

**DEVELOPMENT OF SCHEFFE'S REGRESSION MODEL TO PREDICT THE COMPRESSIVE  
STRENGTH OF CONCRETE USING METAKAOLIN AS PARTIAL REPLACEMENT OF  
CEMENT**

**BY**

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MEng/SIPET/2018/8602**

**DEPARTMENT OF CIVIL ENGINEERING  
FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA**

**AUGUST, 2023**

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**A THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL, FEDERAL UNIVERSITY OF  
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**ABSTRACT**

kaolinite clay, which Nigeria has been proven to have about 3 billion tonnes scattered across all the geo-political zones, can be used to produce Metakaolin through a simple calcination process. Metakaolin may be used as a cement replacing material in concrete, to reduce cement consumption, increase strength and the rate of strength gain, decrease permeability, and improve durability. In this study, it served as a fifth component of a concrete blend as it replaces between 0% to 20% of cement. The other four ingredients are water, cement, fine aggregates (sharp sand), and coarse aggregates (granite). Scheffe's simplex theory was used for the five-mix design in a {5,2} experimental design which resulted in an additional ten mix ratios. For the purpose of testing and verification, an additional fifteen mix ratios were prepared and subsequently cast. The thirty concrete mix ratios were subjected to laboratory experiments to determine the 28-day compressive strengths. The results of the first fifteen compressive strengths (model mixes) were used for the calibration of the model constant coefficients, while those from the second compressive strength (control mixes) were used for the model verification. A mathematical Scheffe's regression model was derived from the experimental results, which was used to predict the compressive strength of the concrete. The regression model was subjected to a t-test with 5% significance, which ascertained the model to be adequate with an  $R^2$  value of 0.9417. The study reveals that Metakaolin can replace up to 20% of cement without compromising the 28-day compressive strength.

## TABLE OF CONTENTS

<b>CONTENTS</b>	<b>PAGE</b>
Cover Page	
Title Page	i
Declaration	ii
Certification	iii
Dedication	iv
Acknowledgments	v
Abstract	vi
Table of Contents	vii
List of Tables	x
List of Figures	xi
List of Plates	xii
 <b>CHAPTER ONE</b>	
<b>1.0 INTRODUCTION</b>	<b>1</b>
1.1 Background to the Study	1
1.2 Statement of the Research Problem	3
1.3 Aim and Objectives	3

1.4	Justification of Study	3
1.5	Scope of Study	
<b>CHAPTER TWO</b>		
<b>2.0</b>	<b>LITERATURE REVIEW</b>	<b>5</b>
2.1	Cement as Concrete Material	5
2.2	Properties of Ordinary Portland Cement	7
2.2.1	Physical properties of Portland cement	7
2.2.1.1	<i>Setting time of portland cement</i>	7
2.2.1.2	<i>Soundness of ordinary portland cement</i>	8
2.2.1.3	<i>Consistency of portland cement</i>	9
2.2.2	Chemical properties of portland cement	9
2.3	Metakaolin	10
2.4	Pozzolan Materials in Concrete Production	13
2.5	Metakaolin in Concrete	16
2.5.1	Heat of hydration	24
2.5.2	Shrinkage	25
2.5.3	Compressive strength of concrete	27
2.6	Mathematical Modelling	28
2.6.1	Scheffe's simplex lattice design	
<b>CHAPTER THREE</b>		
<b>3.0</b>	<b>MATERIALS AND METHOD</b>	<b>31</b>

3.1	Materials	31
3.1.1	Kaolin clay	31
3.1.2	Ordinary Portland Cement (OPC)	31
3.1.3	Coarse aggregates	31
3.1.4	Fine Aggregates	31
3.1.5	Potable water	31
3.2	Method	32
3.2.1	Scheffe's simplex theory	32
3.2.2	Concrete mix design	37
3.3	Simplex Lattice Design Formulation for (5, 2) System	41
3.3.1	Simplex lattice method	41
3.3.2	Actual and pseudo components	41
3.4	Determination of the Physical Properties of Aggregates	45
3.4.1	Sieve analysis test	45
3.4.2	Bulk density test	46
3.4.3	Specific gravity test	47
3.4.4	Water absorption test	48
3.4.5	Aggregate impact value (AIV) test	49
3.5	Compressive Strength of Concrete	49

## **CHAPTER FOUR**

<b>4.0</b>	<b>RESULTS AND DISCUSSION</b>	<b>52</b>
4.1	Sieve Analysis	52
4.2	Water Absorption	54
4.3	Specific Gravity	54
4.4	Bulk Density	52
4.5	Aggregates Impact Value (AIV)	54
4.6	Compressive strength	54
4.7	Scheffe's model for 28 days compressive strength	54
4.8	Test of Adequacy of the Model	55
4.9	Discussion of Results	57
 <b>CHAPTER FIVE</b>		
<b>5.0</b>	<b>CONCLUSION AND RECOMMENDATIONS</b>	<b>59</b>
5.1	Conclusion	59
5.2	Recommendations	60
5.3	<a href="#">Contribution to Knowledge</a>	61
 <b>REFERENCES</b>		
		<b>62</b>
 <b>APPENDICES</b>		
		<b>71</b>





## LIST OF TABLES

<b>TABLES</b>		<b>PAGE</b>
2.1:	Approximate oxide composition limits of ordinary Portland cement (Neville, 1996)	10
2.2:	Physical properties of metakaolin (Siddique and Khan, 2011)	13
2.3:	Pozzolanas requirements of metakaolin (ASTM C 618) (Siddique, 2007)	15
2.4:	Typical chemical composition of the metakaolin	15
3.1:	Mix proportions	31
3.2:	Final design mix proportions	40
3.3:	Mix design ratios for a (5, 2) component system	41
3.4:	Actual and pseudo mix ratios of the model	44
3.5:	Actual and pseudo mix ratios of control observation points	45

## LIST OF FIGURES

FIGURES	PAGE
4.1: Sieve analysis curve for fine aggregates	53
4.2: Sieve analysis curve for coarse aggregates	53
4.3: Scatter plot of predicted vs. Experimental 28 days compressive Strength	57
4.4: Comparison between Experimental and predicted 28 days Compressive strength	57

## LIST OF PLATES

<b>PLATE</b>		<b>PAGE</b>
I:	Scheffe's simplex lattice design	29
II:	Metakaolin used as Pozzolana	32
III:	Concrete cubes after casting	50
IV:	Concrete cubes after curing	50
V:	Crushing of concrete cubes	51



## **CHAPTER ONE**

### **1.0 INTRODUCTION**

#### **1.1 Background to the Study**

Concrete is one of the most widely used construction materials in the world, with 2.8 billion tons placed worldwide each year (Schneider, 2011). It is attractive in many applications because it offers considerable strength at a relatively low cost. Concrete can generally be produced of locally available constituents. It can be cast into a wide variety of structural configurations, and requires minimal maintenance during service (Najimi, *et al.*, 2012). Portland cement industry is responsible for approximately 8% of global CO<sub>2</sub> emission (Chatham House, 2018). Partial replacement of Portland Cement by one or more additives to obtain blended cements not only provides reduction in CO<sub>2</sub> emission and energy saving in cement production but also supplies more durable cementitious system to the construction industry.

Supplementary cementitious materials (SCMs) are finely ground solid materials that are used to replace part of cement in a concrete mixture. These materials react chemically with hydrating cement to form a modified paste microstructure. In addition to their positive environmental impact, SMCs may improve concrete workability, mechanical properties, and durability. SCMs may possess pozzolanic or latent hydraulic reactivity or a combination of these. The term pozzolan refers to a siliceous material, which, in finely divided form and in the presence of water, will react chemically with calcium

hydroxide to form a cementitious compound. SCMs, such as natural or artificial pozzolan like metakaolin, fly ash, slag and silica fume, have been utilized towards solving these issues. While partial replacement of Portland cement (PC) with SCMs leads to decreases in CO<sub>2</sub> emission, their inclusion in concrete mixtures have been proven to be effective in the enhancement of concrete properties in terms of late-age strength and durability. Using pozzolans has become one of the most common ways to increase the service life of concrete structures. Pozzolans primarily affect the pore structure refinement of concrete, which leads to higher strength and lower permeability.

Metakaolin (MK) is produced by controlled thermal treatment of kaolin. Different optimum temperature (600–850 °C) and period (1–12h) for heating kaolin to obtain MK with a high pozzolanic index has been introduced by different researchers. Therefore, MK can replace cement in concrete because of its pozzolanic properties (Elavarasan *et al.*, 2020). When used in concrete, metakaolin undergoes a pozzolanic reaction and refines the microstructure of the hydrated cement paste. Due to the small particle size and high surface area, MK reacts quickly and reduces the diffusion coefficient compared with plain Portland cement (Basheer *et al.*, 2002). Research suggests that Silica fumes and MK have similar influences on the chloride ingress resistance of concrete. Typical replacement levels for MK range from 5% to 10% (Holland *et al.*, 2016).

