N/mm^2$)	Error	% Error
C10	7	6.9170	7.0004	-0.0834	-1.2057
C11	7	8.6240	8.1940	0.4300	4.9861
C12	7	7.6280	7.6692	-0.0412	-0.5401
C13	7	7.9840	7.5185	0.4655	5.8304
C14	7	5.7360	5.9598	-0.2238	-3.9017
C15	7	8.2500	8.2584	-0.0084	-0.1018
C10	14	12.0450	11.9055	0.1395	1.1582
C11	14	10.8220	10.7240	0.0980	0.9056
C12	14	10.0920	10.5683	-0.4763	-4.7196
C13	14	10.3160	10.3533	-0.0373	-0.3616
C14	14	12.0020	11.8249	0.1771	1.4756
C15	14	9.9110	10.0007	-0.0897	-0.9051
C10	21	12.9090	12.8657	0.0433	0.3354
C11	21	12.4120	11.8890	0.5230	4.2137
C12	21	11.4530	11.4279	0.0251	0.2192
C13	21	13.0590	12.9596	0.0994	0.7612
C14	21	13.2420	13.1496	0.0924	0.6978
C15	21	10.0850	10.0730	0.0120	0.1190
C10	28	13.0230	12.3119	0.7111	5.4603
C11	28	12.4860	11.5468	0.9392	7.5220
C12	28	11.4790	11.4299	0.0491	0.4277
C13	28	13.1450	13.4755	-0.3305	-2.5143
C14	28	13.3860	13.0273	0.3587	2.6797
C15	28	10.1750	10.3444	-0.1694	-1.6649

The networks output values, were plotted against their experimental values in the form of line graphs and presented in Fig 4.49 to Fig 4.55.

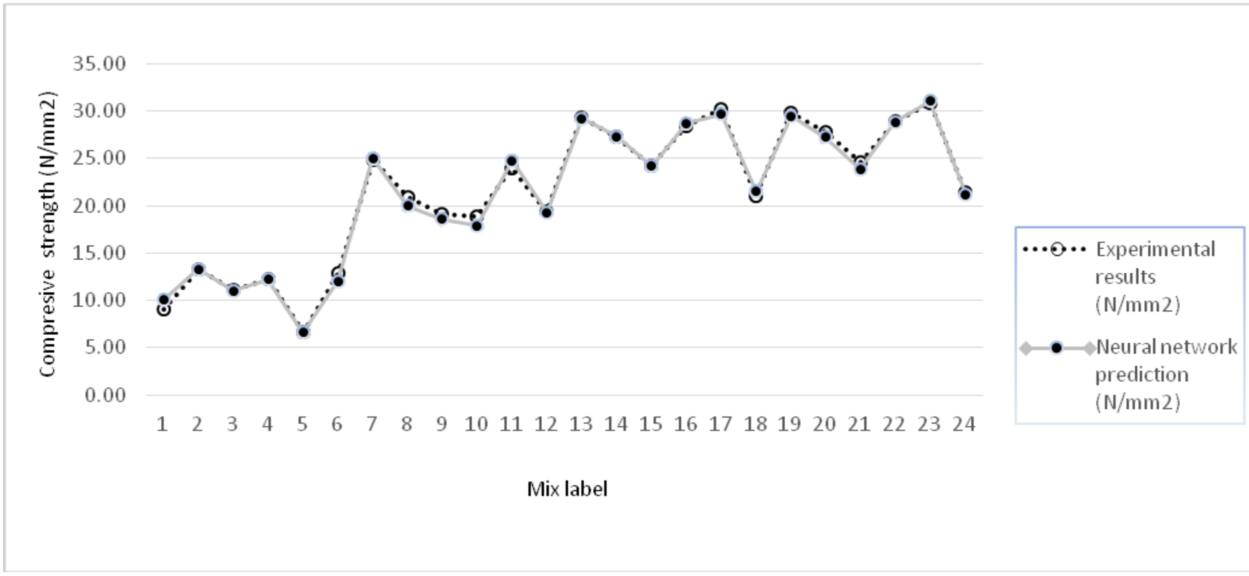

Fig 4.49: Line graph comparing experimental results of compressive strengths of lime cement concrete to neural network predictions

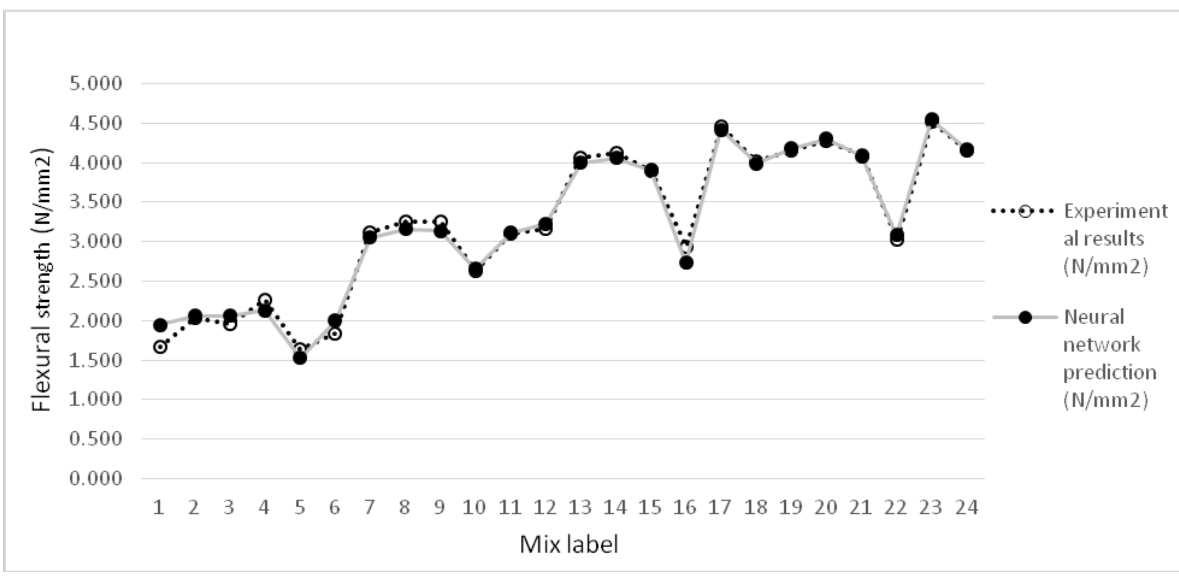

Fig 4.50: Line graph comparing experimental results of flexural strengths of lime cement concrete to neural network predictions

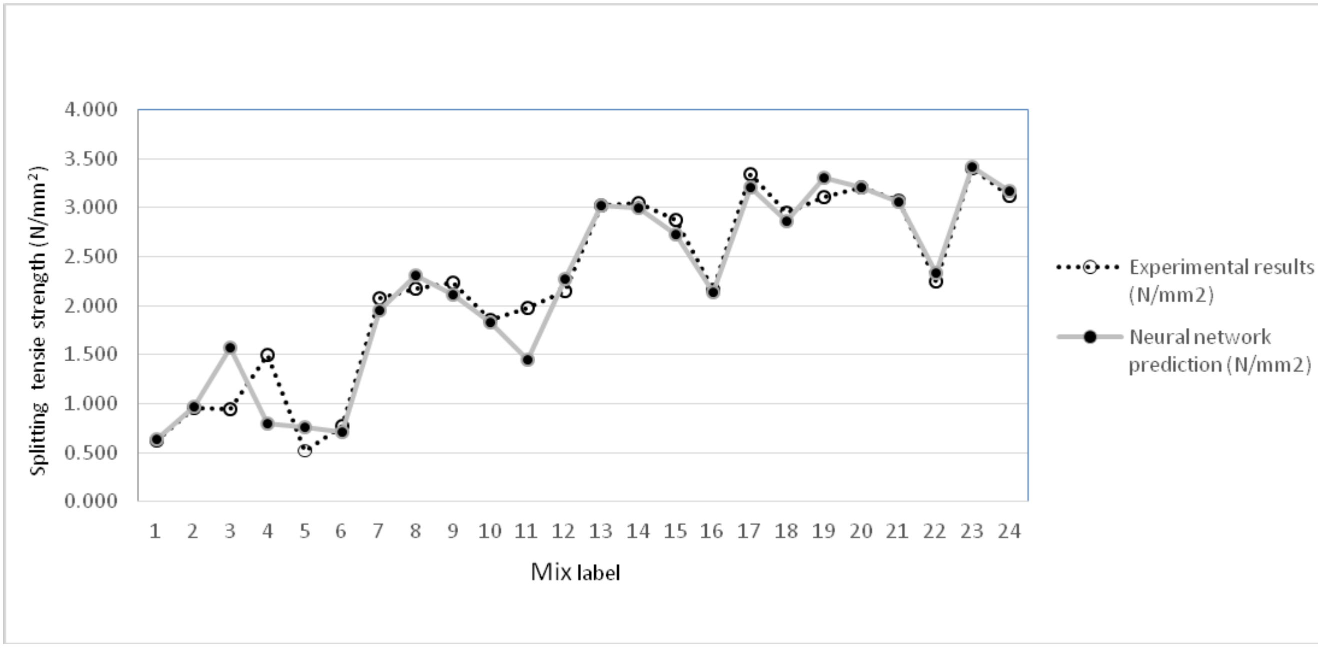

Fig 4.51: Line graph comparing experimental results of splitting tensile strengths of lime cement concrete to neural network predictions

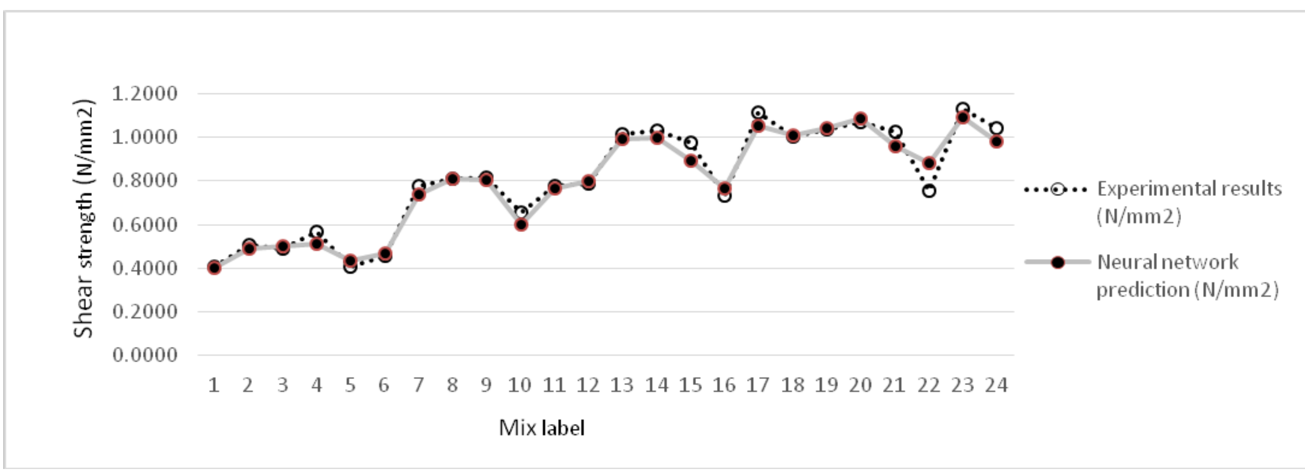

Fig 4.52: Line graph comparing experimental results of shear strengths of lime cement concrete to neural network predictions

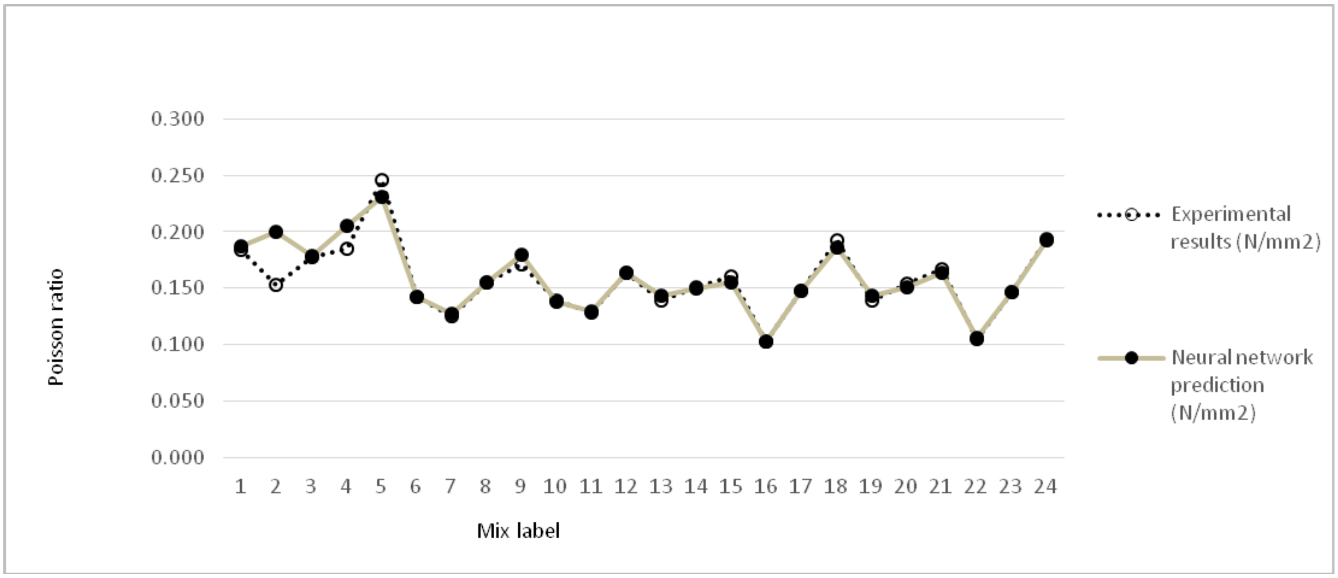

Fig 4.53: Line graph comparing experimental results of poisson ratios of lime cement concrete to neural network predictions

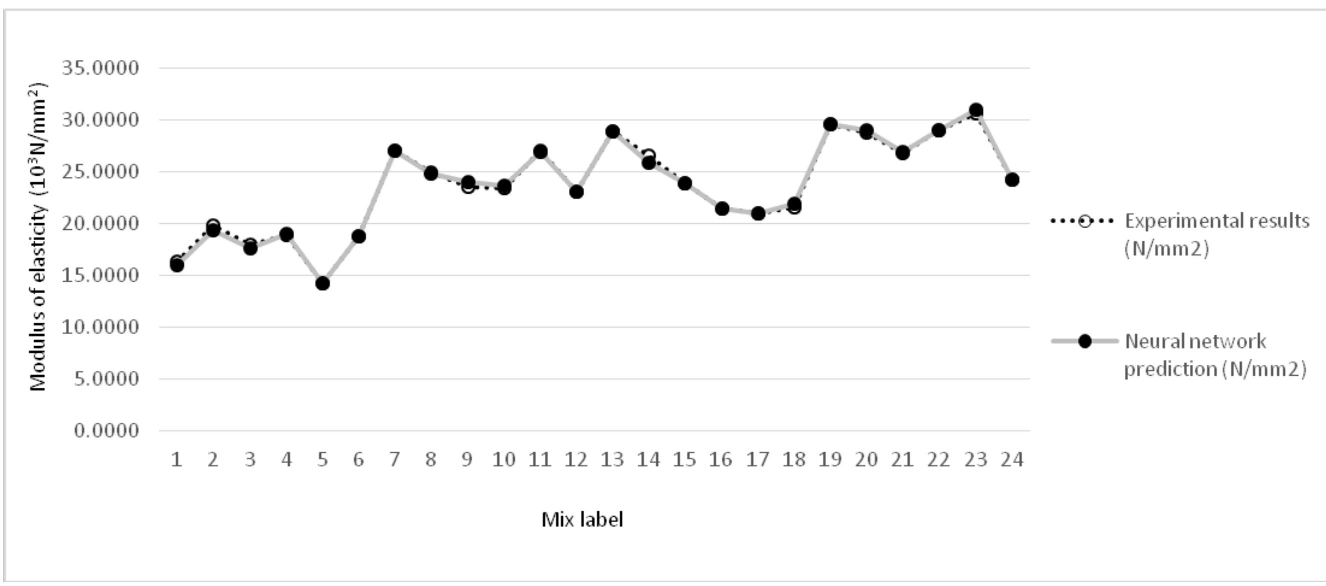

Fig 4.54: Line graph comparing experimental results of modulus of elasticity of lime cement concrete to neural network predictions

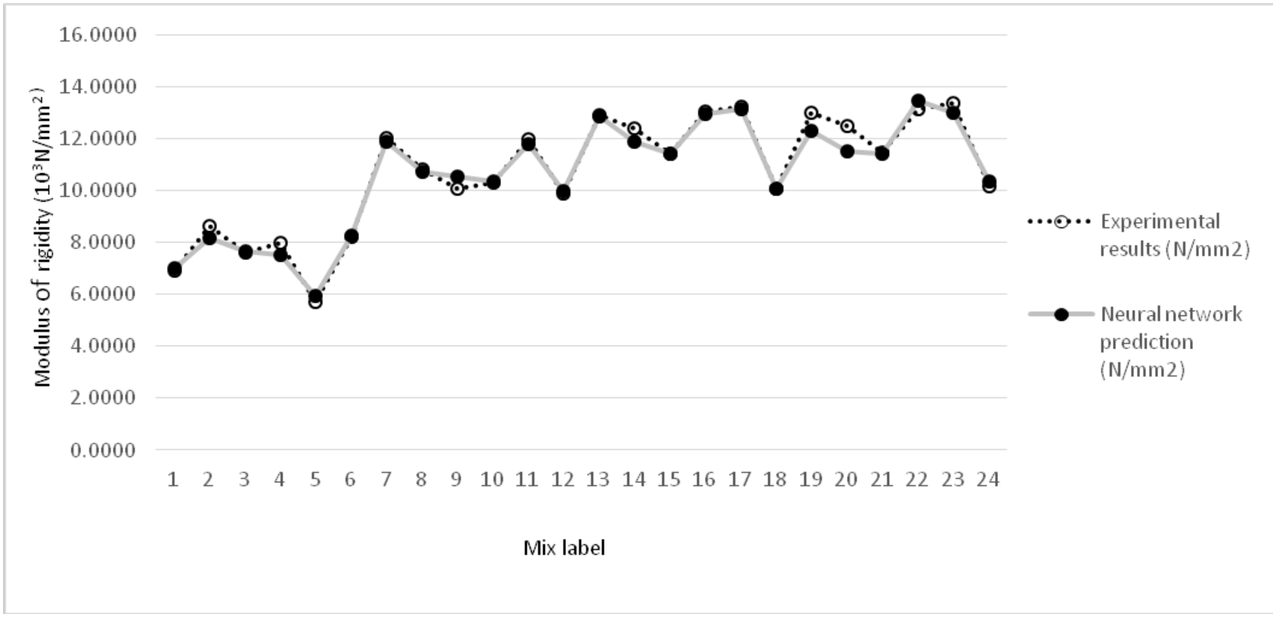

Fig 4.55: Line graph comparing experimental results of modulus of rigidity of lime cement concrete to neural network predictions

4.1.7 Graphical user interface (GUI) for predicting the structural properties of lime cement concrete

The GUI for predicting the structural properties of lime cement concrete (as shown on Plate 4.1), was developed from the Matlab Graphical User Interface Development Environment (GUIDE) and not by writing programs.

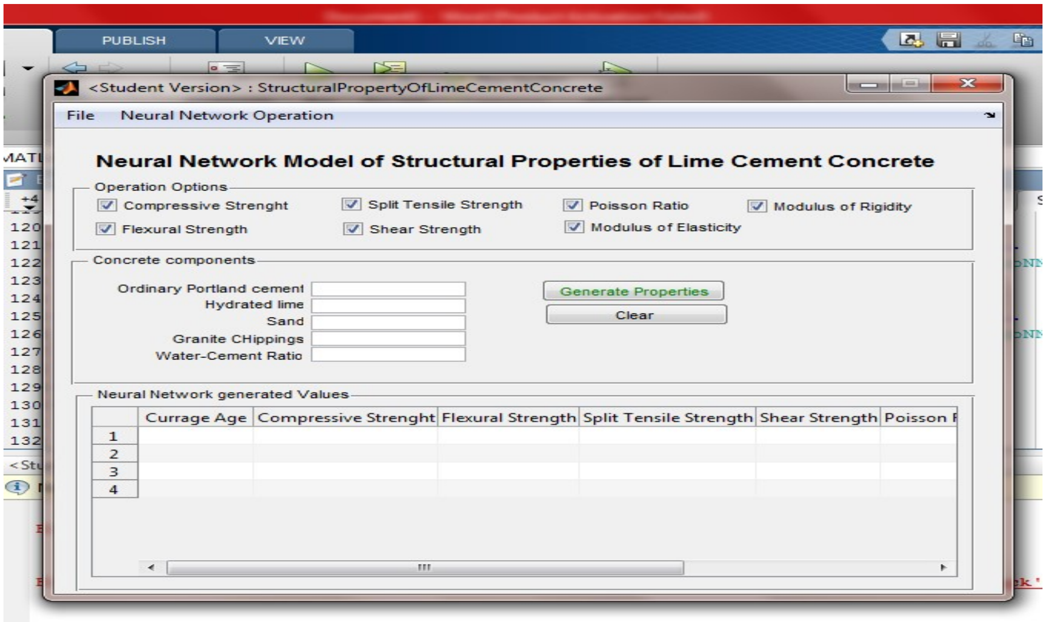

Plate 4.1: Graphical user interface for predicting structural properties of lime cement concrete

4.2 Discussion

The results presented in section 4.1 are discussed as follows;

4.2.1 Characterization of the fresh lime cement concrete and its constituent.

Results of the characterization of the fresh lime cement concrete and its constituent are presented below.