Modelling involves setting up mathematical formulations of physical or other systems. Such formulations are constructed for the assessment of the objective function after the hindsight of observed operating variables. Hence or otherwise, model could be constructed for a proper observation of response from the integration of the factors through controlled experimentations followed by schematic design where such simplex lattice approach of the type of (Scheffe, 1958) optimization theory could be employed.

Entirely different physical systems may correspond to the same mathematical model so they can be solved by the methods. This study seeks to develop a mathematical regression model known as the Scheffe's model to predict the compressive strength of concrete when cement is partially replaced with Metakaolin (MK).

### **1.2 Statement of the Research Problem**

With the recent modernization agenda of Nigeria government, the need for civil engineering projects such as rail infrastructures, roads, high rise buildings and airports is on the rise (Suleiman, 2010). This leads to the search for cheaper and readily available sources of ingredients for the production of high-grade concrete. In a bid to reduce pollution, increase concrete strength and produce high-grade concrete at a relatively cheaper rate the need arises for the use of pozzolan such as Metakaolin as a partial replacement of cement in concrete production.

### **1.3 Aim and Objectives**

The aim of this study is to develop Scheffe's regression model to predict the compressive strength of concrete using Metakaolin.

While the objectives are to:

1. Determine physical properties of aggregates.
2. Determine the compressive strength tests on the Metakaolin hardened concretes samples after 28days of curing
3. Develop a mathematical regression model to predict the compressive strength of concrete when ordinary Portland cement is partially replaced with Metakaolin (MK)

### **1.4 Justification of the Study**

Due to the demand for low-cost construction materials in the construction of major infrastructure, the need for the use of pozzolan like Metakaolin (MK) to partially



replaced cement has been found to be beneficiary for the reduction of cost of concrete. Replacing ordinary Portland cement with MK will reduce the use of cement in construction thereby leading to a reduction in construction cost. It will also reduce the level of carbon dioxide emission caused by ordinary Portland cement production. The need to optimize concrete strength is of great importance to concrete production. Hence, developing Scheffe's regression model will help in predicting the compressive strength of concrete.

### **1.5 Scope of the Study**

The research work focuses on the development of a predictive regression model for determining the compressive strength of a Metakaolin concrete using Scheffe's simplex theory, the routine laboratory tests such as specific gravity, grain size distribution, and bulk density were carried out on all the aggregates. Crushing test was also carried out on the hardened concrete to determine the compressive strength. Scheffe's regression model was developed to predict the compressive strength of the concrete. Finally, the results from the predictive regression model and experimental results were compared and check for adequacy of the model using F-Statistics (Fisher) Test Method.

## **CHAPTER TWO**

### **2.0 LITERATURE REVIEW**

#### **2.1 Cement as Concrete Material**

Cement can be defined as a material that can bind solid particles such as gravel, sand, in to a compact whole. Different form of materials exhibits cementitious properties. Ordinary Portland cement has the ability to set and harden in the presence of water. They are usually produced from calcareous raw material containing silicate, aluminate and iron oxides (Neville, 1995).

The process of manufacture of cement consists of essentially of grinding the raw materials mixing them intimately in certain proportions and burning in a kiln at 1400-1450°C to form predominantly clinker. The clinker is cooled and ground to a fine powder with some gypsum added and the resulting product yields the commercially produced Ordinary Portland cement widely used throughout the world (Alp, 2009). Ordinary Portland cement is the most common type of cement used in construction application. Since the cost of cement is exorbitant and demand is so high, other cheap inorganic materials with cementitious properties can be used as partial replacement of Portland cement (Alp, 2009).

Cement may be pure Portland cement, or it made from Portland cement mixed with other materials that also have cementitious properties such as supplementary cementing materials (SCMs). SCMs are important and necessary components for modern concrete structures by helping to produce high-performance concrete (Aitcin, 2011). The mortar

and concrete properties, both in fresh and hardened cases, can be enhanced by cement composed of mixtures of Portland cement with these other additives, which have been used in more and more concrete projects (Zongjin, 2011). The outgrowth of such high-performance concrete has brought the fundamental need for additives, both chemical and supplementary cementing materials, to enhance the concrete properties. Concrete enhancement worldwide has been corroborated by continuous improvement of these additives (Murthy *et al.*, 2012). Hence, SCMs have become a complementary part of high-performance concrete mix design. It is including natural materials, by-products, and industrial wastes from other manufacturing processes. Several attempts have been made to develop sustainable binders through the use of SCMs as partial replacement of cement in concrete, such as slag, fly ash (FA), palm oil fuel ash (POFA), silica fume (SF), rice husk ash (RHA), ground granulated blast furnace slag (GGBFS) and metakaolin (MK). These SCMs have been utilized very commonly as pozzolanas materials in concrete and have showed a considerable effect to improve the mechanical and durability properties of concrete (Siddique and Klaus, 2009).

Furthermore, the use of limestone Portland cement in concrete also contributes to environmental conservation because the incorporation of limestone in cement manufacturing contributes to reducing the emissions of CO<sub>2</sub>, in addition to its improvement in concrete properties as compared with using ordinary Portland cement. The limestone cements indicate appropriate strength but in general demand less water than the ordinary Portland cements. The incorporation of limestone enhances the clinker reaction and the exploitation of its hydraulic potential. The Portland limestone cements indicate competitive concrete properties and improve the corrosion performance of the concrete as mentioned by (Tsiviliset *al.*,2002). Finally, incorporation of fibres into concrete improves the mechanical strength including flexural strength, compressive

strength, toughness, splitting tensile strength and improve the long-term durability of concrete as compared to conventional concrete.

## **2.2 Properties of Ordinary Portland Cement**

The most commonly used binding materials in building and civil engineering works are considered as that which will set and harden under water, as such, are often called Ordinary Portland cement (Neville, 1996). Others are the slag-containing cements, high alumina cements, and the fly ash cements but most importantly of these is the Ordinary Portland cement.

### **2.2.1 Physical properties of portland cement**

Ordinary Portland cement is capable of setting, hardening and remains stable under water. It is composed of calcium silicates and some amount of gypsum. (ASTM C150, 1994) and (BS EN 197 part 1, 2000) gives the physical properties of Portland cement to include setting time, soundness, consistency, fineness, strength, heat hydration, etc. and their impact on the performance of cement in concrete.

#### ***2.2.1.1 Setting time of portland cement***

The setting time of Portland cement is in two stages; initial setting time and final setting time. The initial setting time which is the beginning of a noticeable stiffening in the cement paste and it is measured from when water is poured for mixing of paste of standard consistency to time when a needle with a diameter  $1.13 \pm 0.05$ mm penetrates the paste not deeper than 5 mm from the bottom. The final setting time is measured from the moment when mixing water was added to the cement. This is when the needle gently lowered to the surface of the paste; penetrate it to a depth of 0.5mm but the circular cutting edge fail to make an impression on the surface of the paste. BS 12

(1995) recommends initial and final setting times to be not more than 45 minutes and 2 hours respectively.

American Concrete Institute defines setting of a concrete as a measure of the rate of release of hydration. The compound gypsum added to clinker in the production of cement serves as a retarder (ASTM C191, 1992). Setting characteristics of concrete is highly important part in the field of concrete construction (Brooks *et al.*, 2000). It helps in the preparation of different stages of concreting operations which includes transporting, placing, consolidating and finishing. Placement of concrete in formworks depends on the setting time of concrete which make the concrete strong and rigid (Niragi, 2016). The setting time are the initial and final setting which are to be determine accordance to (BS 12, 1995) and (BS 4550 part 3, 1978)

Setting time is the stiffening of the cement paste or the change from the plastic state to a solid state and this is achieved due to selective hydration of cement compounds. The two first to react are  $C_3A$  and  $C_3S$ . The setting time of cement decreases with a rise in temperature. The setting times indicate that a paste is or is not undergoing normal hydration reactions. Sulfate (from gypsum or other sources) in the Ordinary Portland cement regulates setting time, but setting time is also affected by cement fineness, water-cement ratio, and any admixtures that may be used (ASTM C191, 1992).

The importance of setting in concrete works comes from the importance to keep the fresh concrete in the plastic stage for enough time necessary to complete its mixing and placing under practical conditions (this is the purpose from initial setting time). But, from the economical side, it is important that the concrete hardens at convenient period after casting. (ASTM C191, 1992).

#### **2.2.1.2 Soundness of ordinary portland cement**

Soundness is a physical property of cement paste, which determines the ability of the cement paste to retain its volume after setting is completed. The expansion after setting is caused by the slow of hydration or other reactions which may result to unsoundness of the cement (ASTM C150, 1994). The unsoundness is due to the presence of free CaO(lime) and free MgO (magnesia) in cement. These constituents hydrate very slowly after setting of cement. Since  $\text{Ca}(\text{OH})_2$  and  $\text{Mg}(\text{OH})_2$  occupy larger volume, expansion takes place.