4.2.1.1 Sieve analysis of the river sand and granite chippings.

Fig.4.1 and Fig. 4.2 show the results of the seive analysis conducted on the river sand and granite chippings respectively. Cu and Cc for the river sand were calculated to be 3.24 and 1 respectively, from Eqn. 2.2 and Eqn. 2.3 of section 2.2.3. Similarly, Cu and Cc for the granite chippings were calculated to be 1.4 and 1.02 respectively. According to the unified soil classification system (ASTM D-2487, 2011) as stated in section 2.2.3, the condition Cu ≥ 6 and 1 < Cc < 3 were not satisfied by the river sand, therefore it is a poorly graded sand. The conditions, Cu > 4 and 1 < Cc < 3 were also not satisfied by the granite chippings, therefore, it was classified as a "poorly graded" coarse aggregate having uniform range of particle sizes.

From Table 2.8 of section 2.2.3, the river sand is seen to fall under zone 1, and has a fineness modulus of 3.79 as shown in Table 4.1. This means that the sand is a coarse sand, and will produced a harsh concrete mix. It can be used for reinforced concrete works.

4.2.1.2 Bulk densities for river sand and granite chippings.

Table 4.3 and Table 4.4 presents the average bulk density of the granite chippings and river sand used for this study. Average bulk density for the granite chipping was 1706.225kg/m^3, while that for the river sand was 1656.022kg/m^3, making them normal weight aggregates as stated by ASTM C330 (2014) in section 2.2.2.The aggregates were made of particles of same size, therefore limiting the extent to which they can be packed. This created lots of voids, thereby reducing their actual densities. To effectively use these aggregates for concrete making, the concrete designer will have to add smaller particle sizes that can help fill up the voids and increase density.

4.2.1.3 Workability test of the fresh lime cement concrete

The workability of the concrete mixtures as shown in Table 4.5, reveals that this property is largely determined by the proportions of fine and coarse aggregates added to a given quantity of paste. It was observed that mix numbers; N1, N3, N12, N13, N14, N23, C1, C2, C6, C8, C10, C13, and C14, having more proportions of fine and coarse aggregates recorded "very low" to "low" workability. Compressive strength values recorded for these mixes were 15.12N/mm^2, 17.86N/mm^2, 20.85N/mm^2, 22.70n/mm^2, 22.17N/mm^2, 23.81N/mm^2, 20.85N/mm^2, 22.45N/mm^2, 23.56N/mm^2, 28.50N/mm^2, 29.85N/mm^2, 28.90N/mm^2 and 30.83N/mm^2 respectively. Only two out of these values fell below 20N/mm^2, which is the bench mark for a structural concrete (IS 456, 2000). This implies that low workable concrete, produce stronger concrete depending on the water cement ratio used, the percentage replacement of portland cement with hydrated lime, and if there is enough water available for the starting and completion of the hydration process.

According to ASTM C143 (2010) in section 2.3.4.1, it can be seen that concrete mixes; N1, N13, C2 and C13, having 'very low slump' values, find application in road construction. Concrete mixes; N3, N12, N14, N23, C1, C6, C8, C10 and C1, having 'low slump' values, find application in the construction of foundations with light reinforcements. Concrete mixes; N15, N24, N34, C3, C11, C12, and C15, having 'medium slump' values, can be used in manual compacted flat slabs, normal reinforced concrete constructions, and for heavily reinforced sections compacted using vibrations. Finally, concrete mixes; N2, N4, N5, N25, N35, N45, C4, C5, C7, and C9, having high slump values, can be used for sections with congested reinforcement that are not manually vibrated. Generally, it was observed that these concrete mixes, have percentage replacements of Portland cement with hydrated lime from 30% up to 40%.

4.2.1.4 Setting time test results for hydrated lime paste and portland cement paste

From Table 4.5, the initial and final setting time for portland cement paste were recorded at 60mins (i.e. 1 hour) and 430mins (i.e. 7 hours) respectively. Those for the hydrated lime paste were 2880mins (i.e. 2 days) and 4320mins (i.e. 3 days) respectively. Hydrated lime paste takes a much longer time to set than the Portland cement paste. Therefore, partially replacing portland cement with hydrated lime, will increase the rate at which the hydrated lime will set.

4.2.1.5 Chemical analysis test results for hydrated lime and portland cement

The result of chemical analysis of the hydrated lime is shown in Table 4.7. The results indicates a calcium oxide (CaO) content of 93%, silicon oxide (SiO_2) of 2.38%, aluminum oxide (Al_2O_3) of 2.04%, and magnesium oxide (MgO) content of 2%. It also indicates a water content of 0.58% and a pH value of 8.6. These results satisfied the provisions of ASTM C207 (2006), which require that the CaO content should not be less than 75.56%. Chemical analysis carried out on OPC by Awodiji (2012), showed these cement conformed to the BS 12 (1978) standard. It had a calcium oxide content of 67.62%, 0.003% moisture (H_2O), 20.39% silicon oxide (SiO_2), 6.03% aluminum oxide (Al_2O_3), 2.29% Iron oxide (Fe_2O_3), 1.31% magnesium oxide (MgO), 0.54% potassium oxide (K_2O), 0.2% titanium oxide (TiO_2), loss of ignition at 2.80% and finally, a pH value of 9.2.

4.2.2 Structural characteristics test results on the hardened lime cement concrete.

Discussion on the results obtained from the various test carried out to determine the structural characteristics of hardened lime cement concrete are as stated below;

(a) Density of the hardened lime cement concrete.

The densities of the hardened concrete cubes were determined. Their values ranged from 2449Kg/m^2 to 2616Kg/m^2 for the concrete cubes, showing that the concrete studied is a normal weight concrete as stated by Naik (1997) in section 2.3.5. The greater the density of hardened concrete, the stronger and more durable it will be.

(b) Compressive strength

The highest compressive strength values obtained at 7 days, 14 days, 21 days and 28 days of curing were 13.24N/mm^2, 24.01N/mm^2, 30.23N/mm^2 and 30.83N/mm^2 respectively. These strength values corresponded to mix label C12 for the 7 days strength, and C14 for the 14 days, 21 days, and 28 days strength respectively. Lowest values obtained for 7 days, 14 days, 21 days, and 28 days were, 5.60N/mm^2, 11.24N/mm^2, 14.72N/mm^2, and 15.12N/mm^2 respectively. These strengths corresponded to mix label N1.

Optimum mix proportion at the 28th day was 0.8125:0.1875:2.225:4.450 at a water-cement ratio of 0.562. The compressive strength values of the lime cement concrete increased with increasing curing age, which informs non-deterioration of concrete. Optimum percentage replacement of portland cement with hydrated lime was 18.75% as against 15% portland cement replacement with limestone by Dhir et al. (2007); 10% portland cement replacement with limestone by Blair (2010); and 20% replacement of portland cement with lime by Rizwan et al. (2004) as stated in section 2.3.2.3. From the works of Sounthararajan and Sivakumar (2013), it can be deduced that compressive strength values for concrete produced by partially replacing Portland cement with lime content in marble powder, are higher than those with hydrated lime replacement. The higher values showed greater resistance to crushing.

(c) Flexural strength

The highest flexural strength values obtained at 7 days, 14 days, 21 days and 28 days of curing were 2.45N/mm^2, 3.51N/mm^2, 4.91N/mm^2 and 5.03N/mm^2 respectively. These strength values corresponded to mix label N13 for the 7 days strength, and C6 for the 14 days, 21 days, and 28 days strength respectively. Lowest values obtained for 7 days, 14 days, 21 days, and 28 days were, 1.40N/mm^2, 1.63N/mm^2, 2.16N/mm^2, and 2.28N/mm^2 respectively. These strengths corresponded to mix label C4 for the 7 days strength, N35 for the 14 days strength, and N1 for the 21 days and 28 days strengths.

Optimum mix proportion at the 28th day was 0.862:0.138:2.625:5.250 at a water cement ratio of 0.58. Optimum percentage replacement recorded was 13.8%. But Southararajan and Sivakumar (2013) reported an optimum replacement of portland ement with lime content in marble of 10% (for mix proportion of 1:2:3 at water cement ratio of 0.3) and this gave a 28 days flexural strength value of 4.21N/mm^2. Higher values of flexural strength, show greater resistance to bending.

(d) Splitting tensile strength

The highest splitting tensile strength values obtained at 7 days, 14 days, 21 days and 28 days of curing were 1.50N/mm^2, 2.235N/mm^2, 3.605N/mm^2 and 3.725N/mm^2 respectively. These strength values corresponded to mix label C13 for the 7 days strength, and C12 for the 14 days strength, and C6 for the 21 days, and 28 days strength respectively. Lowest values obtained for 7 days, 14 days, 21 days, and 28 days were, 0.490N/mm^2, 0.82N/mm^2, 1.85N/mm^2, and 2.00N/mm^2 respectively. These strengths corresponded to mix label N14 for the 7 days strength, C4 for the 14 days strength, and N45 for the 21 days and 28 days strengths.

Optimum mix proportion at the 28th day was 0.863:0.138:2.625:5.250 at a water-cement ratio of 0.58. This results shows that the optimum 28 days splitting tensile strength was obtained at 13.82% replacement of portland cement with hydrated lime, with a strength value of 3.725N/mm^2. But Southararajan and Sivakumar (2013), reported an optimum replacement of 10% portland cement replacement with marble powder, having a strength of 4.35N/mm^2, while Ahmed et al. (2009) reported an optimum replacement of portland cement with limestone of 15% with strength values up to 4N/mm^2. Higher strength values of splitting tensile strength, shows greater resistance to tensile forces acting on the concrete member.

(e) Shear strength

The highest shear strength values obtained at 7 days, 14 days, 21 days and 28 days of curing were 0.771N/mm^2, 0.895N/mm^2, 1.227N/mm^2 and 1.257N/mm^2 respectively. These strength values corresponded to mix label C7 for the 7 days strength, and C3 for the 14 days strength, and C6 for the 21 days, and 28 days strength respectively. Lowest values obtained for 7 days, 14 days, 21 days, and 28 days were, 0.349N/mm^2, 0.416N/mm^2, 0.535N/mm^2, and 0.569N/mm^2 respectively. These strengths corresponded to mix label C4 for the 7 days and 14 days strengths, and N1 for the 21 days and 28 days strengths. Optimum mix proportion at the 28th day was 0.863:0.138:2.625:5.250 at a water-cement ratio of 0.58. The higher values shows higher resistance to shear force.

(f) Poisson ratio

The highest poisson ratio values obtained at 7 days, 14 days, 21 days and 28 days of curing were 0.35, 0.237, 0.215 and 0.2147 respectively. These strength values corresponded to mix label C7 for the 7 days strength, and C6 for the 14 days, 21 days, and 28 days strength respectively. Lowest values obtained for 7 days, 14 days, 21 days, and 28 days were, 0.133, 0.125, 0.103, and 0.105 respectively. These ratios corresponded to mix label C8 for the 7 days value, C10 for the 14 days value, and C13 for the 21 days and 28 days.

Optimum mix proportion at the 28th day was 0.863:0.138:2.625:5.250 at a water-cement ratio of 0.58. Values of poisson ratio obtained here, corresponded with the report by Shetty (2006), that poisson ratio for normal concrete was between 0.2 and 0.24. Osadebe and Nwakonobi (2007) reported a possion ratio of 0.26 for an optimum mix proportion of 1:1:2 (cement: laterite: gravel) at 0.65 water-cement ratio. The values of poisson ratio obtained in their study, shows that poisson ratio for laterized concrete are higher than those of lime cement concrete. The lower the poisson ratio, the more resistance the concrete is to bending. Therefore, higher strength concrete will have a lower value of poisson ratio. This explains why the 28th day poisson ratio values of Fig 4.9 in section 4.1.6, where much lower than those of the 7th day values.

(g) Modulus of elasticity

The maximum values of modulus of elasticity were obtained at 7 days, 14 days, 21 days and 28 days of curing as 19.887 x 10^3 N/mm^2, 27.101 x 10^3 N/mm^2, 28.916 x 10^3 N/mm^2, and 30.708 x 10^3 N/mm^2 respectively. These values corresponded to mix label C11for the 7 days results, C10 for the 14 days results, C10 and N23 for the 21 days, and C14 for the 28 days results respectively. Lowest values obtained for 7 days, 14 days, 21 days, and 28 days were, 12.332 x 10^3 N/mm^2, 17.058 x 10^3 N/mm^2, 19.994 x 10^3 N/mm^2, and 20.264 x 10^3 N/mm^2 respectively. These strengths corresponded to mix label N1 for the 7 days, C5 for the 14 days strengths, and N1 for the 21 days and 28 days strengths.

Optimum mix proportion at the 28th day was 0.8125:0.1875:2.225:4.450 at a water-cement ratio of 0.562. The higher the modulus of elasticity, the stiffer and more rigid the material. Ata (2007), reported in section 2.3.3.6, that modulus of elasticity for laterized concrete was between 7GPa and 9.5 x 10^3 N/mm^2. These values were far lower than those obtained in this study. Osadebe and Nwakonobi (2007) reported an optimum modulus of elasticity value of 18.89 x 10^3 N/mm^2 for an optimum mix proportion of 1:1:2 (cement: laterite: gravel) at water-cement ratio of 0.65. Therefore values of modulus of elasticity of lime cement concrete are higher than those of laterized concrete. Materials with low modulus of elasticity are less resistant to stress, while materials with high modulus of elasticity resist stress and hold their shape better.

(f) Modulus of rigidity

The maximum values of modulus of rigidity were obtained at 7 days, 14 days, 21 days and 28 days of curing as 8.6247x10^3 N/mm^2, 12.002x10^3 N/mm^2, 13.242x10^3 N/mm^2, and 13.386 x 10^3 N/mm^2 respectively. These values corresponded to mix label C11 for the 7 days results, and C14 for the 14 days, 21 days, and 28 days results respectively. Lowest values obtained for 7 days, 14 days, 21 days, and 28 days were, 4.293x10^3 N/mm^2, 7.448x10^3 N/mm^2, 8.731x10^3 N/mm^2, and 8.803x10^3 N/mm^2 respectively. These strengths corresponded to mix label N5 for the 7 days, N45 for the 14 days strengths, and N1 for the 21 days and 28 days strengths.

Optimum mix proportion at the 28^{th} day was 0.8125:0.1875:2.225:4.450 at 0.562 water-cement ratio. The higher the modulus of rigidity, the more resistance to deformation via shear stress a material will possess. Ata (2007) reported that modulus of rigidity for laterized concrete was between 5x10^3 N/mm^2 and 6x10^3 N/mm^2. This also shows that modulus of rigidity of hydrated lime cement concrete is higher than those of laterized concrete.

4.2.3 Performance validation of artificial neural network (NN) models developed

The results of the various neural networks formulated and validated, are discussed in this section as follows;

(a) Compressive strength NN model

From Fig 4.14, the compressive strength NN training had 14 epochs (rounds of training) to meet the best training state out of 1000 epochs at time 0 second. A performance of 0.742 targeting 0.0 and gradient of 5.18 targeting 1.0e^{-07} were achieved after performing 6 validation checks before convergence. Fig 4.15 shows that the best validation check occurred at the 8^{th}epoch at a mean square error of 10^0 and best performance at 5.3198. From Fig 4.16, the gradient at the very last epoch (Mu) was 0.01. The error histogram of Fig 4.17 shows that the 9thbin has zero error at 0.05811 and produced the best performance for the network. Fig 4.18 shows the regression values (R) for the training, validation, and testing data set. The R value is an indication of the relationship between the outputs and targets. If R = 1, then there is a linear relationship between the output and the targets (Beale et al., 2014). R = 0.98417 for training; 0.91226 for validation; 0.901 for testing and finally 0.9555 for the combination of the three. These values are very close to 1, showing that the ANN developed for predicting compressive strength of lime cement concrete has good predicting ability.

(b) Flexural strength NN model

From Fig 4.19, the flexural strength NN training had 14 epochs (rounds of training) to meet the best training state out of 1000 epochs at time 0 second. A performance of 0.0431 targeting 0.0 and gradient of 0.111 targeting 1.0e^{-07} were achieved after performing 6 validation checks before convergence. Fig 4.20 shows that the best validation check occurred at the 8th epoch at a mean square error of 0.1024. From Fig 4.21, the gradient at the very last epoch (Mu) was 0.001. The error histogram of Fig 4.22 shows that the 7thbin has zero error at -0.05 and produced the best performance for the network. Fig 4.23 shows the regression values (R) for the training, validation, and testing data set. R = 0.96904 for training; 0.93069 for validation; 0.7223 for testing and finally 0.94026 for the combination of the three. These values are very close to 1, showing that the ANN developed for predicting flexural strength of lime cement concrete has good predicting ability.

(c) Splitting tensile strength NN model

From Fig 4.24, the split tensile strength NN training had 11 epochs (rounds of training) to meet the best training state out of 1000 epochs at time 0 second. A performance of 0.0271 targeting 0.0 and gradient of 0.0284 targeting 1.0e^{-07} were achieved after performing 6 validation checks before convergence. Fig 4.25 shows that the best validation check occurred at the 6th epoch at a mean square error of 0.16084. From Fig 4.26, the gradient at the very last epoch (Mu) was 0.001. The error histogram of Fig 4.27 shows that the 8th bin has zero error at 0.005341 and produced the best performance for the network. Fig 4.28 shows the regression values (R) for the training, validation, and testing data set. R = 0.95651 for training; 0.8599 for validation; 0.96633 for testing and finally 0.94204 for the combination of the three. These values are very close to 1, showing that the ANN developed for predicting split tensile strength of lime cement concrete has good predicting ability.

(d) Shear force NN model

From Fig 4.29, the shear strength NN training had 14 epochs (rounds of training) to meet the best training state out of 1000 epochs at time 0 second. A performance of 0.00165 targeting 0.0 and gradient of 0.00273 targeting $1.0e^{-07}$ were achieved after performing 6 validation checks before convergence. Fig 4.30 shows that the best validation check occurred at the 8th epoch at a mean square error of 0.0046744. From Fig 4.31, the gradient at the very last epoch (Mu) was 0.0001. The error histogram of Fig 4.32 shows that the 9th bin has zero error at -0.00074 and produced the best performance for the network. Fig 4.33 shows the regression values (R) for the training, validation, and testing data set. R = 0.96978 for training; 0.96303 for validation; 0.95739 for testing and finally 0.96624 for the combination of the three. These values are very close to 1, showing that the ANN developed for predicting shear strength of lime cement concrete has good predicting ability.

(e) Poisson ratio NN model

From Fig 4.34, the poisson ratio NN training had 9 epochs (rounds of training) to meet the best training state out of 1000 epochs at time 0 second. A performance of 0.000743 targeting 0.0 and gradient of 0.000374 targeting $1.0e^{-07}$ were achieved after performing 6 validation checks before convergence. Fig 4.35 shows that the best validation check occurred at the 3rd epoch at a mean square error of 0.00038042. From Fig 4.36, the gradient at the very last epoch (Mu) was $1e^{-05}$. The error histogram of Fig 4.37 shows that the 8th bin has zero error at 0.004037 and produced the best performance for the network. Fig 4.38 shows the regression values (R) for the training, validation, and testing data set. R = 0.991 for training; 0.94636 for validation; 0.94146 for testing and finally 0.9776 for the combination of the three. These values are very close to 1, showing that the ANN developed for predicting poisson ratio of lime cement concrete has good predicting ability.

(f) Modulus of elasticity NN model

From Fig 4.39, the modulus of elasticity NN training had 17 epochs (rounds of training) to meet the best training state out of 1000 epochs at time 0 second. A performance of 0.0379 targeting 0.0 and gradient of 0.147 targeting $1.0e^{-07}$ were achieved after performing 6 validation checks before convergence. Fig 4.40 shows that the best validation check occurred at the 11^{th} epoch at a mean square error of 0.2875. From Fig 4.41, the gradient at the very last epoch (Mu) was 0.0001. The error histogram of Fig 4.42 shows that the 9^{th} bin has zero error at -0.00387 and produced the best performance for the network. Fig 4.43 shows the regression values (R) for the training, validation, and testing data set. R = 0.96883 for training; 0.84081 for validation; 0.93282 for testing and finally 0.93903 for the combination of the three. These values are very close to 1, showing that the ANN developed for predicting modulus of elasticity of lime cement concrete has good predicting ability.

(f) Modulus of rigidity NN model

From Fig 4.44, the modulus of rigidity NN training had 9 epochs (rounds of training) to meet the best training state out of 1000 epochs at time 0 second. A performance of 0.0819 targeting 0.0 and gradient of 0.0955 targeting $1.0e^{-07}$ were achieved after performing 6 validation checks before convergence. Fig 4.45 shows that the best validation check occurred at the 3^{rd}epoch at a mean square error of 0.19132. From Fig 4.46, the gradient at the very last epoch (Mu) was 0.001. The error histogram of Fig 4.47 shows that the 10^{th} bin has zero error at -0.09532 and produced the best performance for the network. Fig 4.48 shows the regression values (R) for the training, validation, and testing data set. R = 0.90536 for training; 0.81836 for validation; 0.8336 for testing and finally 0.8764 for the combination of the three. These values are close to 1, showing that the ANN developed for predicting modulus of rigidity of lime cement concrete has good predicting ability.

4.2.4 Test of adequacy of the neural network models

Predictions from the seven neural networks developed were tested for adequacy against their experimental values using the student's t-test. Table 4.18 to Table 4.24 presents the various results obtained from the test. Calculated 'T' values for the compressive strength, flexural strength, split tensile strength, shear strength, poisson ratio, modulus of elasticity and modulus of rigidity ANNs are given as 1.437, 0.1598, 0.4607, 1.4642, -1.0555, 0.4631, and 1.7069 respectively. These values fell below the allowable 'T' value which is at T = 2.064 from statistical table (see Appendix D). This is to say that null hypothesis (H_0) is accepted and alternative hypothesis is rejected as there is no significant difference between the neural network model results and the experimental results. This affirms that the result from the neural network models as obtained herein are reliable and the models could be used to predict the 7, 14, 21 and 28 days compressive strength, flexural strength, split tensile strength, shear strength, poisson ratio, modulus of elasticity and modulus of rigidity of lime cement concrete at 95% confidence level.