Most specifications for Portland cement limit the magnesia content and the maximum expansion as measured by the autoclave expansion test. Since adoption of the autoclave expansion test (ASTM C150, 1994). In 1943, there have been exceedingly few cases of abnormal expansion attributed to unsound cement. (BS 4550 part 3, 1978)limitation specified for various Portland cements require that the measured expansion in the test be not more than 10mm.

### ***2.2.1.3 Consistency of portland cement***

Consistency is the percentage of mass of water to cement required to produce cement paste of desired consistency. It is used in the determination of the initial and final setting times and soundness of cement (BS EN 197 part 1, 2000)and (Neville, 1995). The consistency is measured by the Vicat apparatus, and it is defined as that consistency which will permit a Vicat plunger having 10 mm diameter to penetrate the paste to a point ( $6 \pm 1$  mm) from the bottom of the mould. (BS EN 197 part 1, 2000)specified 26% - 33% as percentage mass of for a standard paste.

### **2.2.2 Chemical properties of portland cement**

The raw materials used for the manufacture of cement consist mainly of lime, silica, alumina and iron oxide. These oxides interact with one another in the kiln at high

temperature to form more complex compounds. The relative proportions of these oxide compositions are responsible for influencing the various properties of cement; in addition to rate of cooling and fineness of grinding.

The calculated quantity of the compounds in cement varies greatly even for a relatively small change in the oxide composition of the raw materials. To manufacture a cement of stipulated compound composition, it becomes absolutely necessary to closely control the oxide composition of the raw materials.  $\text{SO}_3$  also appear in cement analysis which comes from adding gypsum (4 - 6)% during clinker grinding. The Iraqi and British specification for normal high rapid Portland cement pointed that  $\text{SO}_3$  content must be between (3 - 2.5)% according to type of cement and  $\text{C}_3\text{A}$  content. The percentage of  $\text{MgO}$  in cement which comes from Magnesia compounds in raw material is about (4 - 10%) and 5% as maximum range to control expansion from hydration of this oxide in hard concrete. An increase in lime ( $\text{CaO}$ ) content beyond a certain value makes it difficult to combine with other compounds and free lime will exist in the clinker which causes unsoundness in cement. Table 2.1 shows the Approximate Oxides Composition Limits of Ordinary Portland Cement.

**Table 2.1:** Approximate oxides composition limits of ordinary Portlandcement (Neville, 1996)

Oxide	Percentage content
$\text{CaO}$	60 - 67.0
$\text{SiO}_2$	17.0 - 25.0
$\text{Al}_2\text{O}_3$	3.0 - 8.0
$\text{Fe}_2\text{O}_3$	0.5 - 6.0
$\text{MgO}$	0.1 - 4.0
Alkalies ( $\text{K}_2\text{O}$ , $\text{Na}_2\text{O}$ )	0.4 - 1.3
$\text{SO}_3$	1.3 - 3.0
Insoluble residue	0.3 - 5.0

### 2.3 Metakaolin

Metakaolin is produced by heat-treating kaolin, one of the most abundant natural minerals. Kaolin is a fine, white clay that has traditionally been used in the manufacture of porcelain and as a coating for paper. The term kaolin is derived from the name of the Chinese town *Kao-ling*, which translates loosely to "high ridge" and is home to the mountain that yielded the first kaolin to be sent to Europe (High Reactivity Metakaolin: Engineered Mineral Admixture for Use with Portland Cement, 2004).

Kaolinite is the most common clay mineral, and entire clay deposits can be composed of this mineral. There are many commercial Kaolinite mines where this mineral is mined in large volumes for its various industrial uses which can be found in Nigeria. It was estimated by Raw Material Research Council of Nigeria (RMRDC) that the country has a reserve of about (3) three billion metric tons of kaolin deposit scattered in difference parts of the country which includes Ogun, Edo, Plateau, Nassarawa, Katsina, Ekiti, Kogi, Abia, Kano, Niger, Bauchi, Sokoto, Kaduna, Oyo, Delta, and Borno states. The market for kaolin is large, sustainable and expanding because of the numerous applications of its products. Good prospects exist in kaolin mining and prospecting in Nigeria (RMRDC (TB) 2008). Kaolinite is the mineralogical term for hydratealuminium disilicate,  $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ , the primary constituent of kaolin (40-70%). Other minerals comprising kaolin include quartz, muscovite-like micas, and rutile (Moulin, 2001).

Metakaolin is one of the SCMs considered as an environmentally friendly material in contrast to the environmental impact of cement. It is created from kaolinite clay that is calcined at temperatures around  $800\pm 100^\circ\text{C}$  (Klimesch and Ray, 1998; Siddique, 2007), which is much less than the temperature required to produce cement which is around



1450°C. Actually, production of 1 kg of cement releases about 0.95 kg of CO<sub>2</sub>, while production of 1 kg of metakaolin releases about 0.1 kg of CO<sub>2</sub> (Nicholas, 2012; Habert, 2013; Torgal *et al.*, 2011). Hence, partial replacement of cement by metakaolin contributes to reducing the CO<sub>2</sub> emission in addition to improving concrete properties (Kumar *et al.*, 2012). According to Mehta (2010) pointed out that consumption of less cement in concrete mixtures, consumption of less concrete for new structures, and the consumption of less clinker in the cementing material are the main ways to reduce CO<sub>2</sub> emission. Previous work has found that while the presence of metakaolin in the cement concrete mix improved concrete strength, concrete modified by metakaolin required a water reducer, such as a super plasticiser or polymer, to offset the water demand by the reactions of the metakaolin component with the cement hydration products. Reducing the cement to water ratio leads to an improvement in strength as long as there is sufficient water available to fully hydration of the cement phase present. The amount of water reducer added to the concrete mix is in direct proportion to the amount of metakaolin replacement (Wild *et al.*, 1996).

According to Vikas *et al.* (2012), Metakaolin is a waste/non-conventional material which can be utilized beneficially in the construction industry. The advantages of this material as partial replacement of cement in concrete cannot be under estimated. Metakaolin may be used as a cement replacing material in concrete, to reduce cement consumption, to increase strength and the rate of strength gain, to decrease permeability and to improve durability (Khatib and Wild, 1998; Aquino *et al.*, 2001; Asbridge *et al.*, 2001; Boddy *et al.*, 2001; Justice, *et al.*, 2005).

Niveditta and Manuivel, (2014) in their work reported that metakaolin produced by calcinations of pure kaolinite clay can greatly influence both the mechanical and ductility properties of concrete. Biljana *et al.*, (2010), also reported that the

development of pozzolanic reactivity in fired kaolin clay, measured by indirect method based on strength development occurring with reaction time, which is the main characteristics of the produced metakaolin, depends on the nature and abundance of the kaolinites in the kaolin clay materials. Velosa *et al.*, (2009), in their study on influence of chemical and mineralogical composition of metakaolin on concrete characteristics, reported that concrete using metakaolin is rich in SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub>, and being also poor in alkali but showed better mechanical results.

Nevertheless, the ‘meta’ prefix in the term is used to denote change. In the case of metakaolin, the change that is taking place is dehydrocyclization (Siddique, 2007; Ramezaniapour, 2014). Kaolin clay is the raw material input in the production of metakaolin (Al<sub>2</sub>Si<sub>2</sub>O<sub>7</sub>). It is fine and white, clay mineral that has been used in the production of porcelain. Physical properties of metakaolin are shown in Table 2.2.

**Table 2.2:** Physical properties of metakaolin

Property	Poon <i>et al.</i> (2001)	Al-Akhras (2006)	Tafraoui <i>et al.</i> (2009)
Specific gravity	2.62	2.5	2.5
Average particle Fineness		1	12
(m <sup>2</sup> /kg)	12680	12000	15000 - 30000
Colour		White	

Source: (Siddique and Khan, 2011)

#### 2.4 Pozzolanic Materials in Concrete Production

Pozzolans are defined as siliceous and aluminous materials which themselves possess little or no cementitious value but will, in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties (Justice, 2005). Pozzolana can be divided in to two groups: natural and artificial, depending on the source of the material. Natural pozzolanas

include volcanic ash and diatomite, etc. artificial pozzolanas include calcium clay, by-products from industrial processes such as fly ash, ground granulated blast furnace slag, silica fume, and ash from burnt agricultural waste such rice husk, bagasse, corn cob ash, groundnut ash etc. apart from the cost benefit of use of pozzolanas with ordinary Portland cement, other advantages of pozzolanas as reported in (Neville,1996)include; improved workability improve water retention/ reduced bleeding, improved sulphate resistance, improved resistance to alkali aggregate reaction, low heat of hydration and enhanced long term strength. The only disadvantage of blended pozzolanic cement as reported in (Neville,1996) and many other researches is that their early strength gain is slightly lower. However, the only benefits can be achieved with a good pozzolana.

According to EN 197-1 (2000), Pozzolanic materials do not harden in themselves when mixed with water but, when finely ground and in the presence of water, they react at normal ambient temperature with dissolved calcium hydroxide ( $\text{Ca(OH)}_2$ ) to form hydrated calcium silicate and calcium aluminate compounds. In this view pozzolanas consist mainly of reactive silicon dioxide ( $\text{SiO}_2$ ) and aluminium oxides ( $\text{Al}_2\text{O}_3$ ), and the remains contain part of iron oxide ( $\text{Fe}_2\text{O}_3$ ) and other oxides.

Natural pozzolans are usually materials of volcanic origin or sedimentary with a high content of sum of ( $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ ) not greater than 80% ( $\geq 80\%$ ), but a low content of MgO and  $\text{SiO}_3$  generally exhibit a high pozzolanic activity (Alp, 2009).

Metakaolin (MK) has become one of the new materials, which has been used as a SCM in the field of civil engineering applications that conforms to ASTM C 618, Class N Pozzolanas Specifications as shown in Table 2.3 (Siddique, 2007). The use of metakaolin in concrete is relatively new, and it is being investigated because of its high pozzolanic properties, making it possible to modify the concrete properties to suit the desired application, as analysed by Moiseas and Joseph (2000).

The main contents of metakaolin are silica oxide ( $\text{SiO}_2$ ), alumina oxide ( $\text{Al}_2\text{O}_3$ ) and iron oxide ( $\text{Fe}_2\text{O}_3$ ). The chemical contents of metakaolin are shown in Table 2.4 (Siddique and Khan, 2011).

**Table 2.3:** Pozzolanas requirements of metakaolin (ASTM C 618)

Modified specification requirements	
Item	Limit
Silicon dioxide ( $\text{SiO}_2$ ) plus aluminium oxide ( $\text{Al}_2\text{O}_3$ ) plus iron oxide	Min 85%
Available alkalis	Max 1.0%
Loss on Ignition	Max 3.0%
Fineness: amount retained when wet-sieved on 45 $\mu\text{m}$ sieve	Max 1.0%
Strength activity index at 7 days (% of control)	85
Increase of drying shrinkage of mortar bars at 28 days	Max 0.03%

*Source:* (Siddique, 2007)

**Table 2.4:** Typical chemical composition of the metakaolin

Chemical composition	Ambroise <i>et al.</i> (1994)	Wild and Khatib (1997)	Tafraoui <i>et al.</i> (2009)	Thomas (2013)
$\text{SiO}_2$	51.52	52.1	58.1	52
$\text{Al}_2\text{O}_3$	40.18	41	35.14	45
$\text{Fe}_2\text{O}_3$	1.23	4.32	1.21	0.6
CaO	2	0.07	1.15	0.05
MgO	0.12	0.19	0.2	-
$\text{K}_2\text{O}$	0.53	0.63	1.05	0.16
$\text{SO}_3$	-	-	0.03	-
$\text{TiO}_2$	2.27	0.81	-	-
$\text{Na}_2\text{O}$	0.08	0.26	0.07	0.21
LOI	2.01	0.6	1.85	0.51

Zhang and Malhotra (1995) indicated that metakaolin is a silica-based product that, when reacted with  $\text{Ca}(\text{OH})_2$ , produces CSH gel. Metakaolin also contains alumina that

reacts with CH to produce more alumina phases, including  $C_4AH_{13}$ ,  $C_2ASH_8$ , and  $C_3AH_6$ .

The pozzolanic nature of metakaolin, when used with cement as a partial replacement, means it is able to react with portlandite which is produced by the cement hydration to shape supplementary calcium-silicate-hydrate gel, similar in components and structure to the cement hydration productions, as highlighted by Terrence *et al.*, (2000). Metakaolinite is considered a good synthetic pozzolanas as it reacts, especially with lime, and produces hydrate components of Ca and Al silicates in the presence of water. The quality and abundance of clay minerals in the raw material, the calcination status and the final product fineness affect the development of pozzolanic properties as indicated in a different study by (Kakaliet *al.*, 2001). The main reaction product of the activation of metakaolin with highly alkaline solutions in the presence of calcium hydroxide is a sodium aluminosilicate, the same as that produced when metakaolin is activated without calcium hydroxide. In addition, the formation of CSH gel as a by-product is also observed (Alonso and Palomo, 2001). The by-products of the metakaolin action with the cement hydration product reduce the cost of the concrete due to decreasing the quantity of the cement used. In addition, the durability properties of concrete improve, consequently, due to the refining of the pores system by the secondary hydrates (Chadbourn, 1997). Metakaolin has been used to replace some parts of the cement of concrete to increase the strength properties and reduce the permeability of the concrete in order to enhance the service life of concrete structures, as carried out by (Gruber *et al.*, 2001; Aiswaryaet *al.*, 2013a; Khatib *et al.*, 2014).

## **2.5 Metakaolin in Concrete**

The reaction between cement particles and water is the main chemical and physical process in the hydration of cement. The properties of fresh concrete and hardened

concrete, such as setting, hardening, and strength are the direct results of the process of hydration. The mechanism of cement hydration is the reaction of the main two calcium silicate components of the cement. These hydrations are similar in terms of the chemical reaction, differing only in the amount of calcium hydroxide formed, the heat released and the reaction rate. Typical reactions are shown in the following equations (Neville, 2011):



The principal hydration product is  $C_3S_2H_8$ . It is a widely held view that CSH is the major strength provider for Portland cement concrete due to its amount and small size. Nevertheless, the other product of the cement hydration is CH. This product is a good crystalline with a plate shape in most cases. CH is formed in solution by crystallisation and occupies about 25% of the structural component of cement paste. CH can bring the pH value to over 12 and it is good for corrosion protection of steel. From a durability of the concrete point of view, CH may lead to leaching due to its solubility, carbonation due to its reaction with carbon dioxide, alkali-aggregate reaction due to its high pH value, or sulphate attack due to its reaction with sulphate. Hence, in contemporary concrete technology concepts, there has been a trend to reduce the amount of CH in concrete as much as possible. However, a minimum amount of CH is needed to keep the high alkali environment in concrete as conducted by Zongjin (2011).

Supplementary cementing materials, such as metakaolin, when used as a partial replacement substance for cement in concrete, has high pozzolanic properties which are similar in many aspects to those of Portland or blended cement systems, as mentioned by De Silva and Glasser (1993). It reacts with  $Ca(OH)_2$  and results in an additional CSH gel which results in increased strength. Metakaolin also reduces the hardened

cement permeability to liquids and gases, resulting in an increase in the service life of buildings. The chemical reaction as shown below becomes important within the interfacial transition zone located between the aggregate and paste fractions (Justice *et al.*, 2005; Aiswarya *et al.*, 2013a)



The experimental study of a partial replacement of cement by metakaolin showed that cement hydration products represented by CH crystals are quickly consumed, and the microstructure of the cement mortar appears with a high level of CSH and stratlingite ( $\text{C}_2\text{ASH}_8$ ), the pore size distribution tends towards a smaller size, and the CH content was considerably reduced as mentioned by Ambroise *et al.* (1994). They investigated the effects of partial replacement of metakaolin by cement. Four mortar mixtures were prepared at 0, 10, 20 and 30% metakaolin replacement. It was found that after 7 days of curing the compressive strength of modified pastes becomes higher than that of the conventional mix for 10% and 20% of metakaolin replacement. However, utilisation of high contents of metakaolin increases the demand for water needed to reach the same workability as in a plain cement mix due to high reactivity of pozzolanic materials in metakaolin (Siddique and Khan, 2011). It is essential to use superplasticisers in conjunction with metakaolin in the cement paste to reduce the water demand. The increase in metakaolin content leads to a displacement of pore diameters towards smaller values. This explanation of properties improvement is also put forward by Wild *et al.*, (1996), in their study which showed that the filler effect, the acceleration of cement hydration, and the pozzolanic action of metakaolin with CH are the factors which affect the contribution made by metakaolin to improving the strength when it partially replaces some of the cement in concrete.

The research study by Zhang and Malhotra (1995) presented the results of the physical and chemical properties of a thermally activated alumina-silicate material metakaolin and deals with the properties of fresh and hardened concrete incorporating this material. The results of this limited study show that the thermally activated aluminosilicate material is highly pozzolanic and appears to have excellent potential as a supplementary cementing material for improving concrete properties and produce high-performance concrete. The concrete incorporating 10% metakaolin required more super plasticizer and air-entraining admixture and improved the strength up to 180 days of curing compared with the conventional concrete. Incorporation of metakaolin improved the resistance to chloride diffusion compared to conventional concrete.