4.2.5 Comparison of results of experimental values with artificial neural network (ANN) predictions.

The modeling and simulation of the neural networks with the data obtained experimentally in this investigation has produced considerably encouraging results. The results have been analyzed by their percentage errors as shown from Table 4.25 to Table 4.31. Generally the highest percentage error recorded for all ANN models were not up to 11%. But it was observed that a few of the mixes in some of the ANN models developed, encountered some percentage error larger than 11%.This was attributed to experimental errors encountered during the laboratory testing of the structural characteristic of the lime cement concrete specimen at those points. The network output values were plotted against the experimental values in the form of line graphs as shown in Fig

4.40 to Fig 4.46. All of these results confirm that neural networks have been satisfactorily trained, as all the outputs given by the network are close to the values of the experimental results.

4.2.6 Graphical User Interface (GUI) developed.

The GUI shown in Plate 4.1, was developed from the Matlab Graphical User Interface Development Environment (GUIDE) and not by writing programs. This GUI has the ability of predicting the compressive strength, flexural strength, splitting tensile strength, shear strength, poisson ratio, modulus of elasticity, and modulus of rigidity of lime cement concrete at 7, 14, 21, and 28 days, when a given mix ratio is inputed. It also has the ability of re-training the network in order to achieve optimal values.

4.2.7 Effects of partial replacement of portland cement with hydrated lime in concrete production.

A comparison of the 28^{th} day compressive strengths of Portland cement concrete to lime cement concrete is presented in Fig 4.3 of section 4.1.6. Mix N1 with 10% replacement of portland cement with hydrated lime, experienced a 17.01% reduction in strength. Mix N2 having a 15% portland cement replacement with hydrated lime, experienced a strength loss of 23.90%. Mix N3, N4, and N5 with percentage replacements of 20%, 30%, and 40% respectively, experienced strength losses of 29.49%, 13.93% and 27.29%.These results show that the inclusion of hydrated lime as a partial replacement of portland cement in concrete production results to lower strength. This corresponded with the findings of Rizwan et al. (2004), that compressive strength of concrete decreases with the inclusion of lime as a partial replacement of portland cement.

It was observed from Table 4.9, that the mix ratios that gave compressive strength values above $20N/mm^2$ had their percentage replacement of portland cement with hydrated lime ranging from 12.5% to 26.8%. Optimum percentage replacement of portland cement with hydrated lime was observed at 18.75% for compressive strength, modulus of elasticity and modulus of rigidity while those for flexural strength, splitting tensile strength, shear strength and poisson ratio were observed at 13.8%. Tyagher et al. (2012) suggested that a lime replacement of up to 20% would yield a structural concrete. However, Ravasan et al. (2013) suggested a lime replacement of not more than 25%.

A comparison of the measure of workability for mix nos. N1, N2, N3, N4 and N5, having percentage replacement of portland cement with hydrated lime, of 10%, 15%, 20%, 30%, and 40% respectively, experienced improved workability as shown in Fig 4.4. Percentage improvement recorded were 100%, 16.6%, 30.74%, 3.93%, and 22.34% for mix nos.N1, N2, N3, N4, and N5 respectively. These results also proves that mixtures having portland cement replacement with hydrated lime, have improved workability when compared with concrete made with only portland cement.

This improvement in workability was as a result of the better water retention ability of the hydrated lime. This helped the mortar remain workable and retain enough water to cure properly (Looney and Pavia, 2015). The water retention ability of the lime cement concrete is enhanced by the high surface area of hydrated lime (Hendrick, Van and Van, 2008). Also, lime particles are in the ratio of 1:500 of cement particles (Speweik, 1996). Lime of this size have the ability to coat the sand grains, allowing enhanced workability and water retention properties to be fully developed.

Strength values for all properties of lime cement concrete studied, increased with increase in curing age, which informs non deterioration of lime cement concrete.

4.2.8 Effect of water cement ratio on the structural properties of lime cement concrete.

A study of Fig 4.5 to Fig 4.11 shows that a water-cement ratio of 0.6, resulted to a drastic decline in the structural properties of lime cement concrete, except for the poisson ratio. Optimum water cement ratio recorded for compressive strength, modulus of elasticity, and modulus of rigidity properties was 0.562, while that recorded for flexural strength, splitting tensile strength, shear strength, and poisson ratio properties was 0.58. Considering the line of best fit for the various properties studied, it could be said that the magnitude of each property of lime-cement concrete at 28th day of curing, increased as the water cement ratio increased, until the optimum values of 0.562 and 0.58 were reached.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, the structural properties of lime cement concrete were obtained at 7 days, 14 days, 21 days and 28 days. This concrete was made of portland cement, hydrated lime, river sand, granite chippings and water. The highest value of compressive strength recorded from experimental works at 28 days of curing was 30.83N/mm^2. This occurred at a water-cement (w/c) ratio of 0.562, having a percentage replacement of portland cement with hydrated lime of 18.75%. Highest values of flexural strength, splitting tensile strength, shear strength, poisson ratio, modulus of elasticity and modulus of rigidity recorded at 28 days of curing were 5.03N/mm^2, 3.725N/mm^2, 1.257N/mm^2, 0.216, 30.708 x 10^3 N/mm^2 and 13.386 x 10^3 N/mm^2 respectively. Lowest values recorded for compressive strength, flexural strength, split tensile strength, shear strength, poisson ratio, modulus of elasticity and modulus of rigidity recorded at 28 days of curing were 15.12N/mm^2, 2.28N/mm^2, 2.00N/mm^2, 0.569N/mm^2, 0.105, 20.264 x 10^3 N/mm^2 and 8.803 x 10^3 N/mm^2 respectively.

For lime cement concrete to be used as a structural concrete, potland cement replacement with hydrated lime must not be up to 30%. Optimum percentage replacement of portland cement with hydrated lime was observed at 18.75% for compressive strength, modulus of elasticity and modulus of rigidity while those for flexural strength, split tensile strength, shear strength and poisson ratio were observed at 13.8%. Partial replacement of portland cement with hydrated lime was observed to improve the workability of the fresh concrete, but reduced its strength. The magnitude of the various structural properties of lime cement concrete investigated, increased with increase in water cement ratio, until the optimum water cement ratios were reached.

The experimental results of 114 samples for each property of lime cement concrete considered, were applied to generate seven Levenberg-Marquardt back-propagation artificial neural networks

(ANNs). These were used to predict the compressive strength, flexural strength, splitting tensile strength, shear strength, poisson ratio, modulus of elasticity and modulus of rigidity of lime cement concrete respectively. 80data samples were used for training each of the networks. 17 data samples were used for verifying the network while another 17 were used to test the network. The training function used was the “trainlm” (i.e. the Levernberg-Marquardt back propagation training function), while the activation function used was the “Tansig” i.e. the tangent sigmoid function. Outcomes of the developed ANNs were compared with the results of the experimental work.

The outcome of results of the created networks were close to that of the experimental efforts. Generally, the maximum percentage error encountered was not up to 11%. Also the lowest and highest correlation coefficient recorded for all data samples used for developing the seven networks were 0.8764 and 0.9776 respectively. These values were close to 1. The adequacy of the network was further tested using the Student’s T test. The value of ‘T’ calculated for the compressive strength, flexural strength, splitting tensile strength, shear strength, poisson ratio, modulus of elasticity, and modulus of rigidity neural networks were; 1.437, 0.1598, 0.4607, 1.4642, -1.0555, 0.4631, and 1.7069 respectively. Allowable ‘T’ value from the statistical table was 2.064 as shown in Appendix D. This affirms that the result from the neural network models, as obtained herein are reliable and the models could be used to predict the 7, 14, 21 and 28 days structural properties of lime cement concrete at 95% confidence level.

With the use of the developed artificial neural networks (ANNs), mix design procedure for lime cement concrete can be carried out with lesser time and energy requirements, when compared to the traditional method. This is because, the need to prepare trial mixes that will be cured, and tested in the laboratory, will no longer be required. Also, the Graphical User Interface (GUI) developed, has helped in providing a very friendly environment for the implementation of the ANN models.

5.2 Recommendations

The following recommendations were made at the end of the present study;

a) Lime cement concrete could be used as a structural concrete in various civil and building works at 28^{th} day curing age.

b) The neural network models developed, can be used in predicting the structural properties of lime cement concrete prepared manually in the laboratory.

c) Government should encourage the production and sales of hydrated lime cement in Nigeria by creating favourable business environment and policy frameworks for the cement manufacturing industry. This will go a long way in reducing the CO_2 emission that is associated with the production of portland cement.

d) Research works could still be carried out using other types of artificial neural networks such as generalized regression, radial basis, self-organizing, genetic algorithm and probabilistic networks.

e) Research works on non-structural characteristics of lime cement concrete could be investigated.

5.3 Contributions to knowledge

The following contributions to knowledge have been achieved as a result of this study;

(i) This research work provides the details of the structural characteristics of lime cement concrete which include; compressive strength, flexural strength, splitting tensile strength, shear strength, poisson ratio, modulus of elasticity and modulus of rigidity.

(ii) Optimum values obtained at 28 days age for compressive strength, modulus of elasticity and modulus of rigidity at a mix proportion of 0.8125:0.1875:2.225:4.45 having a water-cement ratio of 0.562 and optimum percentage replacement at 18.75% were $30.83N/mm^2$, 30.708×10^3 N/mm^2 and 13.386×10^3 N/mm^2 respectively. Also, Optimum values for flexural strength, splitting tensile strength and shear strength at a mix proportion of 0.862:0.138:2.625:5.20 having a water-cement ratio of 0.58 and optimum percentage replacement at 13.8% were, 5.03N/mm^2, 3.725N/mm^2, and 1.257N/mm^2 respectively.

(iii) Seven artificial neural network models were formulated for predicting the compressive strength, flexural strength, splitting tensile strength, shear strength, poisson ratio, modulus of elasticity and modulus of rigidity of lime cement concrete.

(iv) The partial replacement of portland cement with hydrated lime was seen to improve the workability of the fresh lime cement concrete thereby giving enough time for the concrete to be produced, placed, compacted and finished without setting. In addition, it was seen that inclusion of hydrated lime in portland cement reduced strength but replacement not greater than 26% yielded concrete with compressive strength values up to 20N/mm^2, which is required for it to be used as a structural concrete (ACI 318, 1995).

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Appendix A: Results of structural characteristics test on lime cement concrete

Table A1: 28th day compressive strength results for normal mix of lime cement concrete cubes

S/No.	Mix No.	Replicates	Mass (Kg)	Density Kg/m^3	Av. Density Kg/m^3	Failure Load (KN)	Compressive strength (N/mm^2)	Av. Compr. strength (N/mm^2)
1	N1	a	8.10	2400	2449	330.30	14.68	15.12
		b	8.40	2489		342.00	15.20	
		c	8.30	2459		348.30	15.48	
2	N2	a	8.50	2519	2514	414.45	18.42	18.50
		b	8.35	2474		400.50	17.80	
		c	8.60	2548		433.80	19.28	
3	N3	a	8.30	2459	2489	376.20	16.72	17.86
		b	8.40	2489		412.62	18.34	
		c	8.50	2519		416.70	18.52	
4	N4	a	8.40	2489	2499	499.95	22.22	22.00
		b	8.40	2489		468.68	20.83	
		c	8.50	2519		516.38	22.95	
5	N5	a	8.70	2578	2558	453.15	26.14	19.56
		b	8.60	2548		429.98	19.11	
		c	8.60	2548		437.18	19.43	
6	N12	a	8.40	2489	2521	450.45	20.02	20.85
		b	8.30	2459		441.45	19.62	
		c	8.83	2616		515.48	22.91	
7	N13	a	8.70	2578	2539	503.55	22.38	22.70
		b	8.50	2519		497.25	22.10	
		c	8.50	2519		531.45	23.62	
8	N14	a	8.60	2548	2558	466.88	20.75	22.17
		b	8.60	2548		491.18	21.83	
		c	8.70	2578		538.43	23.93	
9	N15	a	8.40	2489	2504	477.00	21.20	21.56
		b	8.50	2519		490.05	21.78	
		c	8.45	2504		488.25	21.70	
10	N23	a	8.81	2610	2616	600.08	26.67	23.81
		b	8.90	2637		611.78	27.19	
		c	8.78	2601		598.05	26.58	
11	N24	a	8.50	2519	2568	519.98	23.11	23.34
		b	8.80	2607		524.25	23.30	
		c	8.70	2578		531.23	23.61	
12	N25	a	8.30	2459	2464	445.05	19.78	21.33
		b	8.40	2489		514.13	22.85	
		c	8.25	2444		480.60	21.36	
13	N34	a	8.40	2489	2499	353.70	15.72	16.22
		b	8.30	2459		336.15	14.94	
		c	8.60	2548		405.00	18.00	
14	N35	a	8.30	2459	2499	322.20	14.32	16.16
		b	8.40	2489		380.70	16.92	
		c	8.60	2548		387.90	17.24	
15	N45	a	8.30	2459	2449	431.55	19.18	19.00
		b	8.20	2430		409.50	18.20	
		c	8.30	2459		441.45	19.62	

Table A2: 28th day compressive strength results for control mix of lime cement concrete cube

S/No.	Mix No.	Repli-cates	Mass (Kg)	Density Kg/m^3	Av. Density Kg/m^3	Failure Load (KN)	Compressive strength (N/mm^2)	Av. Compr. strength (N/mm^2)
1	C1	a	8.70	2578	2578	455.21	20.23	20.85
		b	8.80	2607		485.50	21.58	
		c	8.60	2548		466.65	20.74	
2	C2	a	8.70	2578	2578	464.21	23.63	22.45
		b	8.90	2637		501.30	22.28	
		c	8.50	2519		482.30	21.44	
3	C3	a	8.50	2519	2509	590.13	26.23	26.68
		b	8.50	2519		610.11	27.12	
		c	8.40	2489		600.53	26.69	
4	C4	a	8.40	2489	2469	362.25	16.10	16.20
		b	8.40	2489		367.88	16.35	
		c	8.20	2430		363.38	16.15	
5	C5	a	8.31	2462	2471	425.93	18.93	19.15
		b	8.38	2483		433.13	19.25	
		c	8.33	2468		433.58	19.27	
6	C6	a	8.80	2607	2607	516.60	22.96	23.56
		b	8.90	2637		545.00	24.22	
		c	8.70	2578		528.73	23.50	
7	C7	a	8.70	2578	2528	551.00	24.49	23.87
		b	8.30	2459		530.78	23.59	
		c	8.60	2548		526.41	23.53	
8	C8	a	8.40	2489	2529	640.05	28.45	28.50
		b	8.70	2578		642.10	28.54	
		c	8.50	2519		641.48	28.51	
9	C9	a	8.70	2578	2548	548.32	24.37	23.94
		b	8.60	2548		542.48	24.11	
		c	8.50	2519		525.20	23.34	
10	C10	a	8.60	2548	2517	692.55	30.78	29.85
		b	8.38	2483		670.32	29.79	
		c	8.50	2519		652.10	28.98	
11	C11	a	8.60	2548	2528	632.18	28.10	27.80
		b	8.40	2489		623.50	27.11	
		c	8.60	2548		634.28	28.19	
12	C12	a	8.50	2519	2509	558.68	24.83	24.58
		b	8.50	2519		542.50	24.11	
		c	8.40	2489		558.00	24.80	
13	C13	a	8.60	2548	2509	670.25	29.79	28.90
		b	8.50	2519		659.93	29.33	
		c	8.30	2459		620.50	27.58	
14	C14	a	8.60	2548	2548	691.00	30.71	30.83
		b	8.50	2519		692.50	30.78	
		c	8.70	2578		697.50	31.00	
15	C15	a	8.20	2430	2460	483.17	21.47	21.45
		b	8.20	2430		475.03	21.11	
		c	8.50	2519		489.83	21.77	

Table A3: 21st day compressive strength results for normal mix of lime cement concrete cubes

S/No.	Mix No.	Replicates	Av. Density Kg/m^3	Failure Load (KN)	Compressive strength (N/mm^2)	Av. Compressive strength (N/mm^2)
1	N1	a	2449	345.00	15.33	14.72
		b		319.50	14.20	
		c		329.18	14.63	
2	N2	a	2514	415.80	18.48	18.30
		b		393.75	17.50	
		c		425.70	18.92	
3	N3	a	2489	337.50	15.00	16.06
		b		347.85	15.46	
		c		398.70	17.72	
4	N4	a	2499	489.00	21.72	21.68
		b		473.40	21.04	
		c		501.30	22.28	
5	N5	a	2558	373.00	16.57	15.78
		b		358.00	15.91	
		c		334.00	14.86	
6	N12	a	2521	427.05	18.98	20.02
		b		489.00	21.75	
		c		435.00	19.33	
7	N13	a	2539	512.10	22.76	22.30
		b		486.90	21.64	
		c		506.25	22.50	
8	N14	a	2558	501.53	22.29	22.10
		b		478.13	21.25	
		c		512.10	22.76	
9	N15	a	2504	462.60	20.56	21.43
		b		540.00	24.00	
		c		443.90	19.73	
10	N23	a	2616	602.78	26.79	25.26
		b		577.80	25.68	
		c		524.48	23.31	
11	N24	a	2568	493.20	21.92	22.56
		b		513.00	22.80	
		c		516.60	22.96	
12	N25	a	2464	501.98	22.31	20.65
		b		444.60	19.76	
		c		447.30	19.88	
13	N34	a	2499	316.35	14.06	16.00
		b		418.95	18.62	
		c		344.70	15.32	
14	N35	a	2499	330.30	14.68	15.35
		b		361.13	16.05	
		c		344.70	15.32	
15	N45	a	2449	440.30	19.57	17.23
		b		389.00	17.28	
		c		334.00	14.84	

Table A4: 21st day compressive strength results for control mix of lime cement concrete cubes

S/No.	Mix No.	Replicates	Av. Density Kg/m^3	Failure Load (KN)	Compressive strength (N/mm^2)	Av. Compressive strength (N/mm^2)
1	C1	a	2578	470.03	20.89	20.10
		b		456.75	20.30	
		c		430.00	19.11	
2	C2	a	2578	502.88	22.35	22.27
		b		500.63	22.25	
		c		499.73	22.21	
3	C3	a	2509	600.08	26.67	26.37
		b		600.08	26.67	
		c		580.05	25.78	
4	C4	a	2469	365.00	16.22	16.11
		b		359.33	15.97	
		c		363.15	16.14	
5	C5	a	2471	387.45	17.22	17.48
		b		402.53	17.89	
		c		389.93	17.33	
6	C6	a	2607	540.00	24.00	23.11
		b		570.00	25.33	
		c		450.00	20.00	
7	C7	a	2528	550.00	24.44	23.55
		b		500.00	22.22	
		c		539.78	23.99	
8	C8	a	2529	610.00	27.11	28.00
		b		639.90	28.44	
		c		639.90	28.44	
9	C9	a	2548	540.00	24.00	23.56
		b		550.35	24.46	
		c		499.95	22.22	
10	C10	a	2517	659.93	29.33	29.33
		b		639.90	28.44	
		c		679.95	30.22	
11	C11	a	2528	659.93	29.33	27.33
		b		564.75	25.10	
		c		620.10	27.56	
12	C12	a	2509	555.08	24.67	24.22
		b		549.90	24.44	
		c		530.10	23.56	
13	C13	a	2509	636.53	28.89	28.42
		b		669.83	29.77	
		c		600.08	26.67	
14	C14	a	2548	660.00	29.33	30.23
		b		690.01	30.67	
		c		690.50	30.69	
15	C15	a	2460	454.95	20.22	21.00
		b		470.03	20.89	
		c		490.05	21.78	

Table A5: 14th day compressive strength results for normal mix of lime cement concrete

S/No.	Mix No.	Replicates	Av. Density Kg/m³	Failure Load (KN)	Compressive strength (N/mm²)	Av. Compressive strength (N/mm²)
1	N1	a	2449	273.97	12.18	11.24
		b		230.90	10.26	
		c		253.40	11.29	
2	N2	a	2514	350.11	15.56	16.24
		b		389.53	17.31	
		c		356.70	15.85	
3	N3	a	2489	343.13	15.25	14.61
		b		308.46	13.71	
		c		334.56	14.87	
4	N4	a	2499	434.25	19.30	19.34
		b		418.50	18.60	
		c		452.70	20.12	
5	N5	a	2558	327.73	14.57	14.35
		b		337.05	14.98	
		c		303.65	13.50	
6	N12	a	2521	442.44	19.66	19.18
		b		420.90	18.71	
		c		432.00	19.20	
7	N13	a	2539	405.45	18.02	19.17
		b		445.28	19.79	
		c		443.25	19.70	
8	N14	a	2558	433.80	19.28	18.72
		b		416.70	18.52	
		c		413.10	18.36	
9	N15	a	2504	348.75	15.50	15.87
		b		378.68	16.83	
		c		343.80	15.28	
10	N23	a	2616	447.08	19.87	19.32
		b		444.15	19.74	
		c		412.86	18.35	
11	N24	a	2568	474.30	21.08	18.76
		b		375.75	16.70	
		c		416.25	18.50	
12	N25	a	2464	379.13	16.85	18.32
		b		461.93	20.53	
		c		395.55	17.58	
13	N34	a	2499	280.13	12.45	11.93
		b		248.63	11.05	
		c		276.53	12.29	
14	N35	a	2499	258.75	11.50	10.78
		b		229.50	10.20	
		c		239.40	10.64	
15	N45	a	2449	266.85	11.86	10.90
		b		220.28	9.79	
		c		248.63	11.05	

Table A6: 14th day compressive strength results for control mix of lime cement

S/No.	Mix No.	Replicates	Av. Density Kg/m^3	Failure Load (KN)	Compressive strength (N/mm^2)	Av. Compressive strength (N/mm^2)
1	C1	a	2578	433.35	19.26	19.15
		b		412.43	18.33	
		c		446.85	19.86	
2	C2	a	2578	441.45	19.62	19.21
		b		429.08	19.07	
		c		426.15	18.94	
3	C3	a	2509	460.27	20.46	20.67
		b		480.00	21.33	
		c		454.95	20.22	
4	C4	a	2469	239.18	10.63	10.72
		b		239.85	10.66	
		c		244.58	10.87	
5	C5	a	2471	234.90	10.44	10.43
		b		233.78	10.39	
		c		235.35	10.46	
6	C6	a	2607	350.35	15.57	14.90
		b		310.32	13.79	
		c		345.15	15.34	
7	C7	a	2528	430.12	19.12	20.01
		b		460.15	20.45	
		c		460.35	20.46	
8	C8	a	2529	500.23	22.23	22.02
		b		480.45	21.35	
		c		505.80	22.48	
9	C9	a	2548	450.82	20.04	20.03
		b		440.31	19.57	
		c		460.08	20.48	
10	C10	a	2517	590.00	26.22	24.91
		b		540.79	24.04	
		c		550.58	24.47	
11	C11	a	2528	460.65	20.47	20.92
		b		470.72	20.92	
		c		480.82	21.37	
12	C12	a	2509	440.32	19.57	19.13
		b		450.45	20.02	
		c		400.05	17.80	
13	C13	a	2509	420.32	18.68	18.91
		b		440.64	19.58	
		c		415.58	18.47	
14	C14	a	2548	540.00	24.00	24.01
		b		535.00	23.77	
		c		545.85	24.26	
15	C15	a	2460	450.21	20.01	19.34
		b		390.81	17.34	
		c		465.08	20.67	

Table A7: 7th day compressive strength results for normal mix of lime cement concrete cubes.

S/No.	Mix No.	Replicates	Av. Density Kg/m^3	Failure Load (KN)	Compressive strength (N/mm^2)	Av. Compressive strength (N/mm^2)
1	N1	a	2449	125.58	5.58	5.60
		b		123.43	5.49	
		c		128.93	5.73	
2	N2	a	2514	204.53	9.09	8.68
		b		183.83	8.17	
		c		197.55	8.78	
3	N3	a	2489	159.75	7.10	7.37
		b		164.25	7.30	
		c		173.48	7.71	
4	N4	a	2499	134.55	5.98	5.67
		b		125.10	5.56	
		c		123.08	5.47	
5	N5	a	2558	101.70	4.52	4.55
		b		105.25	4.68	
		c		99.90	4.44	
6	N12	a	2521	219.38	9.75	9.78
		b		214.88	9.55	
		c		225.90	10.04	
7	N13	a	2539	235.80	10.48	10.29
		b		220.50	9.80	
		c		238.28	10.59	
8	N14	a	2558	177.08	7.87	7.59
		b		171.45	7.62	
		c		163.80	7.28	
9	N15	a	2504	172.80	7.68	7.76
		b		167.18	7.43	
		c		183.83	8.17	
10	N23	a	2616	158.18	7.03	7.03
		b		156.60	6.96	
		c		159.75	7.10	
11	N24	a	2568	191.48	8.51	8.63
		b		194.40	8.64	
		c		196.65	8.74	
12	N25	a	2464	164.73	7.32	7.48
		b		166.88	7.42	
		c		173.25	7.70	
13	N34	a	2499	194.73	8.65	8.71
		b		198.00	8.80	
		c		195.30	8.68	
14	N35	a	2499	205.88	9.15	9.08
		b		198.00	8.80	
		c		209.03	9.29	
15	N45	a	2449	154.13	6.85	6.61
		b		144.00	6.40	
		c		148.05	6.58	

Table A8: 7th day compressive strength result for control mix of lime cement concrete cubes

S/No.	Mix No.	Replicates	Av. Density Kg/m^3	Failure Load (KN)	Compressive strength (N/mm^2)	Av. Compressive strength (N/mm^2)
1	C1	a	2578	212.40	9.44	9.62
		b		209.48	9.31	
		c		227.48	10.11	
2	C2	a	2578	241.88	10.75	10.47
		b		233.33	10.37	
		c		231.53	10.29	
3	C3	a	2509	250.10	11.11	11.09
		b		247.95	11.02	
		c		250.65	11.14	
4	C4	a	2469	204.30	9.08	8.92
		b		199.58	8.87	
		c		198.23	8.81	
5	C5	a	2471	145.58	6.47	6.80
		b		160.20	7.12	
		c		153.23	6.81	
6	C6	a	2607	231.78	10.30	10.97
		b		241.88	10.75	
		c		266.85	11.86	
7	C7	a	2528	196.43	8.73	8.81
		b		197.78	8.79	
		c		200.50	8.91	
8	C8	a	2529	275.88	12.26	12.31
		b		276.08	12.27	
		c		279.00	12.40	
9	C9	a	2548	195.30	8.68	8.65
		b		193.95	8.62	
		c		194.60	8.65	
10	C10	a	2517	205.23	9.12	9.10
		b		202.05	8.98	
		c		207.00	9.20	
11	C11	a	2528	310.18	13.79	13.24
		b		284.40	12.64	
		c		299.25	13.30	
12	C12	a	2509	227.70	10.12	11.06
		b		259.78	11.56	
		c		258.75	11.50	
13	C13	a	2509	272.25	12.10	12.26
		b		277.45	12.33	
		c		277.88	12.35	
14	C14	a	2548	142.65	6.34	6.68
		b		155.93	6.93	
		c		152.25	6.77	
15	C15	a	2460	279.90	12.44	12.90
		b		298.35	13.26	
		c		292.50	13.00	

Table A9: 28th day flexural strength results for normal mix of lime cement concrete prototype beams

S/No.	Mix No.	Repli-cates	Mass (Kg)	Density Kg/m^3	Av. Density Kg/m^3	Failure Load (KN)	Flexural strength (N/mm^2)	Av. flexural strength (N/mm^2)
1	**N1**	**a**	**35.30**	**2615**	2657	**12.43**	**2.21**	2.28
		b	36.80	2726		13.73	2.44	
		c	35.50	2630		12.26	2.18	
2	N2	a	35.10	2600	2580	20.03	3.56	3.86
		b	35.00	2593		21.88	3.89	
		c	34.40	2548		23.23	4.13	
3	N3	a	35.80	2652	2642	20.14	3.58	3.62
		b	35.20	2607		20.31	3.61	
		c	36.00	2667		20.70	3.68	
4	N4	a	34.80	2578	2588	19.41	3.45	3.49
		b	34.40	2548		18.96	3.37	
		c	35.60	2638		20.53	3.65	
5	N5	a	34.20	2533	2511	16.93	3.01	2.96
		b	33.60	2489		16.37	2.91	
		c	33.90	2511		16.71	2.97	
6	N12	a	34.90	2585	2590	24.13	4.29	4.37
		b	34.90	2585		24.24	4.31	
		c	35.10	2600		25.43	4.52	
7	N13	a	35.40	2622	2625	21.94	3.90	3.91
		b	35.10	2600		21.49	3.82	
		c	35.80	2652		22.61	4.02	
8	N14	a	35.00	2593	2608	22.84	4.06	3.98
		b	35.50	2630		23.12	4.11	
		c	35.10	2600		21.26	3.78	
9	N15	a	36.00	2667	2701	17.44	3.10	3.23
		b	36.60	2711		18.34	3.26	
		c	36.80	2726		18.68	3.32	
10	N23	a	35.10	2600	2590	26.21	4.66	4.39
		b	35.10	2600		24.30	4.32	
		c	34.70	2570		23.63	4.20	
11	N24	a	36.00	2667	2696	23.74	4.22	4.26
		b	36.60	2711		23.96	4.26	
		c	36.60	2711		24.19	4.30	
12	N25	a	34.40	2548	2583	20.98	3.43	3.58
		b	35.40	2622		21.49	3.69	
		c	34.80	2578		21.38	3.62	
13	N34	a	34.40	2578	2546	16.14	2.87	2.77
		b	34.20	2533		15.98	2.84	
		c	34.10	2526		14.68	2.61	
14	N35	a	35.00	2593	2558	17.44	2.97	2.94
		b	34.20	2533		16.71	2.90	
		c	34.40	2548		17.10	2.95	
15	N45	a	34.80	2578	2556	15.64	2.78	2.67
		b	34.30	2541		14.96	2.66	
		c	34.40	2548		14.51	2.58	

Table A10: 28th day flexural strength results for control mix of lime cement concrete prototype beams.

S/No.	Mix No.	Repli-cates	Mass (Kg)	Density Kg/m^3	Av. Density Kg/m^3	Failure Load (KN)	Flexural strength (N/mm^2)	Av. flexural strength (N/mm^2)
1	C1	a	36.60	2711	2629	26.72	4.75	4.51
		b	35.30	2614		25.93	4.61	
		c	34.60	2563		23.46	4.17	
2	C2	a	36.20	2681	2617	18.84	3.35	3.27
		b	35.10	2600		18.34	3.26	
		c	**34.70**	**2570**		**18.06**	**3.21**	
3	**C3**	**a**	**35.10**	**2600**	2592	**22.61**	**4.02**	4.02
		b	35.30	2614		22.78	4.05	
		c	34.60	2563		22.50	4.00	
4	C4	a	33.90	2511	2501	15.98	2.84	2.82
		b	34.00	2519		16.59	2.95	
		c	33.40	2474		14.96	2.66	
5	C5	a	34.60	2563	2558	15.36	2.73	2.70
		b	34.90	2585		15.58	2.77	
		c	34.10	2526		14.57	2.59	
6	C6	a	37.40	2770	2733	28.29	5.03	5.03
		b	35.20	2607		28.13	5.00	
		c	38.10	2822		28.46	5.06	
7	C7	a	35.00	2593	2590	21.60	3.84	3.85
		b	34.70	2570		21.49	3.82	
		c	35.20	2607		21.94	3.90	
8	C8	a	32.70	2422	2439	24.36	4.33	4.36
		b	33.00	2444		24.47	4.35	
		c	33.10	2452		24.75	4.40	
9	C9	a	33.70	2496	2464	22.67	4.03	3.67
		b	33.20	2459		20.53	3.65	
		c	32.90	2437		18.73	3.33	
10	C10	a	36.40	2696	2560	23.46	4.17	4.15
		b	34.30	2541		23.34	4.15	
		c	33.00	2444		23.23	4.13	
11	C11	a	34.60	2563	2627	23.79	4.23	4.28
		b	35.20	2607		24.19	4.30	
		c	36.60	2711		24.24	4.31	
12	C12	a	34.60	2696	2676	22.78	4.05	4.10
		b	36.20	2681		23.23	4.13	
		c	35.80	2652		23.23	4.12	
13	C13	a	34.90	2585	2565	17.11	3.04	3.02
		b	34.70	2570		16.99	3.02	
		c	34.30	2541		16.88	3.00	
14	C14	a	36.40	2696	2617	26.49	4.71	4.52
		b	34.90	2585		26.04	4.63	
		c	34.70	2570		23.74	4.22	
15	C15	a	33.80	2504	2509	23.46	4.17	4.16
		b	33.00	2444		23.12	4.11	
		c	34.80	2578		23.63	4.20	

Table A11: 21st day flexural strength results for normal mix of lime cement concrete prototype beams.

S/No.	Mix No.	Replicates	Av. Density Kg/m^3	Failure Load (KN)	Flexural strength (N/mm^2)	Av. flexural strength (N/mm^2)
1	N1	a	2657	12.94	2.30	2.16
		b		11.36	2.02	
		c		11.81	2.10	
2	N2	a	2580	19.97	3.55	3.56
		b		20.93	3.72	
		c		19.13	3.40	
3	N3	a	2642	20.08	3.57	3.39
		b		18.68	3.32	
		c		18.45	3.28	
4	N4	a	2652	18.90	3.36	3.33
		b		18.51	3.29	
		c		19.07	3.39	
5	N5	a	2511	15.02	2.67	2.63
		b		13.16	2.34	
		c		16.20	2.88	
6	N12	a	2590	24.02	4.27	4.20
		b		23.23	4.13	
		c		23.57	4.19	
7	N13	a	2625	19.18	3.41	3.41
		b		19.24	3.42	
		c		19.07	3.39	
8	N14	a	2608	18.96	3.37	3.42
		b		19.24	3.42	
		c		19.52	3.47	
9	N15	a	2701	16.20	2.88	3.02
		b		17.61	3.13	
		c		17.10	3.04	
10	N23	a	2590	24.30	4.32	4.27
		b		23.06	4.10	
		c		24.75	4.40	
11	N24	a	2696	23.18	4.12	4.08
		b		22.22	3.95	
		c		23.51	4.18	
12	N25	a	2583	18.79	3.34	3.40
		b		19.69	3.50	
		c		18.90	3.36	
13	N34	a	2546	15.19	2.70	2.60
		b		14.23	2.53	
		c		14.46	2.57	
14	N35	a	2558	15.30	2.72	2.89
		b		16.54	2.94	
		c		14.34	2.55	
15	N45	a	2556	14.29	2.54	2.52
		b		13.95	2.48	
		c		14.23	2.53	

Table A12: 21st day flexural strength results for control mix of lime cement concrete prototype beams.

S/No.	Mix No.	Replicates	Av. Density Kg/m^3	Failure Load (KN)	Flexural strength (N/mm^2)	Av. flexural strength (N/mm^2)
1	C1	a	2629	25.76	4.58	4.38
		b		24.24	4.31	
		c		23.91	4.25	
2	C2	a	2617	17.33	3.08	3.04
		b		16.99	3.02	
		c		16.99	3.02	
3	C3	a	2592	21.71	3.86	3.84
		b		22.11	3.93	
		c		20.93	3.72	
4	C4	a	2501	13.22	2.35	2.36
		b		13.61	2.42	
		c		12.99	2.31	
5	C5	a	2558	15.36	2.73	2.70
		b		15.58	2.77	
		c		14.57	2.59	
6	C6	a	2733	27.73	4.93	4.91
		b		27.11	4.82	
		c		27.96	4.97	
7	C7	a	2590	20.98	3.73	3.73
		b		20.76	3.69	
		c		21.21	3.77	
8	C8	a	2439	23.18	4.12	4.20
		b		24.02	4.27	
		c		23.68	4.21	
9	C9	a	2464	20.08	3.57	3.48
		b		19.80	3.52	
		c		18.84	3.35	
10	C10	a	2560	23.29	4.14	4.06
		b		22.73	4.04	
		c		22.50	4.00	
11	C11	a	2627	22.83	4.06	4.12
		b		23.29	4.14	
		c		23.40	4.16	
12	C12	a	2676	21.83	3.88	3.90
		b		22.05	3.92	
		c		21.94	3.90	
13	C13	a	2565	16.82	2.99	2.93
		b		16.37	2.91	
		c		16.26	2.89	
14	C14	a	2617	25.31	4.50	4.46
		b		25.20	4.48	
		c		24.75	4.40	
15	C15	a	2509	22.67	4.03	4.02
		b		22.39	3.98	
		c		22.78	4.05	

Table A13: 14th day flexural strength results for normal mix of lime cement concrete prototype beams.

S/No.	Mix No.	Replicates	Av. Density Kg/m^3	Failure Load (KN)	Flexural strength (N/mm^2)	Av. flexural strength (N/mm^2)
1	N1	a	2657	9.84	1.75	1.72
		b		9.56	1.70	
		c		9.62	1.71	
2	N2	a	2580	13.16	2.34	2.35
		b		13.78	2.45	
		c		12.66	2.25	
3	N3	a	2642	12.04	2.14	2.16
		b		11.93	2.12	
		c		12.49	2.22	
4	N4	a	2652	17.89	3.18	3.00
		b		16.76	2.98	
		c		16.03	2.85	
5	N5	a	2511	10.74	1.91	1.95
		b		11.03	1.96	
		c		11.14	1.98	
6	N12	a	2590	16.31	2.90	2.86
		b		15.64	2.78	
		c		16.31	2.90	
7	N13	a	2625	16.14	2.87	2.84
		b		16.88	3.00	
		c		14.91	2.65	
8	N14	a	2608	15.08	2.68	2.65
		b		14.29	2.54	
		c		15.36	2.73	
9	N15	a	2701	12.38	2.20	2.22
		b		12.15	2.16	
		c		12.94	2.30	
10	N23	a	2590	15.81	2.81	2.89
		b		16.09	2.86	
		c		16.88	3.00	
11	N24	a	2696	16.88	2.67	2.78
		b		15.92	2.83	
		c		15.98	2.84	
12	N25	a	2583	14.12	2.51	2.54
		b		14.51	2.58	
		c		14.23	2.53	
13	N34	a	2546	10.18	1.81	1.80
		b		10.41	1.85	
		c		9.79	1.74	
14	N35	a	2558	8.89	1.58	1.63
		b		9.39	1.67	
		c		9.23	1.64	
15	N45	a	2556	9.11	1.62	1.68
		b		9.34	1.66	
		c		9.90	1.76	

Table A14: 14th day flexural strength result for control mix of lime cement concrete prototype beams.

S/No.	Mix No.	Replicates	Av. Density (Kg/m^3)	Failure Load (KN)	Flexural strength (N/mm^2)	Av. flexural strength (N/mm^2)
1	C1	A	2629	17.83	3.17	2.96
		b		13.95	2.48	
		c		18.23	3.24	
2	C2	a	2617	15.47	2.75	2.56
		b		13.61	2.42	
		c		14.12	2.51	
3	C3	a	2592	20.19	3.59	3.58
		b		20.31	3.61	
		c		19.91	3.54	
4	C4	a	2501	9.34	1.66	1.66
		b		9.62	1.71	
		c		9.11	1.62	
5	C5	a	2558	10.18	1.81	1.74
		b		9.96	1.77	
		c		9.23	1.64	
6	C6	a	2733	19.29	3.43	3.51
		b		21.15	3.76	
		c		18.73	3.33	
7	C7	a	2590	19.24	3.42	3.33
		b		18.34	3.26	
		c		18.62	3.31	
8	C8	a	2439	17.21	3.06	2.99
		b		15.56	2.82	
		c		17.44	3.10	
9	C9	a	2464	15.58	2.77	2.67
		b		15.98	2.84	
		c		15.86	2.82	
10	C10	a	2560	17.67	3.14	3.12
		b		17.49	3.11	
		c		17.44	3.10	
11	C11	a	2627	18.56	3.30	3.25
		b		18.00	3.20	
		c		18.28	3.25	
12	C12	a	2676	18.39	3.27	3.26
		b		17.89	3.18	
		c		18.68	3.32	
13	C13	a	2565	15.24	2.71	2.63
		b		14.85	2.64	
		c		14.23	2.53	
14	C14	a	2617	17.49	3.11	3.10
		b		17.55	3.12	
		c		17.27	3.07	
15	C15	a	2509	17.61	3.13	3.16
		b		18.00	3.20	
		c		17.72	3.15	

Table A15: 7th day flexural strength result for normal mix of lime-cement concrete prototype beam

S/No.	Mix No.	Replicates	Av. Density Kg/m^3	Failure Load (KN)	Flexural strength (N/mm^2)	Av. flexural strength (N/mm^2)
1	N1	a	2657	8.16	1.45	1.48
		b		8.83	1.57	
		c		7.93	1.41	
2	N2	a	2580	10.29	1.83	1.75
		b		9.45	1.68	
		c		9.79	1.74	
3	N3	a	2642	9.51	1.69	1.63
		b		8.78	1.56	
		c		9.23	1.64	
4	N4	a	2652	9.06	1.61	1.60
		b		9.28	1.65	
		c		8.66	1.54	
5	N5	a	2511	10.07	1.79	1.74
		b		10.01	1.78	
		c		9.23	1.64	
6	N12	a	2590	12.88	2.29	2.30
		b		12.60	2.24	
		c		13.33	2.37	
7	N13	a	2625	12.94	2.30	2.45
		b		14.79	2.63	
		c		13.67	2.43	
8	N14	a	2608	10.97	1.95	1.93
		b		10.86	1.93	
		c		10.80	1.92	
9	N15	a	2701	9.96	1.77	1.82
		b		10.29	1.83	
		c		10.46	1.86	
10	N23	a	2590	9.28	1.65	1.65
		b		9.45	1.68	
		c		9.06	1.61	
11	N24	a	2696	12.71	2.26	2.25
		b		12.54	2.23	
		c		12.77	2.27	
12	N25	a	2583	12.38	2.20	2.17
		b		11.98	2.13	
		c		12.26	2.18	
13	N34	a	2546	9.17	1.63	1.62
		b		8.89	1.58	
		c		9.23	1.64	
14	N35	a	2558	8.50	1.51	1.47
		b		8.21	1.46	
		c		8.04	1.43	
15	N45	a	2556	8.55	1.52	1.58
		b		8.83	1.57	
		c		9.23	1.64	

Table A16: 7th day flexural strength result for control mix of lime cement concrete prototype beams.

S/No.	Mix No.	Replicates	Av. Density (Kg/m^3)	Load (KN)	Flexural strength (N/mm^2)	Av. flexural strength (N/mm^2)
1	C1	a	2629	14.46	2.57	2.43
		b		12.38	2.20	
		c		14.18	2.52	
2	C2	a	2617	12.32	2.19	2.25
		b		12.94	2.30	
		c		12.66	2.25	
3	C3	a	2592	12.04	2.14	2.14
		b		12.21	2.17	
		c		11.93	2.12	
4	C4	a	2501	7.82	1.39	1.40
		b		7.99	1.42	
		c		7.76	1.38	
5	C5	a	2558	8.33	1.48	1.51
		b		8.38	1.49	
		c		8.76	1.56	
6	C6	a	2733	12.38	2.20	2.22
		b		12.60	2.24	
		c		12.43	2.21	
7	C7	a	2590	17.76	3.16	3.08
		b		16.99	3.02	
		c		17.27	3.07	
8	C8	a	2439	9.23	1.64	1.64
		b		9.17	1.63	
		c		9.28	1.65	
9	C9	a	2464	12.99	2.31	2.32
		b		12.99	2.31	
		c		13.11	2.33	
10	C10	a	2560	9.00	1.63	1.67
		b		9.17	1.70	
		c		9.45	1.68	
11	C11	a	2627	12.09	2.15	2.03
		b		11.64	2.07	
		c		10.46	1.86	
12	C12	a	2676	11.19	1.99	1.96
		b		11.08	1.97	
		c		10.80	1.92	
13	C13	a	2565	12.77	2.27	2.27
		b		12.54	2.23	
		c		13.05	2.32	
14	C14	a	2617	9.51	1.69	1.64
		b		9.00	1.60	
		c		9.11	1.62	
15	C15	a	2509	9.51	1.69	1.83
		b		10.69	1.90	
		c		10.63	1.89	

Table A17: 28th day split tensile strength results for normal mix of lime cement concrete cylinders.