In an investigation by Khatib and Wild (1996), pore size distribution and porosity of modified concrete were observed with partial replacement of ordinary Portland cement by metakaolin at 0, 5, 10 and 15% and w/c ratio 0.55. The samples were under moist curing for the period up to 12 months. It was found that the rate of large pores in the concrete paste reduces with increase in metakaolin percentage and curing time. Partial replacement of cement by metakaolin up to 20% reduces the water absorption by capillary effect due to the filler effect of fine metakaolin particles. Previous studies, as reported by Bredy *et al.*, (1989), showed that when the partial replacement with metakaolin was below 20%, the total porosity of the concrete decreased. Beyond 30%, the porosity of the modified concrete increased, which could be due to the using of metakaolin, required more water/cement ratios due to high reactivity of the pozzolanic components in metakaolin. The development of the strength quality of the hardened concrete made by partial replacement of cement by metakaolin is influenced by three elementary effects. They are the filler influence, acceleration of the hydration of cement, and the metakaolin pozzolanic effect with CH as observed by Wild *et al.*



(1996). This is consistent with the investigation of Khatib and Wild (1998) who performed experimental investigations on the influence of metakaolin on the sulphate resistance of mortar. Cements of high  $C_3A$  and intermediate  $C_3A$  were used, with partial replacement of cement by metakaolin at 5, 10, 15, 20 and 25%. Prisms of size 25 x 25 x 285 mm were moist cured in air for two weeks, and their length was measured before immersing in 5%  $Na_2SO_4$  solution. The result showed the expansion and deterioration decreased significantly with increase in metakaolin level for both types of cement. At least 15% metakaolin replacement with cement is the optimum replacement to provide good sulphate resistance. This is in good agreement with similar work on metakaolin replacement by Wild and Khatib (1997). They observed that removal of CH by pozzolanic action reached a maximum at about 14 days. This is critical, as CH can be detrimental to the durability of concrete and does not significantly contribute to concrete strength; the reduction of the CH by the secondary reaction with the metakaolin greatly improves the concrete strength. The alkali activation of metakaolin is a way to improve strength of cementitious materials, as mentioned by Palomo *et al.*, (1999).

Courard *et al.*, (2003), investigated the sulphate resistance of modified mortars by partial replacement of cement by 0, 5, 10, 15 and 20% metakaolin. The specimens of mixtures were cast with 1:3 cement/sand with w/c ratio 0.50. Regarding behaviours of modified mortar in comparison with conventional mortar, an inhibition of sulphate attack was observed. The optimum percentage of the metakaolin replacement seemed to be between 10 and 15% regarding the low decrease of workability, the best mechanical performances about 19.9% compared with control concrete at 15% metakaolin replacement. Increasing the metakaolin level up to 20% contributed to a decrease in

absorption by capillary action. There is a link between the water absorption, modulus of elasticity, and strength and pore size distribution according to Khatib and Clay (2004).

A study by Batiset *et al.*, (2005), suggests that the increase of the partial cement replacement using metakaolin results in a considerable increase in the required water for the hydration process. The results show improvement in compressive strength about 19.5% with partial replacement of metakaolin of 10% at age 28 days. Using metakaolin as a sand or cement replacement up to 20% and 10% by weight respectively, enhances the corrosion resistance of mortar samples. However, Justice (2005) studied the effect of using metakaolin as a supplementary cementitious material on the concrete properties. With respect to workability and setting time, the use of metakaolin generally required more superplasticizer to achieve adequate concrete workability, because metakaolin caused the highest reductions in workability due to the filler influence, acceleration of the hydration of cement, and the metakaolin pozzolanic effect. Metakaolin also shortened setting time of cement paste by 35-50% as compared to the control cement paste. In addition, compared to the control sample, the samples of metakaolin had the improvement of 42%, 9.5% and 10% in compressive, splitting tensile, flexural strengths respectively over controls for W/C of 0.40, respectively. This finding is consistent with findings of past studies by Sadr *et al.*, (2007), which found that metakaolin improves compressive strength and reduces shrinkage compared with the conventional specimens, and the optimum percentage of replacement is between 10 and 20%. Furthermore, in the same vein, Khatib (2008) showed that the workability reduced with an increase of metakaolin level, as reported before, as the results showed the slump reduce from 17 mm to 0 mm when the metakaolin content increase from 0% to 20% respectively. The maximum contribution of metakaolin to strength was at 14 days and the optimum percentage of metakaolin was 15%. The increase in metakaolin

content of up to at least 20% leads to a decrease in shrinkage and an increase in expansion after 56 days of curing. This is supported by the Bai and Gailius (2009) which revealed that partial replacement of cement by metakaolin significantly affects consistency and early strength of cement paste. Due to high pozzolanic reactivity of the metakaolin and specific surface, water demand increases with increased metakaolin content in the concrete mixture. Meanwhile, Siddique and Klaus (2009) reviewed the available literature on the effect of metakaolin on the mortar and concrete characteristics. Similar results were found to those mentioned above. The literature reviewed clearly demonstrates that metakaolin is an effective pozzolanas and concludes that metakaolin improves the early age strength as well as the long-term properties, and reduces the permeability of the mortar and concrete. Incorporation of metakaolin in a cement system causes a significant change in the chemical composition of the cement hydration products and partial replacement of 10% and 15% metakaolin exhibited excellent durability properties, such as resistance to chemical attack.

In addition, according to Vejmelkova *et al.*, (2010) the durability properties of concrete modified by metakaolin were improved. Its frost resistance was better as compared to Portland cement high performance concrete. The chemical resistance of metakaolin concrete in distilled water and HCl was better than for Portland cement in control concrete.

Anupama *et al.*, (2011) studied the effect of partial replacement of cement by 0%, 10%, 15% of metakaolin using different W/C ratios are 0.35, 0.4, 0.45 and 0.50 at ages 3, 7, 28, 56 and 90 days. The results showed that using metakaolin in concrete increase the rate of early age strength of the concrete paste. Optimum partial replacement was found to be 15% metakaolin at age 90 days. Compressive strength enhances with an increase of metakaolin level. The maximum density of modified concrete was achieved at 0.45

w/c ratio and 10% metakaolin replacement. This is supported by the Beulah and Prahallada (2012) study which investigated the partial replacement of cement by metakaolin at 0, 10, 20 and 30%. It was observed that the addition of metakaolin increases the resistance of the concrete to acid attack. The results also, show that the compressive strength improved by 11.6% at 10% replacement of cement by metakaolin. This is consistent with a study by Murthy *et al.*, (2012) which investigated the influence of partial replacement of 7.5, 10, 12.5, 15 and 17.5% metakaolin by weight of cement on the modulus of elasticity of concrete. Cylinders of size 150 mm diameter and 300 mm height at various percentages of metakaolin were used to determine the modulus of elasticity after curing for 28 days. Variation of Young's modulus at different percentages of metakaolin was compared with conventional concrete. It was found that young's modulus of elasticity increases with metakaolin replacement up to 10% then decreases with further metakaolin increase. In addition, there was an improvement in compressive strength of the concrete mix up to 8.6% at age 28 days for 10% metakaolin replacement by weight of cement.

Shelorkar and Jadhao (2013) investigated the influence of metakaolin replacement on strength properties and rapid chloride permeability of concrete. Specimens with partial replacement of cement by metakaolin at 0, 4, 6 and 8% were prepared. It was observed that there was a remarkable enhancement in compressive strength about 9%, 13.2% and 21% for 4, 6 and 8% cement replacement by metakaolin. The percentage reduction in chloride permeability values in coulombs was 48.57 %, 51.88 % and 56.43% for metakaolin content of 4%, 6% and 8% respectively. Nova (2013), also provided a study of the effects of partial replacement of cement by metakaolin at 5, 10, 15 and 20% on concrete. The results showed the partial replacement with metakaolin admixture effectively improved the mechanical properties of the concrete. It was found that the

mechanical properties increased up to 15% metakaolin replacement and then decreased as metakaolin was increased further. In contrast with conventional concrete, the percentages of the increase in the mechanical strength were 39.2, 8.90 and 15.2 for compressive, splitting and flexural strength respectively.

In a different study, Srinivasuv *et al.*, (2014) discussed the significant relationship between the metakaolin level and the concrete properties. It was emphasized that the inclusion of metakaolin in the concrete led to a 25% increase in strength and enhanced durability. Metakaolin increases the density of the concrete, which displays a low water permeability and absorptivity. It is also improving the acid resistance of the concrete and decreases the chloride penetration. In another study, Khatib *et al.*, (2014) examined that the ‘the properties of the fly ash paste activated by lime and metakaolin, are affected by the metakaolin level and curing time, compared with the paste without metakaolin. Meanwhile, and with the same objective, Kannan and Ganesan (2014) showed similar results. Results of experimental research by Marinos *et al.*, (2015) also point towards improvement in strength and durability of concrete by the partial replacement of cement by metakaolin by mass. Partial replacement of 10% of cement by metakaolin resulted in decreased chloride permeability and increased compressive strength. At a higher level of replacement, chloride penetration further decreased, at the expense of compressive strength. The higher the volume of pozzolanic materials, like metakaolin, in the binder, the higher the carbonation of the micro concrete, due to the low available amount of  $\text{Ca}(\text{OH})_2$  in the matrix.

### **2.5.1 Heat of hydration**

The use of Metakaolin increases the heat evolved during hydration. This has been attributed both to the accelerating effect of Metakaolin on Portland cement hydration

and the high reactivity of Metakaolin with CH. Enhanced temperature rise becomes critical in larger members and slabs, as it may lead to thermal stress cracking. However, in cold weather concreting or where faster set is required, this property can be desirable.