S/No.	Mix No.	Replicates	Mass (Kg)	Density Kg/m^3	Av. Density Kg/m^3	Failure Load (KN)	Split tensile strength (N/mm^2)	Av. split ten. strength (N/mm^2)
1	N1	a	12.70	2396		137.84	1.95	
		b	12.90	2433	2426	144.91	2.05	2.100
		c	12.99	2450		162.58	2.30	
2	N2	a	13.90	2622		215.60	3.05	
		b	13.50	2546	2572	201.46	2.85	2.905
		c	13.50	2546		198.98	2.815	
3	N3	a	13.50	2546		173.18	2.45	
		b	13.80	2603	2578	204.99	2.90	2.700
		c	13.70	2584		194.39	2.75	
4	N4	a	13.30	2509		182.37	2.58	
		b	13.30	2509	2490	185.91	2.63	2.585
		c	13.00	2452		180.25	2.55	
5	N5	a	13.60	2565		154.80	2.19	
		b	13.80	2603	2578	165.41	2.34	2.250
		c	13.60	2565		156.93	2.22	
6	N12	a	13.70	2584		237.51	3.36	
		b	13.60	2565	2578	228.32	3.23	3.280
		c	13.70	2584		229.73	3.25	
7	N13	a	14.40	2716		214.89	3.04	
		b	14.40	2716	2697	204.99	2.90	2.835
		c	14.10	2660		181.67	2.57	
8	N14	a	13.70	2584		169.65	2.40	
		b	14.20	2679	2628	188.03	2.66	2.540
		c	13.90	2622		180.96	2.56	
9	N15	a	14.00	2641		164.35	2.325	
		b	14.00	2641	2647	173.18	2.45	2.425
		c	14.10	2660		176.72	2.50	
10	N23	a	14.30	2697		242.46	3.43	
		b	14.00	2641	2672	233.27	3.30	3.350
		c	14.20	2679		234.68	3.32	
11	N24	a	13.60	2565		212.06	3.00	
		b	13.90	2622	2609	229.03	3.24	3.200
		c	14.00	2641		237.51	3.36	
12	N25	a	13.90	2622		192.27	2.72	
		b	13.40	2528	2546	185.91	2.63	2.650
		c	13.20	2490		183.79	2.60	
13	N34	a	13.70	2584		142.79	2.02	
		b	13.90	2622	2603	152.68	2.16	2.080
		c	13.80	2603		145.62	2.06	
14	N35	a	13.70	2584		139.25	1.97	
		b	14.10	2660	2641	157.63	2.23	2.205
		c	14.20	2679		171.06	2.42	
15	N45	a	13.70	2584		137.84	1.95	
		b	14.10	2660	2603	151.98	2.15	2.00
		c	13.60	2565		134.31	1.90	

TableA18: 28th day splitting tensile strength results for control mix of lime cement concrete cylinders.

S/No.	Mix No.	Repli-cates	Mass (Kg)	Density Kg/m^3	Av. Density Kg/m^3	Failure Load (KN)	Split tensile strength (N/mm^2)	Av. split ten. strength (N/mm^2)
1	C1	a	14.10	2660	2647	238.92	3.38	3.380
		b	14.50	2735		247.40	3.50	
		c	13.50	2546		230.44	3.26	
2	C2	a	14.20	2679	2672	180.25	2.55	2.450
		b	14.10	2660		159.75	2.26	
		c	14.20	2679		179.54	2.54	
3	C3	a	14.10	2660	2641	227.57	3.215	3.015
		b	14.00	2641		210.65	2.98	
		c	13.90	2622		201.46	2.85	
4	C4	a	14.00	2641	2641	144.91	2.05	2.115
		b	13.80	2603		130.77	1.85	
		c	14.20	2679		172.83	2.445	
5	C5	a	13.40	2528	2515	136.07	1.925	2.025
		b	13.40	2528		155.51	2.20	
		c	13.20	2490		137.84	1.95	
6	C6	a	13.80	2603	2641	233.27	3.30	3.725
		b	14.10	2660		268.96	3.805	
		c	14.10	2660		287.69	4.07	
7	C7	a	14.00	2641	2653	194.39	2.75	2.850
		b	13.90	2622		185.20	2.62	
		c	14.30	2697		224.78	3.18	
8	C8	a	14.10	2660	2609	236.80	3.35	3.270
		b	13.30	2509		215.59	3.05	
		c	14.10	2660		241.04	3.41	
9	C9	a	13.90	2622	2609	197.92	2.80	2.750
		b	13.60	2565		180.25	2.55	
		c	14.00	2641		204.99	2.90	
10	C10	a	14.10	2660	2653	222.31	3.145	3.115
		b	13.90	2622		208.52	2.95	
		c	14.20	2679		228.32	3.25	
11	C11	a	14.30	2697	2685	237.51	3.36	3.210
		b	14.20	2679		208.52	2.95	
		c	14.20	2679		234.68	3.32	
12	C12	a	13.80	2603	2641	212.06	3.00	3.075
		b	14.10	2660		219.83	3.11	
		c	14.10	2660		220.19	3.115	
13	C13	a	14.00	2641	2635	162.58	2.30	2.250
		b	13.90	2622		141.37	2.00	
		c	14.00	2641		173.18	2.45	
14	C14	a	14.10	2660	2660	243.87	3.45	3.400
		b	14.20	2679		238.92	3.60	
		c	14.00	2641		222.66	3.15	
15	C15	a	13.90	2622	2609	229.73	3.25	3.120
		b	13.60	2565		201.46	2.85	
		c	14.00	2641		230.44	3.26	

Table A19: 21st day splitting tensile strength results for normal mix of lime cement concrete cylinders.

S/No.	Mix No.	Replicates	Av. Density Kg/m^3	Failure Load (KN)	Split tensile strength (N/mm^2)	Av. Split ten. strength (N/mm^2)
1	N1	a	2426	144.91	2.05	1.980
		b		127.23	1.80	
		c		147.73	2.09	
2	N2	a	2572	180.25	2.55	2.605
		b		187.32	2.65	
		c		184.84	2.615	
3	N3	a	2578	178.84	2.53	2.470
		b		180.96	2.56	
		c		164.00	2.32	
4	N4	a	2490	169.65	2.40	2.425
		b		168.94	2.39	
		c		175.66	2.485	
5	N5	a	2578	151.27	2.14	2.020
		b		137.84	1.95	
		c		139.25	1.97	
6	N12	a	2578	229.73	3.25	3.110
		b		222.66	3.15	
		c		207.11	2.93	
7	N13	a	2697	162.93	2.305	2.335
		b		172.48	2.44	
		c		159.75	2.26	
8	N14	a	2628	162.58	2.30	2.350
		b		176.71	2.50	
		c		159.04	2.25	
9	N15	a	2647	165.76	2.345	2.215
		b		148.44	2.10	
		c		155.51	2.20	
10	N23	a	2672	236.09	3.34	3.230
		b		222.66	3.15	
		c		226.20	3.20	
11	N24	a	2609	209.23	2.96	3.020
		b		212.06	3.00	
		c		219.13	3.10	
12	N25	a	2546	162.58	2.30	2.470
		b		202.16	2.86	
		c		159.04	2.25	
13	N34	a	2603	130.77	1.85	1.910
		b		141.37	2.00	
		c		132.89	1.88	
14	N35	a	2641	156.57	2.215	2.155
		b		159.05	2.25	
		c		141.37	2.00	
15	N45	a	2603	127.23	1.80	1.850
		b		127.23	1.80	
		c		137.84	1.95	

Table A20: 21st day splitting tensile strength results for control mix of lime cement concrete cylinders.

S/No.	Mix No.	Replicates	Av. Density Kg/m^3	Failure Load (KN)	Split tensile strength (N/mm^2)	Av. split ten. strength (N/mm^2)
1	C1	a	2647	222.66	3.15	3.250
		b		236.80	3.35	
		c		229.73	3.25	
2	C2	a	2672	148.44	2.10	2.220
		b		158.34	2.24	
		c		163.99	2.32	
3	C3	a	2641	199.69	2.825	2.835
		b		202.16	2.86	
		c		199.33	2.82	
4	C4	a	2641	148.44	2.10	2.050
		b		151.97	2.15	
		c		134.30	1.90	
5	C5	a	2515	132.89	1.88	1.875
		b		133.95	1.895	
		c		130.77	1.85	
6	C6	a	2641	264.36	3.74	3.605
		b		255.53	3.615	
		c		244.57	3.46	
7	C7	a	2653	187.32	2.65	2.720
		b		207.82	2.94	
		c		181.66	2.57	
8	C8	a	2609	229.02	3.24	3.110
		b		214.18	3.03	
		c		216.30	3.06	
9	C9	a	2609	176.71	2.50	2.560
		b		175.30	2.48	
		c		190.85	2.70	
10	C10	a	2653	208.52	2.95	3.025
		b		222.66	3.15	
		c		210.29	2.975	
11	C11	a	2685	220.54	3.12	3.050
		b		212.06	3.00	
		c		214.18	3.03	
12	C12	a	2641	196.15	2.775	2.875
		b		205.00	2.90	
		c		208.52	2.95	
13	C13	a	2635	155.51	2.20	2.160
		b		153.39	2.17	
		c		149.15	2.11	
14	C14	a	2660	229.73	3.25	3.340
		b		233.26	3.30	
		c		258.00	3.65	
15	C15	a	2609	219.13	3.10	2.950
		b		200.75	2.84	
		c		205.70	2.91	

Table A21: 14th day splitting tensile strength results for normal mix of lime cement concrete cylinders.

S/No.	Mix No.	Replicates	Av. Density Kg/m^3	Failure Load (KN)	Split tensile strength (N/mm^2)	Av. split ten. strength (N/mm^2)
1	N1	a	2426	107.44	1.52	1.540
		b		113.10	1.60	
		c		106.03	1.50	
2	N2	a	2572	102.49	1.45	1.400
		b		95.42	1.35	
		c		98.96	1.40	
3	N3	a	2578	79.17	1.12	1.240
		b		90.48	1.28	
		c		93.30	1.32	
4	N4	a	2490	151.26	2.14	2.095
		b		147.38	2.085	
		c		145.61	2.06	
5	N5	a	2578	86.23	1.22	1.340
		b		91.89	1.30	
		c		106.03	1.50	
6	N12	a	2578	122.99	1.74	1.770
		b		124.40	1.76	
		c		127.94	1.81	
7	N13	a	2697	141.37	2.00	1.785
		b		134.62	1.905	
		c		102.49	1.45	
8	N14	a	2628	93.30	1.32	1.210
		b		83.41	1.18	
		c		79.83	1.13	
9	N15	a	2647	97.90	1.385	1.415
		b		113.09	1.60	
		c		89.06	1.26	
10	N23	a	2672	132.89	1.88	1.850
		b		132.18	1.87	
		c		127.23	1.80	
11	N24	a	2609	141.37	2.00	1.720
		b		127.23	1.80	
		c		102.49	1.45	
12	N25	a	2546	113.09	1.60	1.610
		b		109.56	1.55	
		c		118.75	1.68	
13	N34	a	2603	81.29	1.15	1.110
		b		69.27	0.98	
		c		84.82	1.20	
14	N35	a	2641	68.92	0.975	0.895
		b		57.25	0.81	
		c		63.62	0.90	
15	N45	a	2603	76.34	1.08	1.010
		b		77.75	1.10	
		c		60.08	0.85	

Table A22: 14th day splitting tensile strength results for control mix of lime cement concrete cylinders.

S/No.	Mix No.	Replicates	Av. Density Kg/m^3	Failure Load (KN)	Split tensile strength (N/mm^2)	Av. split ten. strength (N/mm^2)
1	C1	a	2647	128.65	1.82	1.830
		b		132.18	1.87	
		c		127.23	1.80	
2	C2	a	2672	120.17	1.70	1.740
		b		121.58	1.72	
		c		127.24	1.80	
3	C3	a	2641	118.76	1.68	1.575
		b		112.75	1.595	
		c		102.50	1.45	
4	C4	a	2641	62.21	0.88	0.820
		b		53.02	0.75	
		c		58.68	0.83	
5	C5	a	2515	77.40	1.095	1.065
		b		70.69	1.00	
		c		77.76	1.10	
6	C6	a	2641	160.11	2.265	2.205
		b		151.98	2.15	
		c		155.51	2.20	
7	C7	a	2653	162.58	2.30	2.350
		b		180.96	2.56	
		c		159.05	2.25	
8	C8	a	2609	135.01	1.91	1.900
		b		138.55	1.96	
		c		129.36	1.83	
9	C9	a	2609	123.70	1.75	1.750
		b		120.17	1.70	
		c		127.23	1.80	
10	C10	a	2653	153.39	2.17	2.080
		b		149.15	2.11	
		c		138.55	1.96	
11	C11	a	2685	155.51	2.20	2.180
		b		154.81	2.19	
		c		151.98	2.15	
12	C12	a	2641	159.40	2.255	2.235
		b		166.12	2.35	
		c		148.44	2.10	
13	C13	a	2635	141.38	2.00	1.860
		b		136.43	1.93	
		c		117.34	1.66	
14	C14	a	2660	134.31	1.90	1.980
		b		140.67	1.99	
		c		144.91	2.05	
15	C15	a	2609	156.93	2.22	2.150
		b		141.38	2.00	
		c		159.05	2.25	

Table A23: 7th day splitting tensile strength results for normal mix of lime cement concrete cylinders.

S/No.	Mix No.	Replicates	Av. Density Kg/m^3	Failure Load (KN)	Split tensile strength (N/mm^2)	Av. split ten. strength (N/mm^2)
1	N1	a	2426	84.82	1.20	1.300
		b		90.47	1.28	
		c		100.37	1.42	
2	N2	a	2572	57.96	0.82	0.800
		b		65.03	0.92	
		c		46.65	0.66	
3	N3	a	2578	53.01	0.75	0.710
		b		48.06	0.68	
		c		49.48	0.70	
4	N4	a	2490	50.19	0.71	0.690
		b		49.48	0.70	
		c		46.65	0.66	
5	N5	a	2578	78.46	1.11	1.130
		b		75.63	1.07	
		c		84.82	1.21	
6	N12	a	2578	94.72	1.34	1.360
		b		101.08	1.43	
		c		92.60	1.31	
7	N13	a	2697	85.17	1.205	1.225
		b		84.82	1.20	
		c		89.77	1.27	
8	N14	a	2628	35.34	0.50	0.490
		b		28.98	0.41	
		c		39.50	0.56	
9	N15	a	2647	83.70	1.18	1.015
		b		65.26	0.92	
		c		67.15	0.95	
10	N23	a	2672	41.00	0.58	0.610
		b		41.00	0.58	
		c		47.36	0.67	
11	N24	a	2609	82.70	1.17	1.190
		b		81.99	1.16	
		c		87.75	1.24	
12	N25	a	2546	84.82	1.21	1.240
		b		86.94	1.23	
		c		90.47	1.28	
13	N34	a	2603	70.68	1.00	0.930
		b		60.08	0.85	
		c		66.44	0.94	
14	N35	a	2641	50.54	0.715	0.735
		b		56.55	0.80	
		c		48.77	0.69	
15	N45	a	2603	65.74	0.93	0.910
		b		63.62	0.90	
		c		63.62	0.90	

Table A24: 7th day splitting tensile strength results for control mix of lime cement concrete cylinders.

S/No.	Mix No.	Replicates	Av. Density Kg/m^3	Failure Load (KN)	Split tensile strength (N/mm^2)	Av. split ten. strength (N/mm^2)
1	C1	a	2647	100.37	1.42	1.300
		b		84.82	1.20	
		c		90.48	1.28	
2	C2	a	2672	100.00	1.41	1.430
		b		98.96	1.40	
		c		104.96	1.48	
3	C3	a	2641	72.10	1.02	1.135
		b		84.82	1.21	
		c		83.05	1.175	
4	C4	a	2641	49.48	0.70	0.700
		b		53.01	0.75	
		c		56.55	0.80	
5	C5	a	2515	60.08	0.85	0.835
		b		53.01	0.84	
		c		57.61	0.815	
6	C6	a	2641	59.73	0.845	0.915
		b		70.68	1.00	
		c		63.62	0.90	
7	C7	a	2653	96.13	1.36	1.565
		b		120.51	1.705	
		c		115.21	1.63	
8	C8	a	2609	41.00	0.58	0.550
		b		33.22	0.47	
		c		42.41	0.60	
9	C9	a	2609	95.43	1.35	1.400
		b		103.20	1.46	
		c		98.25	1.39	
10	C10	a	2653	42.41	0.60	0.630
		b		43.12	0.61	
		c		48.07	0.68	
11	C11	a	2685	71.39	1.01	0.960
		b		67.15	0.95	
		c		65.03	0.92	
12	C12	a	2641	64.32	0.91	0.940
		b		63.62	0.90	
		c		71.39	1.01	
13	C13	a	2635	101.08	1.43	1.500
		b		110.97	1.57	
		c		106.02	1.50	
14	C14	a	2660	41.00	0.58	0.520
		b		37.46	0.53	
		c		36.19	0.45	
15	C15	a	2609	51.60	0.73	0.770
		b		55.00	0.78	
		c		56.55	0.80	

Table A25: 28th day shear strength results for normal mix of lime cement concrete.

S/No.	Mix No.	Replicates	Shear Load (KN)	Cross sectional area (mm^2)	Shear strength (N/mm^2)	Av. Shear strength (N/mm^2)
1	N1	a	12.43		0.552	
		b	13.73		0.610	0.569
		c	12.26	22,500	0.545	
2	N2	a	20.03		0.890	
		b	21.88		0.972	0.965
		c	23.23	"	1.032	
3	N3	a	20.14		0.895	
		b	20.31		0.903	0.906
		c	20.70	"	0.920	
4	N4	a	19.41		0.863	
		b	18.96		0.843	0.873
		c	20.53	"	0.912	
5	N5	a	16.93		0.752	
		b	16.37		0.728	0.741
		c	16.71	"	0.743	
6	N12	a	24.13		1.072	
		b	24.24		1.077	1.093
		c	25.43	"	1.130	
7	N13	a	21.94		0.975	
		b	21.49		0.955	0.978
		c	22.61	"	1.005	
8	N14	a	22.84		1.015	
		b	23.12		1.028	0.996
		c	21.26	"	0.945	
9	N15	a	17.44		0.775	
		b	18.34		0.815	0.807
		c	18.68	"	0.830	
10	N23	a	26.21		1.165	
		b	24.30		1.080	1.098
		c	23.63	"	1.050	
11	N24	a	23.74		1.055	
		b	23.96		1.065	1.065
		c	24.19	"	1.075	
12	N25	a	20.98		0.932	
		b	21.49		0.955	0.946
		c	21.38	"	0.950	
13	N34	a	16.14		0.717	
		b	15.98		0.710	0.693
		c	14.68	"	0.652	
14	N35	a	17.44		0.775	
		b	16.71		0.743	0.759
		c	17.10	"	0.760	
15	N45	a	15.64		0.695	
		b	14.96		0.665	0.668
		c	14.51	"	0.645	

Table A26: 28th day shear strength results for control mix of lime cement concrete.

S/No.	Mix No.	Replicates	Shear Load (KN)	Cross sectional area (mm^2)	Shear strength (N/mm^2)	Av. Shear strength (N/mm^2)
1	C1	a	26.72		1.188	
		b	25.93		1.152	1.128
		c	23.46	22,500	1.043	
2	C2	a	18.84		0.837	
		b	18.34		0.815	0.818
		c	18.06	"	0.803	
3	C3	a	22.61		1.005	
		b	22.78		1.012	1.006
		c	22.50	"	1.000	
4	C4	a	15.98		0.710	
		b	16.59		0.737	0.704
		c	14.96	"	0.665	
5	C5	a	15.36		0.683	
		b	15.58		0.692	0.674
		c	14.57	"	0.648	
6	C6	a	28.29		1.257	
		b	28.13		1.250	1.257
		c	28.46	"	1.265	
7	C7	a	21.60		0.960	
		b	21.49		0.955	0.963
		c	21.94	"	0.975	
8	C8	a	24.36		1.083	
		b	24.47		1.088	1.090
		c	24.75	"	1.100	
9	C9	a	22.67		1.008	
		b	20.53		0.912	0.917
		c	18.73	"	0.832	
10	C10	a	23.46		1.043	
		b	23.34		1.037	1.037
		c	23.23	"	1.032	
11	C11	a	23.79		1.057	
		b	24.19		1.075	1.070
		c	24.24	"	1.077	
12	C12	a	22.78		1.012	
		b	23.23		1.032	1.026
		c	23.23	"	1.032	
13	C13	a	17.11		0.760	
		b	16.99		0.755	0.755
		c	16.88	"	0.750	
14	C14	a	26.49		1.177	
		b	26.04		1.157	1.130
		c	23.74	"	1.055	
15	C15	a	23.46		1.043	
		b	23.12		1.028	1.040
		c	23.63	"	1.050	

Table A27: 21st day shear strength results for normal mix of lime cement concrete.

S/No.	Mix No.	Replicates	Shear Load (KN)	Cross sectional area (mm^2)	Shear strength (N/mm^2)	Av. Shear strength (N/mm^2)
1	N1	a	12.94		0.575	
		b	11.36		0.505	0.535
		c	11.81	22,500	0.525	
2	N2	a	19.97		0.888	
		b	20.93		0.930	0.889
		c	19.13	"	0.850	
3	N3	a	20.08		0.892	
		b	18.68		0.830	0.848
		c	18.45	"	0.820	
4	N4	a	18.90		0.840	
		b	18.51		0.823	0.837
		c	19.07	"	0.848	
5	N5	a	15.02		0.668	
		b	13.16		0.585	0.657
		c	16.20	"	0.720	
6	N12	a	24.02		1.068	
		b	23.23		1.032	1.049
		c	23.57	"	1.048	
7	N13	a	19.18		0.852	
		b	19.24		0.855	0.852
		c	19.07	"	0.848	
8	N14	a	18.96		0.843	
		b	19.24		0.855	0.855
		c	19.52	"	0.868	
9	N15	a	16.20		0.720	
		b	17.61		0.783	0.754
		c	17.10	"	0.760	
10	N23	a	24.30		1.080	
		b	23.06		1.025	1.068
		c	24.75	"	1.100	
11	N24	a	23.18		1.030	
		b	22.22		0.988	1.021
		c	23.51	"	1.045	
12	N25	a	18.79		0.835	
		b	19.69		0.875	0.850
		c	18.90	"	0.840	
13	N34	a	15.19		0.675	
		b	14.23		0.632	0.650
		c	14.46	"	0.643	
14	N35	a	15.30		0.680	
		b	16.54		0.735	0.684
		c	14.34	"	0.637	
15	N45	a	14.29		0.635	
		b	13.95		0.620	0.629
		c	14.23	"	0.632	

Table A28: 21st day shear strength results for control mix of lime cement concrete.

S/No.	Mix No.	Replicates	Shear Load (KN)	Cross sectional area (mm^2)	Shear strength (N/mm^2)	Av. Shear strength (N/mm^2)
1	C1	a	25.76		1.145	
		b	24.24		1.077	1.095
		c	23.91	22,500	1.063	
2	C2	a	17.33		0.770	
		b	16.99		0.755	0.760
		c	16.99	"	0.755	
3	C3	a	21.71		0.965	
		b	22.11		0.983	0.959
		c	20.93	"	0.930	
4	C4	a	13.22		0.588	
		b	13.61		0.605	0.590
		c	12.99	"	0.577	
5	C5	a	15.36		0.683	
		b	15.58		0.692	0.674
		c	14.57	"	0.648	
6	C6	a	27.73		1.232	
		b	27.11		1.205	1.227
		c	27.96	"	1.243	
7	C7	a	20.98		0.932	
		b	20.76		0.923	0.933
		c	21.21	"	0.943	
8	C8	a	23.18		1.030	
		b	24.02		1.068	1.050
		c	23.68	"	1.052	
9	C9	a	20.08		0.892	
		b	19.80		0.880	0.870
		c	18.84	"	0.837	
10	C10	a	23.29		1.035	
		b	22.73		1.010	1.015
		c	22.50	"	1.000	
11	C11	a	22.83		1.015	
		b	23.29		1.035	1.030
		c	23.40	"	1.040	
12	C12	a	21.83		0.970	
		b	22.05		0.980	0.975
		c	21.94	"	0.975	
13	C13	a	16.82		0.748	
		b	16.37		0.728	0.733
		c	16.26	"	0.723	
14	C14	a	25.31		1.125	
		b	25.20		1.120	1.115
		c	24.75	"	1.100	
15	C15	a	22.67		1.008	
		b	22.39		0.995	1.005
		c	22.78	"	1.012	

Table A29: 14th day shear strength results for normal mix of lime cement concrete.

S/No.	Mix No.	Replicates	Shear Load (KN)	Cross sectional area (mm^2)	Shear strength (N/mm^2)	Av. Shear strength (N/mm^2)
1	N1	a	9.84		0.437	
		b	9.56		0.425	0.430
		c	9.62	22,500	0.428	
2	N2	a	13.16		0.585	
		b	13.78		0.612	0.587
		c	12.66	"	0.563	
3	N3	a	12.04		0.535	
		b	11.93		0.530	0.540
		c	12.49	"	0.555	
4	N4	a	17.89		0.795	
		b	16.76		0.745	0.751
		c	16.03	"	0.712	
5	N5	a	10.74		0.477	
		b	11.03		0.490	0.488
		c	11.14	"	0.495	
6	N12	a	16.31		0.725	
		b	15.64		0.695	0.715
		c	16.31	"	0.725	
7	N13	a	16.14		0.717	
		b	16.88		0.750	0.710
		c	14.91	"	0.663	
8	N14	a	15.08		0.670	
		b	14.29		0.635	0.663
		c	15.36	"	0.683	
9	N15	a	12.38		0.550	
		b	12.15		0.540	0.555
		c	12.94	"	0.575	
10	N23	a	15.81		0.703	
		b	16.09		0.715	0.723
		c	16.88	"	0.750	
11	N24	a	16.88		0.750	
		b	15.92		0.708	0.723
		c	15.98	"	0.710	
12	N25	a	14.12		0.628	
		b	14.51		0.645	0.635
		c	14.23	"	0.632	
13	N34	a	10.18		0.452	
		b	10.41		0.463	0.450
		c	9.79	"	0.435	
14	N35	a	8.89		0.395	
		b	9.39		0.417	0.408
		c	9.23	"	0.410	
15	N45	a	9.11		0.405	
		b	9.34		0.415	0.420
		c	9.90	"	0.440	

Table A30: 14th day shear strength results for control mix of lime cement concrete

S/No.	Mix No.	Replicates	Shear Load (KN)	Cross sectional area (mm^2)	Shear strength (N/mm^2)	Av. Shear strength (N/mm^2)
1	C1	a	17.83		0.792	
		b	13.95		0.620	0.741
		c	18.23	22,500	0.810	
2	C2	a	15.47		0.688	
		b	13.61		0.605	0.640
		c	14.12	"	0.628	
3	C3	a	20.19		0.897	
		b	20.31		0.903	0.895
		c	19.91	"	0.885	
4	C4	a	9.34		0.415	
		b	9.62		0.428	0.416
		c	9.11	"	0.405	
5	C5	a	10.18		0.452	
		b	9.96		0.443	0.435
		c	9.23	"	0.410	
6	C6	a	19.29		0.857	
		b	21.15		0.940	0.877
		c	18.73	"	0.832	
7	C7	a	19.24		0.855	
		b	18.34		0.815	0.833
		c	18.62	"	0.828	
8	C8	a	17.21		0.765	
		b	15.56		0.692	0.744
		c	17.44	"	0.775	
9	C9	a	15.58		0.692	
		b	15.98		0.710	0.703
		c	15.86	"	0.705	
10	C10	a	17.67		0.785	
		b	17.49		0.777	0.779
		c	17.44	"	0.775	
11	C11	a	18.56		0.825	
		b	18.00		0.800	0.812
		c	18.28	"	0.812	
12	C12	a	18.39		0.817	
		b	17.89		0.795	0.814
		c	18.68	"	0.830	
13	C13	a	15.24		0.677	
		b	14.85		0.660	0.657
		c	14.23	"	0.632	
14	C14	a	17.49		0.777	
		b	17.55		0.780	0.775
		c	17.27	"	0.768	
15	C15	a	17.61		0.783	
		b	18.00		0.800	0.790
		c	17.72	"	0.788	

Table A31: 7th day shear strength results for normal mix of lime cement concrete

S/No.	Mix No.	Replicates	Shear Load (KN)	Cross sectional area (mm^2)	Shear strength (N/mm^2)	Av. Shear strength (N/mm^2)
1	N1	a	8.16		0.363	
		b	8.83		0.392	0.369
		c	7.93	22,500	0.352	
2	N2	a	10.29		0.457	
		b	9.45		0.420	0.437
		c	9.79	"	0.435	
3	N3	a	9.51		0.423	
		b	8.78		0.390	0.408
		c	9.23	"	0.410	
4	N4	a	9.06		0.403	
		b	9.28		0.412	0.400
		c	8.66	"	0.385	
5	N5	a	10.07		0.448	
		b	10.01		0.445	0.434
		c	9.23	"	0.410	
6	N12	a	12.88		0.572	
		b	12.60		0.560	0.575
		c	13.33	"	0.592	
7	N13	a	12.94		0.575	
		b	14.79		0.657	0.613
		c	13.67	"	0.608	
8	N14	a	10.97		0.488	
		b	10.86		0.483	0.483
		c	10.80	"	0.480	
9	N15	a	9.96		0.443	
		b	10.29		0.457	0.455
		c	10.46	"	0.465	
10	N23	a	9.28		0.412	
		b	9.45		0.420	0.412
		c	9.06	"	0.403	
11	N24	a	12.71		0.565	
		b	12.54		0.557	0.563
		c	12.77	"	0.568	
12	N25	a	12.38		0.550	
		b	11.98		0.532	0.543
		c	12.26	"	0.545	
13	N34	a	9.17		0.408	
		b	8.89		0.395	0.404
		c	9.23	"	0.410	
14	N35	a	8.50		0.378	
		b	8.21		0.365	0.367
		c	8.04	"	0.357	
15	N45	a	8.55		0.380	
		b	8.83		0.392	0.394
		c	9.23	"	0.410	

Table A32: 7th day shear strength results for control mix of lime cement concrete

S/No.	Mix No.	Replicates	Shear Load (KN)	Cross sectional area (mm^2)	Shear strength (N/mm^2)	Av. Shear strength (N/mm^2)
1	C1	a	14.46		0.643	
		b	12.38		0.550	0.608
		c	14.18	22,500	0.630	
2	C2	a	12.32		0.548	
		b	12.94		0.575	0.562
		c	12.66	"	0.563	
3	C3	a	12.04		0.535	
		b	12.21		0.543	0.536
		c	11.93	"	0.530	
4	C4	a	7.82		0.348	
		b	7.99		0.355	0.349
		c	7.76	"	0.345	
5	C5	a	8.33		0.370	
		b	8.38		0.372	0.377
		c	8.76	"	0.389	
6	C6	a	12.38		0.550	
		b	12.60		0.560	0.554
		c	12.43	"	0.552	
7	C7	a	17.76		0.789	
		b	16.99		0.755	0.771
		c	17.27	"	0.768	
8	C8	a	9.23		0.410	
		b	9.17		0.408	0.410
		c	9.28	"	0.412	
9	C9	a	12.99		0.577	
		b	12.99		0.577	0.579
		c	13.11	"	0.583	
10	C10	a	9.00		0.400	
		b	9.17		0.408	0.409
		c	9.45	"	0.420	
11	C11	a	12.09		0.537	
		b	11.64		0.517	0.507
		c	10.46	"	0.465	
12	C12	a	11.19		0.497	
		b	11.08		0.492	0.490
		c	10.80	"	0.480	
13	C13	a	12.77		0.568	
		b	12.54		0.557	0.568
		c	13.05	"	0.580	
14	C14	a	9.51		0.423	
		b	9.00		0.400	0.409
		c	9.11	"	0.405	
15	C15	a	9.51		0.423	
		b	10.69		0.475	0.457
		c	10.63	"	0.472	

Table A33: 28th day poisson ratio results for normal mix of lime cement concrete.

S/No.	Mix No.	Replicates	flexural strength (N/mm^2)	Compressive strength (N/mm^2)	Poisson ratio	Av. Poisson ratio
1	N1	a	2.21	14.68	0.151	0.151
		b	2.44	15.20	0.161	
		c	2.18	15.48	0.141	
2	N2	a	3.56	18.42	0.193	0.209
		b	3.89	17.80	0.219	
		c	4.13	19.28	0.214	
3	N3	a	3.58	16.72	0.214	0.203
		b	3.61	18.34	0.197	
		c	3.68	18.52	0.199	
4	N4	a	3.45	22.22	0.155	0.159
		b	3.37	20.83	0.162	
		c	3.65	22.95	0.159	
5	N5	a	3.01	26.14	0.115	0.140
		b	2.91	19.11	0.152	
		c	2.97	19.43	0.153	
6	N12	a	4.29	20.02	0.214	0.210
		b	4.31	19.62	0.220	
		c	4.52	22.91	0.197	
7	N13	a	3.90	22.38	0.174	0.172
		b	3.82	22.10	0.173	
		c	4.02	23.62	0.170	
8	N14	a	4.06	20.75	0.196	0.181
		b	4.11	21.83	0.188	
		c	3.78	23.93	0.158	
9	N15	a	3.10	21.20	0.146	0.150
		b	3.26	21.78	0.150	
		c	3.32	21.70	0.153	
10	N23	a	4.66	26.67	0.175	0.164
		b	4.32	27.19	0.159	
		c	4.20	26.58	0.158	
11	N24	a	4.22	23.11	0.183	0.183
		b	4.26	23.30	0.183	
		c	4.30	23.61	0.182	
12	N25	a	3.43	19.78	0.173	0.168
		b	3.69	22.85	0.161	
		c	3.62	21.36	0.169	
13	N34	a	2.87	15.72	0.183	0.173
		b	2.84	14.94	0.190	
		c	2.61	18.00	0.145	
14	N35	a	2.97	14.32	0.207	0.183
		b	2.90	16.92	0.171	
		c	2.95	17.24	0.171	
15	N45	a	2.78	19.18	0.145	0.141
		b	2.66	18.20	0.146	
		c	2.58	19.62	0.131	

Table A34: 28th day poisson ratio results for control mix of lime cement concrete.

S/No.	Mix No.	Replicates	flexural strength (N/mm^2)	Compressive strength (N/mm^2)	Poisson ratio	Av. Poisson ratio
1	C1	a	4.75	20.23	0.235	0.216
		b	4.61	21.58	0.214	
		c	4.17	20.74	0.201	
2	C2	a	3.35	23.63	0.142	0.146
		b	3.26	22.28	0.146	
		c	3.21	21.44	0.150	
3	C3	a	4.02	26.23	0.153	0.151
		b	4.05	27.12	0.149	
		c	4.00	26.69	0.150	
4	C4	a	2.84	16.10	0.176	0.174
		b	2.95	16.35	0.180	
		c	2.66	16.15	0.165	
5	C5	a	2.73	18.93	0.144	0.141
		b	2.77	19.25	0.144	
		c	2.59	19.27	0.134	
6	C6	a	5.03	22.96	0.219	0.214
		b	5.00	24.22	0.206	
		c	5.06	23.50	0.215	
7	C7	a	3.84	24.49	0.157	0.161
		b	3.82	23.59	0.162	
		c	3.90	23.53	0.166	
8	C8	a	4.33	28.45	0.152	0.153
		b	4.35	28.54	0.152	
		c	4.40	28.51	0.154	
9	C9	a	4.03	24.37	0.165	0.153
		b	3.65	24.11	0.151	
		c	3.33	23.34	0.143	
10	C10	a	4.17	30.78	0.135	0.139
		b	4.15	29.79	0.139	
		c	4.13	28.98	0.143	
11	C11	a	4.23	28.10	0.151	0.154
		b	4.30	27.11	0.159	
		c	4.31	28.19	0.153	
12	C12	a	4.05	24.83	0.163	0.167
		b	4.13	24.11	0.171	
		c	4.12	24.80	0.166	
13	C13	a	3.04	29.79	0.102	0.105
		b	3.02	29.33	0.103	
		c	3.00	27.58	0.109	
14	C14	a	4.71	30.71	0.153	0.147
		b	4.63	30.78	0.150	
		c	4.22	31.00	0.136	
15	C15	a	4.17	21.47	0.194	0.194
		b	4.11	21.11	0.195	
		c	4.20	21.77	0.193	

Table A35: 21st day poisson ratio results for normal mix of lime cement concrete.

S/No.	Mix No.	Replicates	flexural strength (N/mm^2)	Compressive strength (N/mm^2)	Poisson ratio	Av. Poisson ratio
1	N1	a	2.30	15.33	0.150	0.145
		b	2.02	14.20	0.142	
		c	2.10	14.63	0.144	
2	N2	a	3.55	18.48	0.192	0.195
		b	3.72	17.50	0.213	
		c	3.40	18.92	0.180	
3	N3	a	3.57	15.00	0.238	0.213
		b	3.32	15.46	0.215	
		c	3.28	17.72	0.185	
4	N4	a	3.36	21.72	0.155	0.154
		b	3.29	21.04	0.156	
		c	3.39	22.28	0.152	
5	N5	a	2.67	16.57	0.161	0.167
		b	2.34	15.91	0.147	
		c	2.88	14.86	0.194	
6	N12	a	4.27	18.98	0.225	0.211
		b	4.13	21.75	0.190	
		c	4.19	19.33	0.217	
7	N13	a	3.41	22.76	0.150	0.153
		b	3.42	21.64	0.158	
		c	3.39	22.50	0.151	
8	N14	a	3.37	22.29	0.151	0.155
		b	3.42	21.25	0.161	
		c	3.47	22.76	0.152	
9	N15	a	2.88	20.56	0.140	0.142
		b	3.13	24.00	0.130	
		c	3.04	19.73	0.154	
10	N23	a	4.32	26.79	0.161	0.170
		b	4.10	25.68	0.160	
		c	4.40	23.31	0.189	
11	N24	a	4.12	21.92	0.188	0.181
		b	3.95	22.80	0.173	
		c	4.18	22.9/6	0.182	
12	N25	a	3.34	22.31	0.150	0.165
		b	3.50	19.76	0.177	
		c	3.36	19.88	0.169	
13	N34	a	2.70	14.06	0.192	0.165
		b	2.53	18.62	0.136	
		c	2.57	15.32	0.168	
14	N35	a	2.72	14.68	0.185	0.178
		b	2.94	16.05	0.183	
		c	2.55	15.32	0.166	
15	N45	a	2.54	19.57	0.130	0.148
		b	2.48	17.28	0.144	
		c	2.53	14.84	0.170	

Table A36: 21st day poisson ratio results for control mix of lime cement concrete.

S/No.	Mix No.	Replicates	flexural strength (N/mm^2)	Compressive strength (N/mm^2)	Poisson ratio	Av. Poisson ratio
1	C1	a	4.58	20.89	0.219	0.218
		b	4.31	20.30	0.212	
		c	4.25	19.11	0.222	
2	C2	a	3.08	22.35	0.138	0.137
		b	3.02	22.25	0.136	
		c	3.02	22.21	0.136	
3	C3	a	3.86	26.67	0.145	0.145
		b	3.93	26.67	0.147	
		c	3.72	25.78	0.144	
4	C4	a	2.35	16.22	0.145	0.147
		b	2.42	15.97	0.152	
		c	2.31	16.14	0.143	
5	C5	a	2.73	17.22	0.159	0.154
		b	2.77	17.89	0.155	
		c	2.59	17.33	0.149	
6	C6	a	4.93	24.00	0.205	0.215
		b	4.82	25.33	0.190	
		c	4.97	20.00	0.249	
7	C7	a	3.73	24.44	0.153	0.159
		b	3.69	22.22	0.166	
		c	3.77	23.99	0.157	
8	C8	a	4.12	27.11	0.152	0.150
		b	4.27	28.44	0.150	
		c	4.21	28.44	0.148	
9	C9	a	3.57	24.00	0.149	0.148
		b	3.52	24.46	0.144	
		c	3.35	22.22	0.151	
10	C10	a	4.14	29.33	0.141	0.139
		b	4.04	28.44	0.142	
		c	4.00	30.22	0.132	
11	C11	a	4.06	29.33	0.138	0.151
		b	4.14	25.10	0.165	
		c	4.16	27.56	0.151	
12	C12	a	3.88	24.67	0.157	0.161
		b	3.92	24.44	0.160	
		c	3.90	23.56	0.166	
13	C13	a	2.99	28.89	0.103	0.103
		b	2.91	29.77	0.098	
		c	2.89	26.67	0.108	
14	C14	a	4.50	29.33	0.153	0.148
		b	4.48	30.67	0.146	
		c	4.40	30.69	0.143	
15	C15	a	4.03	20.22	0.199	0.192
		b	3.98	20.89	0.191	
		c	4.05	21.78	0.186	

Table A37: 14th day poisson ratio results for normal mix of lime cement concrete.

S/No.	Mix No.	Replicates	flexural strength (N/mm^2)	Compressive strength (N/mm^2)	Poisson ratio	Av. Poisson ratio
1	N1	a	1.75	12.18	0.144	0.154
		b	1.70	10.26	0.166	
		c	1.71	11.29	0.151	
2	N2	a	2.34	15.56	0.150	0.145
		b	2.45	17.31	0.142	
		c	2.25	15.85	0.142	
3	N3	a	2.14	15.25	0.140	0.148
		b	2.12	13.71	0.155	
		c	2.22	14.87	0.149	
4	N4	a	3.18	19.30	0.165	0.156
		b	2.98	18.60	0.160	
		c	2.85	20.12	0.142	
5	N5	a	1.91	14.57	0.131	0.136
		b	1.96	14.98	0.131	
		c	1.98	13.50	0.147	
6	N12	a	2.90	19.66	0.148	0.149
		b	2.78	18.71	0.149	
		c	2.90	19.20	0.151	
7	N13	a	2.87	18.02	0.159	0.148
		b	3.00	19.79	0.152	
		c	2.65	19.70	0.135	
8	N14	a	2.68	19.28	0.139	0.142
		b	2.54	18.52	0.137	
		c	2.73	18.36	0.149	
9	N15	a	2.20	15.50	0.142	0.140
		b	2.16	16.83	0.128	
		c	2.30	15.28	0.151	
10	N23	a	2.81	19.87	0.141	0.150
		b	2.86	19.74	0.145	
		c	3.00	18.35	0.163	
11	N24	a	2.67	21.08	0.127	0.150
		b	2.83	16.70	0.169	
		c	2.84	18.50	0.154	
12	N25	a	2.51	16.85	0.149	0.140
		b	2.58	20.53	0.126	
		c	2.53	17.58	0.144	
13	N34	a	1.81	12.45	0.145	0.151
		b	1.85	11.05	0.167	
		c	1.74	12.29	0.142	
14	N35	a	1.58	11.50	0.137	0.152
		b	1.67	10.20	0.164	
		c	1.64	10.64	0.154	
15	N45	a	1.62	11.86	0.137	0.155
		b	1.66	9.79	0.170	
		c	1.76	11.05	0.159	

Table A38: 14th day poisson ratio results for control mix of lime cement concrete.