(Frais & Cabrera, 2000) compared FA, silica fume, and MK in terms of heat evolution using a Langavant calorimeter. This semi-adiabatic method, described in the Spanish standard UNE 80 118, measures the heat generated during cement hydration using a thermally isolated Dewar flask. Heat is defined as the temperature difference between the hydrating mortar and an inert mortar (at least three months old). Blended cement pastes contained 10% or 30% SCM and were used to produce mortars with a sand-to-cement ratio of 3:1 and a w/cm of 0.50. The total heat evolved (up to 120h) was found to decrease significantly with increasing FA substitution, increase slightly on substitution with 10% silica fume, and essentially stay the same for increasing levels of MK substitution. However, these authors also measured the temperature rise, or the peak height relative to controls, for these hydrating mortars. FA mortars exhibited a continual reduction in temperature rise with increase in substitution level, silica fume incorporation resulted in a decrease of 1.5-3.0 °C, and MK caused an increase in temperature peak of 6-7 °C. From this, it is clear that reducing the cement content of a mixture will reduce the heat output from cement hydration, but will not necessarily reduce the initial rate of heat evolution or the maximum temperature reached.

Bai and Wild(2002) looked specifically at the effects of FA and MK on heat evolved using embedded thermocouples. Mortar mixtures were placed in 150 mm plywood cube moulds and thermally isolated by encasement in 100 mm thick expanded polystyrene and another layer of plywood. With increasing replacement levels, the temperature rise in FA systems was found to decrease, while the temperature rise in MK systems was

found to increase substantially. Numeric peak temperature values were as follows: 29 °C, 27 °C, and 31 °C for the control, 10% FA, and 10% MK mixtures, respectively.

### **2.5.2 Shrinkage**

Chemical shrinkage is a result of the volume difference between reactants and products in a hydrating cement system. As hydration proceeds, the volume occupied by the products is smaller than that of the reactants. Thus, unless water is supplied from an external source, this volume discrepancy, or chemical shrinkage, will result in the formation of empty pores within the cement paste microstructure. This empty porosity then leads to a reduction in paste internal relative humidity and a measurable autogenous shrinkage of the material (Bentz, 1999). Free, or drying, shrinkage is the contraction that results as a paste, mortar, or concrete loses water to the environment.

Wild *et al.* (1998) studied autogenous and chemical shrinkage of MK-PC pastes for MK contents in the range 5-25%. Both autogenous and chemical shrinkage were found to increase over control pastes, reaching a maximum between 10% and 15% replacement, indicating an optimum in the combined effect of cement hydration and the removal of water from the system due to reaction of the MK at this composition. At higher MK contents, both autogenous and chemical shrinkage were found to decrease sharply. Wild attributed this to the formation of increased amounts of lower density  $C_2ASH_8$  and reduced amounts of higher density  $C_4AH_{13}$  compounds in the presence of greater MK contents, producing an overall volume increase and thus reducing autogenous shrinkage. Similar conclusions were made by Kinuthia *et al.* (2000), who found autogenous shrinkage to increase for 5 and 10% MK but decrease for 15 and 20% replacement, although this effect could also be related to a reduction in PC content.

In terms of free shrinkage alone, Caldarone *et al.* (1994) found that replacement with 10% MK served to reduce shrinkage of concrete by nearly one third after 156 days of drying at 50% relative humidity. This phenomenon could be attributed, in part, to the fact that the reaction of MK consumed more free water in the system, leaving less evaporable water during shrinkage. This supports the conclusion that Concretes have a lower porosity and finer pore structure, which encourages loss of water by self-desiccation rather than by diffusion to the surrounding environment.

Ding and Li (2002) found free shrinkage of concretes containing MK or silica fume to decrease with increasing replacement percentage. Concrete mixtures containing 15% MK experienced 40% less free shrinkage than controls, while 15% silica fume mixtures shrank 33% less than controls. Ding and Li also calculated shrinkage rate, and found that compared with silica fume mixtures at the same replacement level, MKconcretes showed a faster development of shrinkage during the first week of drying and a slower rate after that. Zhang and Malhotra (1995) reported similar findings although they initially shrank fastest, concrete with 10% MK had a lower drying shrinkage rate than control and silica fume concretes beyond one week of age.

### **2.5.3 Compressive strength of concrete**

Shafieyzadeh (2013), define the compressive strength of concrete as its resistance to crushing load applied directly, this implies the maximum compressive load the concrete can carry per unit area. The strength of concrete is influenced by water cement ratio, aggregate cement ratio, grading, surface texture, shape, strength and stiffness of aggregate particles, and maximum size of aggregate. Concrete for cast-in-situ pile shall have an ultimate compressive strength of not less than 20N/mm<sup>2</sup> at the age of 28 days. Tsadoet *al.*(2014) carried out a comparative analysis of properties of some pozzolana concrete. It was observed that there was a decrease in compressive strength for each ash



beyond 20% replacement. Mahmud (2016) performed an experiment on probability-based design approach of concrete mixed with cow bone ash admixed cement. It was also concluded that, higher comprehensive strength was achieved at both 7 and 28 days.

Ding and Li (2002), who examined 5, 10, and 15% replacement with either or silica fume, found that both were effective in increasing strength beyond 14 days. At all ages, MK and silica fume performed similarly, increasing concrete strength to almost the same extent over controls. MK increased strength nearly linearly during the first 28 days of curing and then slowed down 65-day strength was only 6-8% greater than 28-day strength. Li and Ding (2003) further investigated 10% replacement with MK, combining it with PC alone or with both PC and ultra-fine slag. The compressive strength of the mortar mixture containing only MK was always greater than the control mixture, and was approximately 8 MPa greater by 28 days. Further, although initially lower, the MK-slag mixtures showed the highest 28-day strength.

(Qian and Li, 2001) measured both compressive and tensile strength of concretes incorporating MK. Compressive strength was found to increase substantially with increasing MK content. In samples with 15% replacement, compressive strength had increased 51% over controls by three days of age. In fact, the compressive strengths of samples containing 10% and 15% MK were higher at three days than the 28-day control strength, confirming that MK has a pronounced effect on early strength. Courard *et al.* (2003) came to a similar conclusion, reporting that mortars had achieved 79% of their 28-day compressive strength by just three days of age. (Qian & Li, 2001) found that tensile strength also increased systematically with increasing MK content. The average tensile strength increases over controls were as follows: 7% (5% MK), 16% (10% MK), and 28% (15% MK). This was the only study reporting MK's effects on tensile strength.

## 2.6 Mathematical Modelling

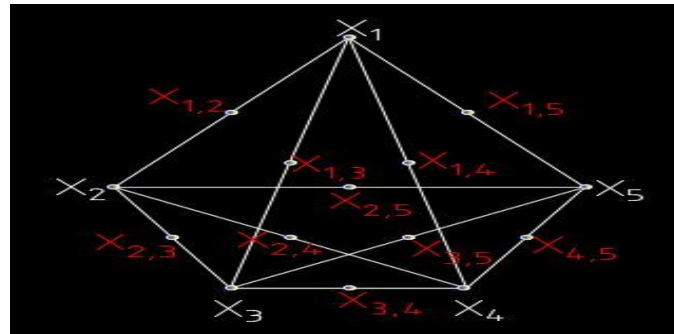
Mathematical modelling is the process of creating a mathematical representation of some phenomenon in order to gain a better understanding of that phenomenon (Osunade, 1994). Lasis and Ogunjimi (1984) described a model as an abstract that uses mathematical language to control the behaviour of a giving system. According to Osadebe (2003), modelling is mathematical equation of dependent variable (Response) and independent variable (Predictor). Manasce *et al.*, (1994) from their studies refers to it as a representation of a system. Simon *et al.*, (1997) stated that the area of application of mathematical modelling includes engineering and natural sciences.

Simon *et al.*, (1997) studies on high performance concrete, which contains many constituents and which are often subjected to several performance constraints can be a difficult and time-consuming task. Different works by Ezeh and Ibearugbulem (2009) and Osadebe (2003) demonstrated the application of mathematical modelling in civil engineering.

Furthermore, several prediction and optimization mathematical polynomials have emerged in the applications of concrete and soil stabilizations to do away with these issues. Of these polynomial regression models, Scheffe (1958) has developed a polynomial equation to be used for optimization to find the optimum content of any factor or materials in additives for experiments with different mixes based on regression theory.

Scheff's (1958) implemented equation for the prediction of UCS for concrete but not in soil property modification. According to study by Mbadike and Osadebe (2013), the equation was used to determine the optimum value of UCS in concrete. In addition to that Onwuka *et al.*, (2011), has used Scheffe's theory to predict the mix ratios for most economical and durable concrete. In another study by Okere *et al.*, (2013), it was

implemented to determine the optimum concrete cost. Gamil and Bakar (2016) have implemented Scheffe's theory to predict Resilient Modulus for mixes used in road construction.



**Plate I:** Scheffe's simplex lattice design

### 2.6.1 Scheffes simplex lattice design

A simplex is a geometric figure with the number of vertices being one more than the variable factor space,  $q$ . It is a projection of  $n$ -dimensional space onto an  $n-1$  dimensional coordinate system. Thus, if  $q$  is 1, the number of vertices is two and the simplex is a straight line; when it is 2, the simplex is a triangle and a tetrahedron when 3. A lattice is an ordered arrangement of points in a regular pattern. Claringbold (1955), first introduced simplex lattice design in his study of joint action on related hormones. Scheffé (1958), however, expanded and generalized the simplex lattice design. His work is often seen as a pioneering work in simplex lattice mixture design. Lattice designs are presently often referred to as Scheffe's simplex lattice designs. It was assumed that each component of the mixture resides on a vertex of a regular simplex-lattice with  $q-1$  factor space. If the degree of the polynomial to be fitted to the design is  $n$ , and the number of components is  $q$ , then the simplex lattice, also called a  $(q,n)$ simplex will consist of uniformly spaced points whose coordinates are defined by

the following combinations of the components: the proportions assumed by each component take the  $n+1$  equally spaced values from 0 to 1, that is;

$$x_i = 0, 1/n, 2/n, \dots, 1 \quad (2.5)$$

Thus, for the quadratic lattice ( $q, n$ ) approximating the response surface with second-degree polynomials, ( $n = 2$ ) the following levels of every factor must be used; 0, 1/2 and 1; for a cubic polynomial, ( $n=3$ ): 0, 1/3 and 1, and for a fourth-degree polynomial

$$(n=4): 0, 1/4, 2/4, 3/4 \text{ and } 1 \quad (2.6)$$

Consider a four-component mixture. The factor space is a tetrahedron. If a second-degree polynomial is to be used to define the factor space's response, then each component ( $X_1, X_2, \dots, X_4$ ) must assume the proportions  $X_i = 0, 1/2$  and 1.

## **CHAPTER THREE**

### **3.0 MATERIALS AND METHOD**

#### **3.1 Materials**

The materials used to achieve the aim of this study include the following;

##### **3.1.1 Kaolin clay**

The kaolin clay was gotten from Kuta and synthesis into Metakaolin (MK) at the material lab, Bosso campus of the Federal University of Technology Minna

##### **3.1.2 Ordinary Portland cement (OPC)**

The Ordinary Portland cement of Dangote brand was obtained from an open Market and conforms to BS 12, (1996).

##### **3.1.3 Coarse aggregates**

The coarse aggregates obtained from a quarry in Maikunkele, Bosso Local Government Area, Niger State, grading of the aggregate was carried out to BS 882, (1992)

##### **3.1.4 Fine aggregates**

The fine aggregates were obtained from a river behind the boy's hostel Gidan Kwano Campus, Federal University of Technology Minna. The grading of the aggregate was carried out to BS 812, (1985)

##### **3.1.5 Potable water**

The potable water used was obtained from the University water mains free from impurities.



**Plate II:** Metakaolin used as Pozzolana

### 3.0 Method

#### 3.2.1 Scheffe's simplex theory

Scheffe's model is based on the simplex lattice and simplex theory or approach (Scheffe, 1958). A lattice is purely an abstract space to achieve the desired strength of concrete. The major factor lies on the adequate proportioning of ingredients needed to make concrete. The simplex approach considers a number of components,  $q$ , and a degree of polynomial,  $m$ . The sum of all the  $i$ th components is not greater than 1. Hence,

$$X_1 + X_2 + \dots + X_{q-1} + X_q = 1 \quad (i.e \ 100\%) \quad (3.1)$$

$$\sum_{i=1}^q x_i = 1 \quad (3.2)$$

with  $0 \leq x \leq 1$ . The factor space becomes  $S_{q-1}$ . According to (Scheffe, 1958), the  $\{q, m\}$  simplex lattice design is a symmetrical arrangement of points within the experimental region in a suitable polynomial equation representing the response surface in the simplex region.

The number of points  $C_m^{(q+m-1)}$  has  $(m+1)$  equally spaced values of  $X_i = 0, \frac{1}{m}, \frac{2}{m}, \dots, \frac{m}{m}$ .

For a 4-component mixture with degree of polynomial 2, the corresponding number of

points with degree of polynomial 2, the corresponding number of points will be  $C_2^{(4+2-1)}$  which gives 10 [Equation (3.3) or Equation (3.4) below] with number of spaced values,  $2+1 = 3$ , that is  $X_i = 0, \frac{1}{2}$ , and 1 as a design points of ( 1, 0, 0,0), (0, 1, 0,0), ( 0, 0, 1,0), (0, 0, 0,1), (1/2, 1/2, 0, 0), (1/2, 0, 1/2, 0), (1/2, 0, 0,1/2), (0, 1/2, 1/2, 0), (0, 1/2, 0, 1/2) and (0, 0, 1/2, 1/2) .

Similarly, for a {5, 2} simplex, there will be 15 points with  $X_i = 0, \frac{1}{2}$  and 1 as spaced value.

The 15 design points are (1,0,0,0,0), (0,1,0,0,0), (0,0,1,0,0), (0,0,0,1,0), (0,0,0,0,1), (1/2,1/2,0,0,0), (1/2,0,1/2,0,0), (1/2,0,0,1/2,0), (1/2,0,0,0,1/2), (0,1/2,1/2,0,0), (0,0,1/2,1/2,0), (0,0,0,1/2,1/2), (0,1/2,0,1/2,0), (0,0,1/2,0,1/2), (0,1/2,0,0,1/2).

$$N = C_m^{(q+m-1)} \quad (3.3)$$

$$N = \frac{(q + m - 1)!}{m! (q - 1)!} \quad (3.4)$$

For a polynomial of degree  $m$  with  $q$  component variables where Equation (3. 2) holds, the general form is:

$$Y = b_0 + \sum b_i x_i + \sum b_{ij} x_i x_j + \sum b_{ijk} x_i x_j x_k + \dots + \sum b_{i_1 i_2 \dots i_n} x_{i_1} x_{i_2} \dots x_{i_n} \quad (3.5)$$

Where  $1 \leq i \leq q$ ,  $1 \leq i \leq j \leq q$ ,  $1 \leq i \leq j \leq k \leq q$ , and  $b_0$  is the constant coefficient.

$x$  is the pseudo component for constituents  $i, j$ , and  $k$ .

When  $\{q, m\} = \{5, 2\}$ , Equation (3.5) becomes:

$$\begin{aligned} Y = & b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_5 x_5 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{14} x_1 x_4 \\ & + b_{15} x_1 x_5 + b_{23} x_2 x_3 + b_{24} x_2 x_4 + b_{25} x_2 x_5 + b_{34} x_3 x_4 + b_{35} x_3 x_5 \\ & + b_{45} x_4 x_5 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{44} x_4^2 \\ & + b_{55} x_5^2 \end{aligned} \quad (3.6)$$

And Equation (3.2) becomes

$$x_1 + x_2 + x_3 + x_4 + x_5 = 1 \quad (3.7)$$

Multiplying Equation (3.7) by  $b_0$  gives

$$b_0x_1 + b_0x_2 + b_0x_3 + b_0x_4 + b_0x_5 = b_0 \quad (3.8)$$

Multiplying Equation (3.7) successively by  $x_1, x_2, x_3, x_4,$  and  $x_5$  and making  $x_1, x_2, x_3, x_4,$  and  $x_5$  the subjects of the respective formulas:

$$\left. \begin{aligned} x_1^2 &= x_1 - x_1x_2 - x_1x_3 - x_1x_4 - x_1x_5 \\ x_2^2 &= x_2 - x_1x_2 - x_2x_3 - x_2x_4 - x_2x_5 \\ x_3^2 &= x_3 - x_1x_3 - x_2x_3 - x_3x_4 - x_3x_5 \\ x_4^2 &= x_4 - x_1x_4 - x_2x_4 - x_3x_4 - x_4x_5 \\ x_5^2 &= x_5 - x_1x_5 - x_2x_5 - x_3x_4 - x_4x_5 \end{aligned} \right\} \quad (3.9)$$