S/No.	Mix No.	Replicates	flexural strength (N/mm^2)	Compressive strength (N/mm^2)	Poisson ratio	Av. Poisson ratio
1	C1	a	3.17	19.26	0.165	0.154
		b	2.48	18.33	0.135	
		c	3.24	19.86	0.163	
2	C2	a	2.75	19.62	0.140	0.133
		b	2.42	19.07	0.127	
		c	2.51	18.94	0.133	
3	C3	a	3.59	20.46	0.175	0.173
		b	3.61	21.33	0.169	
		c	3.54	20.22	0.175	
4	C4	a	1.66	10.63	0.156	0.155
		b	1.71	10.66	0.160	
		c	1.62	10.87	0.149	
5	C5	a	1.81	10.44	0.173	0.167
		b	1.77	10.39	0.170	
		c	1.64	10.46	0.157	
6	C6	a	3.43	15.57	0.220	0.237
		b	3.76	13.79	0.273	
		c	3.33	15.34	0.217	
7	C7	a	3.42	19.12	0.179	0.167
		b	3.26	20.45	0.159	
		c	3.31	20.46	0.162	
8	C8	a	3.06	22.23	0.138	0.136
		b	2.82	21.35	0.132	
		c	3.10	22.48	0.138	
9	C9	a	2.77	20.04	0.138	0.140
		b	2.84	19.57	0.145	
		c	2.82	20.48	0.138	
10	C10	a	3.14	26.22	0.120	0.125
		b	3.11	24.04	0.129	
		c	3.10	24.47	0.127	
11	C11	a	3.30	20.47	0.161	0.155
		b	3.20	20.92	0.153	
		c	3.25	21.37	0.152	
12	C12	a	3.27	19.57	0.167	0.171
		b	3.18	20.02	0.159	
		c	3.32	17.80	0.187	
13	C13	a	2.71	18.68	0.145	0.139
		b	2.64	19.58	0.135	
		c	2.53	18.47	0.137	
14	C14	a	3.11	24.00	0.130	0.129
		b	3.12	23.77	0.131	
		c	3.07	24.26	0.127	
15	C15	a	3.13	20.01	0.156	0.164
		b	3.20	17.34	0.185	
		c	3.15	20.67	0.152	

Table A39: 7th day poisson ratio results for normal mix of lime cement concrete.

S/No.	Mix No.	Replicates	flexural strength (N/mm^2)	Compressive strength (N/mm^2)	Poisson ratio	Av. Poisson ratio
1	N1	a	1.45	5.58	0.260	0.264
		b	1.57	5.49	0.286	
		c	1.41	5.73	0.246	
2	N2	a	1.83	9.09	0.201	0.202
		b	1.68	8.17	0.206	
		c	1.74	8.78	0.198	
3	N3	a	1.69	7.10	0.238	0.221
		b	1.56	7.30	0.214	
		c	1.64	7.71	0.213	
4	N4	a	1.61	5.98	0.269	0.283
		b	1.65	5.56	0.297	
		c	1.54	5.47	0.282	
5	N5	a	1.79	4.52	0.396	0.382
		b	1.78	4.68	0.380	
		c	1.64	4.44	0.369	
6	N12	a	2.29	9.75	0.235	0.235
		b	2.24	9.55	0.235	
		c	2.37	10.04	0.236	
7	N13	a	2.30	10.48	0.219	0.239
		b	2.63	9.80	0.268	
		c	2.43	10.59	0.229	
8	N14	a	1.95	7.87	0.248	0.255
		b	1.93	7.62	0.253	
		c	1.92	7.28	0.264	
9	N15	a	1.77	7.68	0.230	0.235
		b	1.83	7.43	0.246	
		c	1.86	8.17	0.228	
10	N23	a	1.65	7.03	0.235	0.234
		b	1.68	6.96	0.241	
		c	1.61	7.10	0.227	
11	N24	a	2.26	8.51	0.266	0.261
		b	2.23	8.64	0.258	
		c	2.27	8.74	0.260	
12	N25	a	2.20	7.32	0.301	0.290
		b	2.13	7.42	0.287	
		c	2.18	7.70	0.283	
13	N34	a	1.63	8.65	0.188	0.186
		b	1.58	8.80	0.180	
		c	1.64	8.68	0.189	
14	N35	a	1.51	9.15	0.165	0.162
		b	1.46	8.80	0.166	
		c	1.43	9.29	0.154	
15	N45	a	1.52	6.85	0.222	0.239
		b	1.57	6.40	0.245	
		c	1.64	6.58	0.249	

Table A40: 7th day poisson ratio results for control mix of lime cement concrete.

S/No.	Mix No.	Replicates	Flexural strength (N/mm^2)	Compressive strength (N/mm^2)	Poisson ratio	Av. Poisson ratio
1	C1	a	2.57	9.44	0.272	0.253
		b	2.20	9.31	0.236	
		c	2.52	10.11	0.249	
2	C2	a	2.19	10.75	0.204	0.215
		b	2.30	10.37	0.222	
		c	2.25	10.29	0.219	
3	C3	a	2.14	11.11	0.193	0.193
		b	2.17	11.02	0.197	
		c	2.12	11.14	0.190	
4	C4	a	1.39	9.08	0.153	0.157
		b	1.42	8.87	0.160	
		c	1.38	8.81	0.157	
5	C5	a	1.48	6.47	0.229	0.222
		b	1.49	7.12	0.209	
		c	1.56	6.81	0.229	
6	C6	a	2.20	10.30	0.214	0.203
		b	2.24	10.75	0.208	
		c	2.21	11.86	0.186	
7	C7	a	3.16	8.73	0.362	0.350
		b	3.02	8.79	0.344	
		c	3.07	8.91	0.345	
8	C8	a	1.64	12.26	0.134	0.133
		b	1.63	12.27	0.133	
		c	1.65	12.40	0.133	
9	C9	a	2.31	8.68	0.266	0.268
		b	2.31	8.62	0.268	
		c	2.33	8.65	0.269	
10	C10	a	1.63	9.12	0.179	0.184
		b	1.70	8.98	0.189	
		c	1.68	9.20	0.183	
11	C11	a	2.15	13.79	0.156	0.153
		b	2.07	12.64	0.164	
		c	1.86	13.30	0.140	
12	C12	a	1.99	10.12	0.197	0.178
		b	1.97	11.56	0.170	
		c	1.92	11.50	0.167	
13	C13	a	2.27	12.10	0.188	0.185
		b	2.23	12.33	0.181	
		c	2.32	12.35	0.188	
14	C14	a	1.69	6.34	0.267	0.246
		b	1.60	6.93	0.231	
		c	1.62	6.77	0.239	
15	C15	a	1.69	12.44	0.136	0.142
		b	1.90	13.26	0.143	
		c	1.89	13.00	0.145	

Table A41: 28th day modulus of elasticity results for normal mix of lime cement concrete

S/No.	Mix No.	Av. Density Kg/m^3	Compressive strength (N/mm^2)	Modulus of elasticity ($10^3 N/mm^2$)
1	N1	2449	15.12	20.264
2	N2	2514	18.50	23.313
3	N3	2489	17.86	22.566
4	N4	2499	22.00	25.196
5	N5	2558	19.56	24.604
6	N12	2521	20.85	24.853
7	N13	2539	22.70	26.211
8	N14	2558	22.17	26.194
9	N15	2504	21.56	25.018
10	N23	2616	23.81	28.074
11	N24	2568	23.34	27.034
12	N25	2464	21.33	24.290
13	N34	2499	16.22	21.634
14	N35	2499	16.16	21.594
15	N45	2449	19.00	22.716

Table A42: 28th day modulus of elasticity results for control mix of lime cement concrete

S/No.	Mix No.	Av. Density Kg/m^3	Compressive strength (N/mm^2)	Modulus of elasticity ($10^3 N/mm^2$)
1	C1	2578	20.85	25.701
2	C2	2578	22.45	26.669
3	C3	2509	26.68	27.913
4	C4	2469	16.20	21.233
5	C5	2471	19.15	23.113
6	C6	2607	23.56	27.782
7	C7	2528	23.87	26.703
8	C8	2529	28.50	29.195
9	C9	2548	23.94	27.060
10	C10	2517	29.85	29.666
11	C11	2528	27.80	28.818
12	C12	2509	24.58	26.792
13	C13	2509	28.90	29.051
14	C14	2548	30.83	30.708
15	C15	2460	21.45	24.299

Table A43: 21st day modulus of elasticity results for normal mix of lime cement concrete

S/No.	Mix No.	Av. Density Kg/m^3	Compressive strength (N/mm^2)	Modulus of elasticity (10^3N/mm^2)
1	N1	2449	14.72	19.994
2	N2	2514	18.30	23.187
3	N3	2489	16.06	21.398
4	N4	2499	21.68	25.012
5	N5	2558	15.78	22.099
6	N12	2521	20.02	24.353
7	N13	2539	22.30	25.979
8	N14	2558	22.10	26.153
9	N15	2504	21.43	24.942
10	N23	2616	25.26	28.916
11	N24	2568	22.56	26.579
12	N25	2464	20.65	23.900
13	N34	2499	16.00	21.487
14	N35	2499	15.35	21.046
15	N45	2449	17.23	21.632

Table A44: 21st day modulus of elasticity results for control mix of lime cement concrete

S/No.	Mix No.	Av. Density Kg/m^3	Compressive strength (N/mm^2)	Modulus of elasticity (10^3N/mm^2)
1	C1	2578	20.10	25.234
2	C2	2578	22.27	26.562
3	C3	2509	26.37	27.751
4	C4	2469	16.11	21.174
5	C5	2471	17.48	22.083
6	C6	2607	23.11	27.516
7	C7	2528	23.55	26.523
8	C8	2529	28.00	28.938
9	C9	2548	23.56	26.844
10	C10	2517	29.33	29.407
11	C11	2528	27.33	28.573
12	C12	2509	24.22	26.595
13	C13	2509	28.42	28.809
14	C14	2548	30.23	30.408
15	C15	2460	21.00	24.043

Table A45: 14th day modulus of elasticity results for normal mix of lime cement concrete

S/No.	Mix No.	Av. Density Kg/m^3	Compressive strength (N/mm^2)	Modulus of elasticity (10^3N/mm^2)
1	N1	2449	11.24	17.472
2	N2	2514	16.24	21.843
3	N3	2489	14.61	20.409
4	N4	2499	19.34	23.624
5	N5	2558	14.35	21.074
6	N12	2521	19.18	23.837
7	N13	2539	19.17	24.086
8	N14	2558	18.72	24.070
9	N15	2504	15.87	21.464
10	N23	2616	19.32	25.289
11	N24	2568	18.76	24.237
12	N25	2464	18.32	22.511
13	N34	2499	11.93	18.554
14	N35	2499	10.78	17.637
15	N45	2449	10.90	17.205

Table A46: 14th day modulus of elasticity results for control mix of lime cement concrete

S/No.	Mix No.	Av. Density Kg/m^3	Compressive strength (N/mm^2)	Modulus of elasticity (10^3N/mm^2)
1	C1	2578	19.15	24.631
2	C2	2578	19.21	24.669
3	C3	2509	20.67	24.569
4	C4	2469	10.72	17.272
5	C5	2471	10.43	17.058
6	C6	2607	14.90	22.094
7	C7	2528	20.01	24.449
8	C8	2529	22.02	25.663
9	C9	2548	20.03	24.752
10	C10	2517	24.91	27.101
11	C11	2528	20.92	24.999
12	C12	2509	19.13	23.636
13	C13	2509	18.91	23.500
14	C14	2548	24.01	27.100
15	C15	2460	19.34	23.073

Table A47: 7th day modulus of elasticity results for normal mix of lime cement concrete

S/No.	Mix No.	Av. Density Kg/m^3	Compressive strength (N/mm^2)	Modulus of elasticity ($10^3 N/mm^2$)
1	N1	2449	5.60	12.332
2	N2	2514	8.68	15.969
3	N3	2489	7.37	14.496
4	N4	2499	5.67	12.791
5	N5	2558	4.55	11.867
6	N12	2521	9.78	17.021
7	N13	2539	10.29	17.647
8	N14	2558	7.59	15.326
9	N15	2504	7.76	15.009
10	N23	2616	7.03	15.255
11	N24	2568	8.63	16.439
12	N25	2464	7.48	14.384
13	N34	2499	8.71	15.854
14	N35	2499	9.08	16.187
15	N45	2449	6.61	13.398

Table A48: 7th day modulus of elasticity results for control mix of lime cement concrete

S/No.	Mix No.	Av. Density Kg/m^3	Compressive strength (N/mm^2)	Modulus of elasticity ($10^3 N/mm^2$)
1	C1	2578	9.62	17.457
2	C2	2578	10.47	18.212
3	C3	2509	11.09	17.996
4	C4	2469	8.92	15.756
5	C5	2471	6.80	13.773
6	C6	2607	10.97	18.958
7	C7	2528	8.81	16.223
8	C8	2529	12.31	19.188
9	C9	2548	8.65	16.266
10	C10	2517	9.10	16.380
11	C11	2528	13.24	19.887
12	C12	2509	11.06	17.972
13	C13	2509	12.26	18.922
14	C14	2548	6.68	14.294
15	C15	2460	12.90	18.844

Table A49: 28th day modulus of rigidity results for normal mix of lime cement concrete

S/No.	Mix No.	Modulus of elasticity ($10^3 N/mm^2$)	Poisson ratio	Modulus of rigidity ($10^3 N/mm^2$)
1	N1	20.264	0.151	8.803
2	N2	23.313	0.209	9.641
3	N3	22.566	0.203	9.379
4	N4	25.196	0.159	10.870
5	N5	24.604	0.140	10.791
6	N12	24.853	0.210	10.270
7	N13	26.211	0.172	11.182
8	N14	26.194	0.181	11.090
9	N15	25.018	0.150	10.877
10	N23	28.074	0.164	12.059
11	N24	27.034	0.183	11.426
12	N25	24.290	0.168	10.398
13	N34	21.634	0.173	9.222
14	N35	21.594	0.183	9.127
15	N45	22.716	0.141	9.954

Table A50: 28th day modulus of rigidity results for control mix of lime cement concrete

S/No.	Mix No.	Modulus of elasticity ($10^3 N/mm^2$)	Poisson ratio	Modulus of rigidity ($10^3 N/mm^2$)
1	C1	25.701	0.216	10.568
2	C2	26.669	0.146	11.636
3	C3	27.913	0.151	12.126
4	C4	21.233	0.174	9.043
5	C5	23.113	0.141	10.128
6	C6	27.782	0.214	11.442
7	C7	26.703	0.161	11.500
8	C8	29.195	0.153	12.660
9	C9	27.060	0.153	11.735
10	C10	29.666	0.139	13.023
11	C11	28.818	0.154	12.486
12	C12	26.792	0.167	11.479
13	C13	29.051	0.105	13.145
14	C14	30.708	0.147	13.386
15	C15	24.299	0.194	10.175

Table A51: 21st day modulus of rigidity results for normal mix of lime cement concrete

S/No.	Mix No.	Modulus of elasticity ($10^3 N/mm^2$)	Poisson ratio	Modulus of rigidity ($10^3 N/mm^2$)
1	N1	19.994	0.145	8.731
2	N2	23.187	0.195	9.702
3	N3	21.398	0.213	8.820
4	N4	25.012	0.154	10.837
5	N5	22.099	0.167	9.468
6	N12	24.353	0.211	10.055
7	N13	25.979	0.153	11.266
8	N14	26.153	0.155	11.322
9	N15	24.942	0.142	10.920
10	N23	28.916	0.170	12.357
11	N24	26.579	0.181	11.253
12	N25	23.900	0.165	10.258
13	N34	21.487	0.165	9.222
14	N35	21.046	0.178	8.933
15	N45	21.632	0.148	9.422

Table A52: 21st day modulus of rigidity results for control mix of lime cement concrete

S/No.	Mix No.	Modulus of elasticity ($10^3 N/mm^2$)	Poisson ratio	Modulus of rigidity ($10^3 N/mm^2$)
1	C1	25.234	0.218	10.359
2	C2	26.562	0.137	11.681
3	C3	27.751	0.145	12.118
4	C4	21.174	0.147	9.230
5	C5	22.083	0.154	9.568
6	C6	27.516	0.215	11.323
7	C7	26.523	0.159	11.442
8	C8	28.938	0.150	12.582
9	C9	26.844	0.148	11.692
10	C10	29.407	0.139	12.909
11	C11	28.573	0.151	12.412
12	C12	26.595	0.161	11.453
13	C13	28.809	0.103	13.059
14	C14	30.404	0.148	13.242
15	C15	24.043	0.192	10.085

Table A53: 14th day modulus of rigidity results for normal mix of lime cement concrete

S/No.	Mix No.	Modulus of elasticity ($10^3 N/mm^2$)	Poisson ratio	Modulus of rigidity ($10^3 N/mm^2$)
1	N1	17.472	0.154	7.570
2	N2	21.843	0.145	9.538
3	N3	20.409	0.148	8.889
4	N4	23.624	0.156	10.218
5	N5	21.074	0.136	9.276
6	N12	23.837	0.149	10.373
7	N13	24.086	0.148	10.490
8	N14	24.070	0.142	10.539
9	N15	21.464	0.140	9.414
10	N23	25.289	0.150	10.995
11	N24	24.237	0.150	10.538
12	N25	22.511	0.140	9.873
13	N34	18.554	0.151	8.060
14	N35	17.637	0.152	7.655
15	N45	17.205	0.155	7.448

Table A54: 14th day modulus of rigidity results for control mix of lime cement concrete

S/No.	Mix No.	Modulus of elasticity ($10^3 N/mm^2$)	Poisson ratio	Modulus of rigidity ($10^3 N/mm^2$)
1	C1	24.631	0.154	10.672
2	C2	24.669	0.133	10.887
3	C3	24.569	0.173	10.473
4	C4	17.272	0.155	7.477
5	C5	17.058	0.167	7.308
6	C6	22.094	0.237	8.930
7	C7	24.449	0.167	10.475
8	C8	25.663	0.136	11.295
9	C9	24.752	0.140	10.856
10	C10	27.101	0.125	12.045
11	C11	24.999	0.155	10.822
12	C12	23.636	0.171	10.092
13	C13	23.500	0.139	10.316
14	C14	27.100	0.129	12.002
15	C15	23.073	0.164	9.911

Table A55: 7th day modulus of rigidity results for normal mix of lime cement concrete

S/No.	Mix No.	Modulus of elasticity ($10^3 N/mm^2$)	Poisson ratio	Modulus of rigidity ($10^3 N/mm^2$)
1	N1	12.332	0.264	4.878
2	N2	15.969	0.202	6.643
3	N3	14.496	0.221	5.936
4	N4	12.791	0.283	4.985
5	N5	11.867	0.382	4.293
6	N12	17.021	0.235	6.891
7	N13	17.647	0.239	7.121
8	N14	15.326	0.255	6.106
9	N15	15.009	0.235	6.077
10	N23	15.255	0.234	6.181
11	N24	16.439	0.261	6.518
12	N25	14.384	0.290	5.575
13	N34	15.854	0.186	6.684
14	N35	16.187	0.162	6.965
15	N45	13.398	0.239	5.407

Table A56: 7th day modulus of rigidity results for control mix of lime cement concrete

S/No.	Mix No.	Modulus of elasticity ($10^3 N/mm^2$)	Poisson ratio	Modulus of rigidity ($10^3 N/mm^2$)
1	C1	17.457	0.253	6.966
2	C2	18.212	0.215	7.495
3	C3	17.996	0.193	7.542
4	C4	15.756	0.157	6.809
5	C5	13.773	0.222	5.635
6	C6	18.958	0.203	7.879
7	C7	16.223	0.350	6.009
8	C8	19.188	0.133	8.468
9	C9	16.266	0.268	6.414
10	C10	16.380	0.184	6.917
11	C11	19.887	0.153	8.624
12	C12	17.972	0.178	7.628
13	C13	18.922	0.185	7.984
14	C14	14.294	0.246	5.736
15	C15	18.844	0.142	8.250

APPENDIX B

Mat-lab file for the development of the artificial neural network models of lime cement concrete

```
function varargout = StructuralPropertyOfLimeCementConcrete(varargin)

gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
'gui_Singleton',  gui_Singleton, ...
'gui_OpeningFcn', @StructuralPropertyOfLimeCementConcrete_OpeningFcn, ...
'gui_OutputFcn',  @StructuralPropertyOfLimeCementConcrete_OutputFcn, ...
'gui_LayoutFcn',  [] , ...
'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end

function StructuralPropertyOfLimeCementConcrete_OpeningFcn(hObject, eventdata,
handles, varargin)

handles.output = hObject;


guidata(hObject, handles);


function varargout = StructuralPropertyOfLimeCementConcrete_OutputFcn(hObject,
eventdata, handles)

varargout{1} = handles.output;


function cS_Callback(hObject, eventdata, handles)

function fS_Callback(hObject, eventdata, handles)

function STS_Callback(hObject, eventdata, handles)

function SS_Callback(hObject, eventdata, handles)

function PR_Callback(hObject, eventdata, handles)

function ME_Callback(hObject, eventdata, handles)

function MR_Callback(hObject, eventdata, handles)


function pC_Callback(hObject, eventdata, handles)
```

```matlab
function pC_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
set(hObject,'BackgroundColor','white');
end



function hL_Callback(hObject, eventdata, handles)



function hL_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
set(hObject,'BackgroundColor','white');
end



function sand_Callback(hObject, eventdata, handles)

function sand_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
set(hObject,'BackgroundColor','white');
end



function wC_Callback(hObject, eventdata, handles)

function wC_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
set(hObject,'BackgroundColor','white');
end


% --- Executes on button press in gen.
function gen_Callback(hObject, eventdata, handles)
global FlexuralStrengthNN;
global ShearStrengthNN;
global ModulusOfRigidityNN;
global ModulusOfElasticityNN;
global PoissonRatioNN;
global SplitTensilStrengthNN;
global compressiveStrengthNN;
cem = str2double(get(handles.pC,'string'));
hydLim =str2double(get(handles.hL,'string'));
sand =str2double(get(handles.sand,'string'));
granite =str2double(get(handles.gC,'string'));
water =str2double(get(handles.wC,'string'));
v = [cem hydLim sand granite water 7];
```

```
v2 = [cem hydLim sand granite water 14];
v3= [cem hydLim sand granite water 21];
v4= [cem hydLim sand granite water 28];
v = v';
v2=v2';
v3=v3';
v4=v4';
simval1 = [7 sim(compressiveStrengthNN,v) sim(FlexuralStrengthNN,v) ...
sim(SplitTensilStrengthNN,v) sim(ShearStrengthNN,v) sim(PoissonRatioNN,v) ...
sim(ModulusOfRigidityNN,v) sim(ModulusOfElasticityNN,v)];

simval2 = [14 sim(compressiveStrengthNN,v2) sim(FlexuralStrengthNN,v2) ...
sim(SplitTensilStrengthNN,v2) sim(ShearStrengthNN,v2) sim(PoissonRatioNN,v2)
...
sim(ModulusOfRigidityNN,v2) sim(ModulusOfElasticityNN,v2)];

simval3 = [21 sim(compressiveStrengthNN,v3) sim(FlexuralStrengthNN,v3) ...
sim(SplitTensilStrengthNN,v3) sim(ShearStrengthNN,v3) sim(PoissonRatioNN,v3)
...
sim(ModulusOfRigidityNN,v3) sim(ModulusOfElasticityNN,v3)];

simval4 = [28 sim(compressiveStrengthNN,v4) sim(FlexuralStrengthNN,v4) ...
sim(SplitTensilStrengthNN,v4) sim(ShearStrengthNN,v4) sim(PoissonRatioNN,v4)
...
sim(ModulusOfRigidityNN,v4) sim(ModulusOfElasticityNN,v4)];

data=[simval1;simval2;simval3;simval4];
set(handles.tb1,'data',data);


function clear_Callback(hObject, eventdata, handles)
set(handles.hL,'string','');
set(handles.pC,'string','');
set(handles.sand,'string','');
set(handles.gC,'string','');
set(handles.wC,'string','');



function gC_Callback(hObject, eventdata, handles)


function gC_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
set(hObject,'BackgroundColor','white');
end

function file_Callback(hObject, eventdata, handles)

function Untitled_3_Callback(hObject, eventdata, handles)

function retrain_Callback(hObject, eventdata, handles)
global inp;
global flextarg;
global FlexuralStrengthNN;
global compresstarg;
global sheartarg;
global modtarg;
```

```
global modrigtarg;
global poistarg;
global splittarg;
global ShearStrengthNN;
global ModulusOfRigidityNN;
global ModulusOfElasticityNN;
global PoissonRatioNN;
global SplitTensilStrengthNN;
global compressiveStrengthNN;
SplitTensilStrengthNN =train(SplitTensilStrengthNN,inp,splittarg);
compressiveStrengthNN=train(compressiveStrengthNN,inp,compresstarg);
PoissonRatioNN= train(PoissonRatioNN,inp,poistarg);
ModulusOfElasticityNN = train(ModulusOfElasticityNN,inp,modtarg);
ModulusOfRigidityNN = train(ModulusOfRigidityNN,inp,modrigtarg);
ShearStrengthNN =train(ShearStrengthNN,inp,sheartarg);
FlexuralStrengthNN = train(FlexuralStrengthNN,inp,flextarg);


function nnetSt_Callback(hObject, eventdata, handles)
global SplitTensilStrengthNN;
global compressiveStrengthNN
global PoissonRatioNN
global ModulusOfElasticityNN;
global ModulusOfRigidityNN;;
global ShearStrengthNN;
global FlexuralStrengthNN;
view(compressiveStrengthNN);
view(SplitTensilStrengthNN);
view(PoissonRatioNN);
view(ModulusOfElasticityNN);
view(ModulusOfRigidityNN);
view(ShearStrengthNN);
view(FlexuralStrengthNN);

function exit_Callback(hObject, eventdata, handles)
close;


% --------------------------------------------------------------------
function createNN_Callback(hObject, eventdata, handles)
global FlexuralStrengthNN;
global ShearStrengthNN;
global ModulusOfRigidityNN;
global ModulusOfElasticityNN;
global PoissonRatioNN;
global SplitTensilStrengthNN;
global compressiveStrengthNN;
global inputs;
global flexuralStrengthTargets;
global compressiveStrengthTargets;
global shearStrengthTargets;
global modulusOfElasticityTargets;
global modulusOfRigidityTargets;
global poissonRatioTargets;
global splitTensileStressTargets;


poissonRatioTargets=[0.264;0.154;0.145;0.151;0.202;0.145;0.195;0.209;0.221;...

0.148;0.213;0.203;0.283;0.156;0.154;0.159;0.382;0.136;0.167;0.140;0.235;...
```

```
0.149;0.211;0.210;0.239;0.148;0.153;0.172;0.255;0.142;0.155;0.181;0.235;...

0.140;0.142;0.150;0.234;0.150;0.170;0.164;0.261;0.150;0.181;0.183;0.290;...

0.140;0.165;0.168;0.186;0.151;0.165;0.173;0.162;0.152;0.178;0.183;0.239;...

0.155;0.148;0.141;0.253;0.154;0.218;0.216;0.215;0.133;0.137;0.146;0.193;...

0.173;0.145;0.151;0.157;0.155;0.147;0.174;0.222;0.167;0.154;0.141;0.203;...

0.237;0.215;0.214;0.350;0.167;0.159;0.161;0.133;0.136;0.150;0.153;0.268;...
0.140;0.148;0.153;0.184;0.125;0.139;0.139];


modulusOfRigidityTargets=[4.878;7.570;8.731;8.803;6.643;9.538;9.702;9.641;...
    5.936;8.889;8.820;9.379;4.985;10.218;10.837;10.870;4.293;9.276;9.468;...

10.791;6.891;10.373;10.055;10.270;7.121;10.490;11.266;11.182;6.106;10.539;...

11.322;11.090;6.077;9.414;10.920;10.877;6.181;10.995;12.357;12.059;6.518;...
    10.538;11.253;11.426;5.575;9.873;10.258;10.398;6.684;8.060;9.222;9.222;...

6.965;7.655;8.933;9.127;5.407;7.448;9.422;9.954;6.966;10.672;10.359;10.568;...

7.495;10.887;11.681;11.636;7.542;10.473;12.118;12.126;6.809;7.477;9.230;...
    9.043;5.635;7.308;9.568;10.128;7.879;8.930;11.323;11.442;6.009;10.475;...

11.442;11.500;8.468;11.295;12.582;12.660;6.414;10.856;11.692;11.735;6.917;...1
2.045;12.909;13.023];


modulusOfElasticityTargets=[12.332;17.472;19.994;20.264;15.969;21.843;23.187;.
..
    23.313;14.496;20.409;21.398;22.566;12.791;23.624;25.012;25.196;11.867;...
    21.074;22.099;24.604;17.021;23.837;24.353;24.853;17.647;24.086;25.979;...
    26.211;15.326;24.070;26.153;26.194;15.009;21.464;24.942;25.018;15.255;...
    25.289;28.916;28.074;16.439;24.237;26.579;27.034;14.384;22.511;23.900;...
    24.290;15.854;18.554;21.487;21.634;16.187;17.637;21.046;21.594;13.398;...
    17.205;21.632;22.716;17.457;24.631;19.994;25.701;18.212;24.669;23.187;...
    26.669;17.996;24.569;21.398;27.913;15.756;17.272;25.012;21.233;13.773;...
    17.058;22.099;23.113;18.958;22.094;24.353;27.782;16.223;24.449;25.979;...
    26.703;19.188;25.663;26.153;29.195;16.266;24.752;24.942;27.060;16.380;...
    27.101;28.916;29.666];


splitTensileStressTargets=[1.300;1.540;1.980;2.100;0.800;1.400;2.605;2.905;...

0.710;1.240;2.470;2.700;0.690;2.095;2.425;2.585;1.130;1.340;2.020;2.250;...

1.360;1.770;3.110;3.280;1.225;1.785;2.335;2.835;0.490;1.210;2.350;2.540;...

1.015;1.415;2.215;2.425;0.610;1.850;3.230;3.350;1.190;1.720;3.020;3.200;...

1.240;1.610;2.470;2.650;0.930;1.110;1.910;2.080;0.735;0.895;2.155;2.205;...

0.910;1.010;1.850;2.000;1.300;1.830;3.250;3.380;1.430;1.740;2.220;2.450;...

1.135;1.575;2.835;3.015;0.700;0.820;2.050;2.115;0.835;1.065;1.875;2.025;...

0.915;2.205;3.605;3.725;1.565;2.350;2.720;2.850;0.550;1.900;3.110;3.270;...
```

```
1.400;1.750;2.560;2.750;0.630;2.080;3.025;3.115];


shearStrengthTargets=[0.369;0.430;0.535;0.569;0.437;0.587;0.889;0.965;0.408;..
.

0.540;0.848;0.906;0.400;0.751;0.837;0.873;0.434;0.488;0.657;0.741;0.575;...

0.715;1.049;1.093;0.613;0.710;0.852;0.978;0.483;0.663;0.855;0.996;0.455;...

0.555;0.754;0.807;0.412;0.723;1.068;1.098;0.563;0.723;1.021;1.065;0.543;...

0.635;0.850;0.946;0.404;0.450;0.650;0.693;0.367;0.408;0.684;0.759;0.394;...

0.420;0.629;0.668;0.608;0.741;1.095;1.128;0.562;0.640;0.760;0.818;0.536;...

0.895;0.959;1.006;0.349;0.416;0.590;0.704;0.377;0.435;0.674;0.674;0.554;...

0.877;1.227;1.257;0.771;0.833;0.933;0.963;0.410;0.744;1.050;1.090;0.579;...
    0.703;0.870;0.917;0.409;0.779;1.015;1.037];


compressiveStrengthTargets=[5.600;11.240;14.720;15.1200;8.680;16.240;18.300;..
.
    18.5000;7.370;14.610;16.060;17.8600;5.670;19.340;21.680;22.0000;4.550;...
    14.350;15.780;19.5600;9.780;19.180;20.020;
20.8500;10.290;19.170;22.300;...

22.7000;7.590;18.720;22.300;22.1700;7.760;15.870;21.430;21.5600;7.030;19.320;.
..

25.260;23.8100;8.630;18.760;22.560;23.3400;7.480;18.320;20.650;21.3300;8.710;.
..

11.930;16.000;16.2200;9.080;10.780;15.350;16.1600;6.610;10.900;17.230;19.0000;
...

9.620;19.150;20.100;20.8500;10.470;19.210;22.270;22.4500;11.090;20.670;26.370;
...

26.6800;8.920;10.720;16.110;16.2000;6.800;10.430;17.480;19.1500;10.970;14.900;
...

23.110;23.5600;8.810;20.010;23.550;23.8700;12.310;22.020;28.000;28.5000;8.650;
...
    20.030;23.560;23.9400;9.100;24.910;29.330;29.8500];

flexuralStrengthTargets=[1.480;1.720;2.160;2.280;1.750;2.350;3.560;3.860;1.630
;2.160;...

3.390;3.620;1.600;3.000;3.330;3.490;1.740;1.950;2.630;2.960;2.300;2.860;4.200;
4.370;...

2.450;2.840;3.410;3.910;1.930;2.650;3.420;3.980;1.820;2.220;3.020;3.230;1.650;
2.890;...

4.270;4.390;2.250;2.780;4.080;4.260;2.170;2.540;3.400;3.580;1.620;1.800;2.600;
2.770;...

1.470;1.630;2.890;2.940;1.580;1.680;2.520;2.670;2.430;2.960;4.380;4.510;2.250;
2.560;...
```

```
3.040;3.270;2.140;3.580;3.840;4.020;1.400;1.660;2.360;2.820;1.510;1.740;2.700;
2.700;...

2.220;3.510;4.910;5.030;3.080;3.330;3.730;3.850;1.640;2.990;4.200;4.360;2.320;
2.670;...
    3.480;3.670;1.670;3.120;4.060;4.150];


inputs = [0.9000 0.1000 3.0000 6.0000 0.6000 7;0.9000 0.1000 3.0000 ...
    6.0000 0.6000 14;0.9000 0.1000 3.0000 6.0000 0.6000 21;0.9000 0.1000 ...
    3.0000 6.0000 0.6000 28;0.8500 0.1500 2.0000 4.0000 0.5700 7;.8500 ...
    0.1500 2.0000 4.0000 0.5700 14;.8500 0.1500 2.0000 4.0000 0.5700 21;...
    0.8500 0.1500 2.0000 4.0000 0.5700 28;0.8000 0.2000 2.5000 5.0000 ...
    0.5500 7;0.8000 0.2000 2.5000 5.0000 0.5500 14;0.8000 0.2000 2.5000 ...
    5.0000 0.5500 21;0.8000 0.2000 2.5000 5.0000 0.5500 28;0.7000 0.3000 ...
    1.5000 3.0000 0.5300 7;0.7000 0.3000 1.5000 3.0000 0.5300 14;0.7000 ...
    0.3000 1.5000 3.0000 0.5300 21;0.7000 0.3000 1.5000 3.0000 0.5300 28;...
    0.6000 0.4000 1.0000 2.0000 0.5000 7;0.6000 0.4000 1.0000 2.0000 0.5000...
    14;0.6000 0.4000 1.0000 2.0000 0.5000 21;0.6000 0.4000 1.0000 2.0000 ...
    0.5000 28;0.8750 0.1250 2.5000 5.0000 0.5850 7;0.8750 0.1250 2.5000 ...
    5.0000 0.5850 14;0.8750 0.1250 2.5000 5.0000 0.5850 21;0.8750 0.1250 ...
    2.5000 5.0000 0.5850 28;0.8500 0.1500 2.7500 5.5000 0.5750 7;0.8500 ...
    0.1500 2.7500 5.5000 0.5750 14;0.8500 0.1500 2.7500 5.5000 0.5750 21;...
    0.8500 0.1500 2.7500 5.5000 0.5750 28;0.8000 0.2000 2.2500 4.5000
0.5650...
    7;0.8000 0.2000 2.2500 4.5000 0.5650 14;0.8000 0.2000 2.2500 4.5000
0.5650...
    21;0.8000 0.2000 2.2500 4.5000 0.5650 28;0.7500 0.2500 2.0000 4.0000
0.5500...
    7;0.7500 0.2500 2.0000 4.0000 0.5500 14;0.7500 0.2500 2.0000 4.0000
0.5500...
    21;0.7500 0.2500 2.0000 4.0000 0.5500 28;0.8250 0.1750 2.2500 4.5000
0.5600...
    7;0.8250 0.1750 2.2500 4.5000 0.5600 14;0.8250 0.1750 2.2500 4.5000
0.5600...
    21;0.8250 0.1750 2.2500 4.5000 0.5600 28;0.7750 0.2250 1.7500 3.5000
0.5500...
    7;0.7750 0.2250 1.7500 3.5000 0.5500 14;0.7750 0.2250 1.7500 3.5000 0.5500
...
    21;0.7750 0.2250 1.7500 3.5000 0.5500 28;0.7250 0.2750 1.5000 3.0000
0.5350...
    7;0.7250 0.2750 1.5000 3.0000 0.5350 14;0.7250 0.2750 1.5000 3.0000 0.5350
...
    21;0.7250 0.2750 1.5000 3.0000 0.5350 28;0.7500 0.2500 2.0000 4.0000
0.5400...
    7;0.7500 0.2500 2.0000 4.0000 0.5400 14;0.7500 0.2500 2.0000 4.0000
0.5400...
    21;0.7500 0.2500 2.0000 4.0000 0.5400 28;0.7000 0.3000 1.7500 3.5000
0.5250...
    7;0.7000 0.3000 1.7500 3.5000 0.5250 14;0.7000 0.3000 1.7500 3.5000 0.5250
...
    21;0.7000 0.3000 1.7500 3.5000 0.5250 28;0.6500 0.3500 1.2500 2.5000
0.5150 ...
    7;0.6500 0.3500 1.2500 2.5000 0.5150 14;0.6500 0.3500 1.2500 2.5000 0.5150
...
    21;0.6500 0.3500 1.2500 2.5000 0.5150 28;0.8750 0.1250 2.5500 5.0000
0.5860 ...
    7;0.8750 0.1250 2.5500 5.0000 0.5860 14;0.8750 0.1250 2.5500 5.0000 0.5860
...
    21;0.8750 0.1250 2.5500 5.0000 0.5860 28;0.8500 0.1500 2.7500 5.5500
0.5750 ...
```

```
    7;0.8500 0.1500 2.7500 5.5500 0.5750 14;0.8500 0.1500 2.7500 5.5500 0.5750
...
    21;0.8500 0.1500 2.7500 5.5500 0.5750 28;0.7750 0.2250 1.7500 3.5500
0.5500 ...
    7;0.7750 0.2250 1.7500 3.5500 0.5500 14;0.7750 0.2250 1.7500 3.5500 0.5500
...
    21;0.7750 0.2250 1.7500 3.5500 0.5500 28;0.7000 0.3000 1.7500 3.5500
0.5250 ...
    7;0.7000 0.3000 1.7500 3.5500 0.5250 14;0.7000 0.3000 1.7500 3.5500 0.5250
...
    21;0.7000 0.3000 1.7500 3.5500 0.5250 28;0.6500 0.3500 1.2500 2.5000
0.5170 ...
    7;0.6500 0.3500 1.2500 2.5000 0.5170 14;0.6500 0.3500 1.2500 2.5000 0.5170
...
    21;0.6500 0.3500 1.2500 2.5000 0.5170 28;0.8625 0.1375 2.6250 5.2500
0.5800 ...
    7;0.8625    0.1375 2.6250 5.2500 0.5800 14;0.8625   0.1375 2.6250 5.2500
...
    0.5800 21;0.8625    0.1375 2.6250 5.2500 0.5800 28;0.7625 0.2375 1.8750
...
    3.7500 0.5500 7;0.7625 0.2375 1.8750 3.7500 0.5500 14;0.7625 0.2375
1.8750...
    3.7500 0.5500 21;0.7625 0.2375 1.8750 3.7500 0.5500 28;0.8125 0.1870
2.2500...
    4.5000 0.5625 7;0.8125 0.1870 2.2500 4.5000 0.5625 14;0.8125 0.1870 2.2500
...
    4.5000 0.5625 21;0.8125 0.1870 2.2500 4.5000 0.5625 28;0.7320 0.2680
1.8250 ...
    3.6500 0.5429 7;0.7320 0.2680 1.8250 3.6500 0.5429 14;0.7320 0.2680 1.8250
...
    3.6500 0.5429 21;0.7320 0.2680 1.8250 3.6500 0.5429 28;0.7990 0.2010
2.3250 ...
    4.3300 0.5597 7;0.7990 0.2010 2.3250 4.3300 0.5597 14;0.7990 0.2010 2.3250
...
    4.3300 0.5597 21;0.7990 0.2010 2.3250 4.3300 0.5597 28];
global inp;
global flextarg;
global compresstarg;
global sheartarg;
global modtarg;
global modrigtarg;
global poistarg;
global splittarg;

inp= inputs';
flextarg=flexuralStrengthTargets';
compresstarg= compressiveStrengthTargets';
sheartarg=shearStrengthTargets';
modtarg=modulusOfElasticityTargets';
modrigtarg =modulusOfRigidityTargets';
poistarg= poissonRatioTargets';
splittarg=splitTensileStressTargets';
ShearStrengthNN = feedforwardnet(10);
ModulusOfRigidityNN =feedforwardnet(10);
ModulusOfElasticityNN = feedforwardnet(10);
PoissonRatioNN=feedforwardnet(10);
SplitTensilStrengthNN=feedforwardnet(10);
compressiveStrengthNN=feedforwardnet(10);
FlexuralStrengthNN = feedforwardnet(10);
SplitTensilStrengthNN =train(SplitTensilStrengthNN,inp,splittarg);
compressiveStrengthNN=train(compressiveStrengthNN,inp,compresstarg);
PoissonRatioNN= train(PoissonRatioNN,inp,poistarg);
```

```
ModulusOfElasticityNN = train(ModulusOfElasticityNN,inp,modtarg);
ModulusOfRigidityNN = train(ModulusOfRigidityNN,inp,modrigtarg);
FlexuralStrengthNN = train(FlexuralStrengthNN,inp,flextarg);
ShearStrengthNN =train(ShearStrengthNN,inp,sheartarg);
view(FlexuralStrengthNN);
```

APPENDIX C

Test results used to study the effects of partially replacing portland cement (PC) with hydrated lime.

Table C1: 28th day compressive strengths of the five trial mixes without portland cement replacement with hydrated lime.

Mix No.	Mix ratio	w/c	Slump (cm)	Av. Density (Kg/m^3)	28 days PC compressive strength (N/mm^2)
M1	1:3:6	0.6	0	2459	18.22
M2	1:2:4	0.57	12.65	2449	23.85
M3	1:2.5:5	0.55	2.83	2430	25.33
M4	1:1.5:3	0.53	13.47	2420	25.59
M5	1:1:2	0.50	15.53	2380	26.90

Table C2: Comparison of the 28th day compressive strengths of portland cement concrete with lime cement concrete for the five starting mix proportions.

Mix No.	Mix ratio	w/c	Compressive strength (N/mm^2)	Mix No.	Mix ratio	w/c	% replacement of PC with hydrated lime	Compressive strength (N/mm^2)
M1	1:3:6	0.60	18.22	N1	0.9 : 0.1 : 3 : 6	0.600	10	15.12
M2	1:2:4	0.57	23.85	N2	0.85 : 0.15 : 2 : 4	0.570	15	18.15
M3	1:2.5:5	0.55	25.33	N3	0.8 : 0.2 : 2.5: 5	0.550	20	17.86
M4	1:1.5:3	0.53	25.56	N4	0.7 : 0.3 : 1.5 : 3	0.530	30	22.00
M5	1:1:2	0.50	26.90	N5	0.6 : 0.4 : 1 : 2	0.500	40	19.56

Table C3: Comparison of slump values for portland cement concrete to lime cement concrete

Mix No.	Mix ratio	w/c	Slump (cm)	Mix No.	Mix ratio	% replacement of PC with hydrated lime	w/c	Slump (cm)
M1	1:3:6	0.6	0	N1	0.9 : 0.1 : 3 : 6	10	0.600	1.00
M2	1:2:4	0.57	12.65	N2	0.85 : 0.15 : 2 : 4	15	0.570	14.75
M3	1:2.5:5	0.55	2.83	N3	0.8 : 0.2 : 2.5: 5	20	0.550	3.70
M4	1:1.5:3	0.53	13.47	N4	0.7 : 0.3 : 1.5 : 3	30	0.530	14.00
M5	1:1:2	0.50	15.53	N5	0.6 : 0.4 : 1 : 2	40	0.500	19.00

APPENDIX D

Student’s t-test statistical table

Table D1: Student’s t distribution critical table