Substituting Equation (3.8) and (3.9) into Equation (3.6) we have:

$$\begin{aligned} Y &= b_0x_1 + b_0x_2 + b_0x_3 + b_0x_4 + b_0x_5 + b_{11}x_1 + b_{22}x_2 + b_{33}x_3 + b_{44}x_4 + b_{55}x_5 \\ &+ b_{12}x_1x_2 + b_{13}x_1x_3 + b_{14}x_1x_4 + b_{15}x_1x_5 + b_{23}x_2x_3 + b_{24}x_2x_4 \\ &+ b_{25}x_2x_5 + b_{34}x_3x_4 + b_{35}x_3x_5 + b_{45}x_4x_5 \\ &+ b_{11} \left( x_1^2 = x_1 - x_1x_2 - x_1x_3 - x_1x_4 - x_1x_5 \right) \\ &+ b_{22} \left( x_2^2 = x_2 - x_1x_2 - x_2x_3 - x_2x_4 - x_2x_5 \right) \\ &+ b_{33} \left( x_3^2 = x_3 - x_1x_3 - x_2x_3 - x_3x_4 - x_3x_5 \right) \\ &+ b_{44} \left( x_4^2 = x_4 - x_1x_4 - x_2x_4 - x_3x_4 - x_4x_5 \right) \\ &+ b_{55} \left( x_5^2 = x_5 - x_1x_5 - x_2x_5 - x_3x_4 - x_4x_5 \right) \end{aligned}$$



$$\begin{aligned}
Y = & (b_0 + b_1 + b_{11}) x_1 + (b_0 + b_2 + b_{22}) x_2 + (b_0 + b_3 + b_{33}) x_3 + (b_0 + b_4 \\
& + b_{44}) x_4 + (b_0 + b_5 + b_{55}) x_5 + (b_{12} - b_{11} - b_{12}) x_1 x_2 + (b_{13} \\
& - b_{11} - b_{33}) x_1 x_3 + (b_{14} - b_{11} - b_{44}) x_1 x_4 + (b_{15} - b_{11} \\
& - b_{55}) x_1 x_5 + (b_{23} - b_{22} - b_{33}) x_2 x_3 + (b_{24} - b_{22} - b_{44}) x_2 x_4 \\
& + (b_{25} - b_{22} - b_{55}) x_2 x_5 + (b_{34} - b_{33} - b_{44}) x_3 x_4 + (b_{35} - b_{33} \\
& - b_{55}) x_3 x_5 + (b_{45} - b_{44} \\
& - b_{55}) x_4 x_5
\end{aligned} \tag{3.10}$$

Let

$$\begin{aligned}
\beta_1 &= b_0 + b_1 + b_{11} \\
\beta_2 &= b_0 + b_2 + b_{22} \\
\beta_3 &= b_0 + b_3 + b_{33} \\
\beta_4 &= b_0 + b_4 + b_{44} \\
\beta_5 &= b_0 + b_5 + b_{55} \\
\beta_{12} &= b_{12} - b_{11} - b_{22} \\
\beta_{13} &= b_{13} - b_{11} - b_{33} \\
\beta_{14} &= b_{14} - b_{11} - b_{44} \\
\beta_{15} &= b_{15} - b_{11} - b_{55} \\
\beta_{23} &= b_{23} - b_{22} - b_{33} \\
\beta_{24} &= b_{24} - b_{22} - b_{44} \\
\beta_{25} &= b_{25} - b_{22} - b_{55} \\
\beta_{34} &= b_{34} - b_{33} - b_{44} \\
\beta_{35} &= b_{35} - b_{33} - b_{55} \\
\beta_{45} &= b_{45} - b_{44} - b_{55}
\end{aligned} \tag{3.11}$$

Substituting Equation (3.11) into Equation(3.10) gives

$Y$

$$\begin{aligned}
 &= \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{14} x_1 x_4 \\
 &+ \beta_{15} x_1 x_5 + \beta_{23} x_2 x_3 + \beta_{24} x_2 x_4 + \beta_{25} x_2 x_5 + \beta_{34} x_3 x_4 \\
 &+ \beta_{35} x_3 x_5 + \beta_{45} x_4 x_5
 \end{aligned} \tag{3.12}$$

$$Y = \sum_{i=1}^s \beta_i x_i + \sum_{1 \leq i < j \leq 5} \beta_{ij} x_i x_j \tag{3.13}$$

Where the response,  $Y$  is a dependent variable (compressive strength of concrete). Equation (3.12) is the general equation for a  $\{5, 2\}$  polynomial, and it has 15 terms, which conforms to Scheffe's theory in Equation (3.3)

Let  $Y_i$  denote response to pure components, and  $Y_{ij}$  denote response to mixture components in  $i$  and  $j$ . If  $x_i=1$  and  $x_j=0$ , since  $j \neq i$ , then.

$$Y_i = \beta_i \tag{3.14}$$

This means that;

$$\sum_{i=1}^s \beta_i x_i = \sum_{i=1}^s Y_i x_i \tag{3.15}$$

Hence, from Equation (3.14)

$$\left. \begin{aligned}
 Y_1 &= \beta_1 \\
 Y_2 &= \beta_2 \\
 Y_3 &= \beta_3 \\
 Y_4 &= \beta_4 \\
 Y_5 &= \beta_5
 \end{aligned} \right\} \tag{3.16}$$

According to Scheffe (1958),

$$\beta_{ij} = 4Y_{ij} - 2\beta_i - 2\beta_j \tag{3.17}$$

Substituting Equation(3.14) into Equation (3.17)

$$\beta_{ij} = 4Y_{ij} - 2 Y_i - 2 Y_j \quad (3.18)$$

### 3.2.2 Concrete mix design

The Department of Environment (DoE, 1988)mix design will be adopted for the preparation of the concrete due to its versatility and applications in different concrete structures such as buildings, roads and bridges.

#### a. Collected data

Grade Designation = M30 (specified characteristic strength)

Type of Cement = OPC – 43 grades

Specific Gravity of Cement = 3.15

Specific Gravity of Fine Aggregate = 2.61

Specific Gravity of Coarse Aggregate = 2.65

#### b. Target mean strength

Target mean strength = specified characteristic strength + standard deviation x risk factor.

Allow 5% risk factor

$$f_m = 30 + 1.64 \times 5.0$$

$$f_m = 38.20\text{Mpa} \quad (3.20)$$

#### c. Water/cement ratio

Using Table 2 (Approximate Compressive strength of concrete made with a free water/cement ratio) and Figure 4 according to The Department of Environment (DoE, 1988), the water/cement ratio for mean strength of 38Mpa is 0.58. Checking the W/C ratio from durability consideration from table 9.20 (Requirements of BS-8110.1997:

Ensure Durability under Specified Exposure Conditions of Reinforced and Pre-stressed Concrete made with Normal Weight Aggregate) the maximum W/C ratio permitted is 0.50. Adopt the lower of the two, therefore adopt W/C ratio of 0.50.

**d. Calculation of water content**

From Table 3 (Approximate Free Water Contents required to give Various Levels of workability), according to (DoE, 1988), for coarse (crushed) aggregate of 20mm maximum size and assumed slump of 75mm, the water demand for fine aggregate is 195 litres and 225 litres for coarse aggregate.

$$\text{Water Content} = \frac{2}{3} \times W_f + \frac{1}{3} \times W_{ca} \quad 3.21$$

$W_f$  = Water demand for natural fine aggregate = 195l

$W_{ca}$  = Water demand for crushed coarse 20mm aggregate = 225l

$$\begin{aligned} \text{Water Content} &= \frac{2}{3} \times 195 + \frac{1}{3} \times 225 \\ &= 205 \text{ kg/m}^3 \end{aligned}$$

**e. Cement content**

$$\text{Cement Content} = \frac{205}{0.50}$$

$$\text{Cement Content} = 410.0 \text{ kg/m}^3$$

*This is more than 350 kg (As per table No. 9.2 of BS 8110: part I: 1985). Hence ok.*

**f. Weight of total aggregate**

From Figure 5 (Approximate water content and specific gravity of aggregate), according to (DoE, 1988), for a water content of 205 kg/m<sup>3</sup>, 20mm crushed aggregate of specific gravity 2.65, the total weight density is 2405kg/m<sup>3</sup>.

Weight of Total Aggregate = Total wet density – (Weight of cement + Weight of free water) (3.22)

$$\text{Weight of Total Aggregate} = 2405 - (410 + 205) = 1790 \text{ kg/m}^3$$

**g. Weight of fine aggregate**

i. The proportion of fine aggregate is determined in the total aggregate is determined in the total aggregate using Figure 6 (a) is for 10mm size, Figure 6(b) is for 20mm size and Figure 6 (c) is for 40mm size coarse aggregate, according to the (DoE, 1988).

ii. For 20mm aggregate size, W/C ratio of 0.50, Slump of 75mm for 60% fines passing through 600µ sieve, the percentage of

$$\% \text{ Fine Aggregate} = 41 \%$$

$$\text{Weight of Fine Aggregate} = 1790 \times \frac{37}{100} = 662.3 \text{ kg/m}^3$$

$$\begin{aligned} \text{Weight of Coarse Aggregate} &= 1790 \times \frac{63}{100} \\ &= 1127.7 \text{ kg/m}^3 \end{aligned}$$

**h. Proportions**

**Table 3.1:** Mix proportions

<b>Ingredients</b>	<b>Water</b>	<b>Cement</b>	<b>Fine Aggregate</b>	<b>Coarse Aggregate</b>
Quantity ( $\text{kgm}^3$ )	205.0	410.0	662.3	1127.7
Ratio	0.50	1	1.62	2.75
1 Bag of Cement	25.0	50.0	81.0	137.5

**i Adjustment for field condition**

1. The proportions are required to be adjusted for the field conditions. Field Aggregate has surface moisture of 2%.

$$\begin{aligned} \text{Weight of Fine Aggregate} &= 662.3 + \frac{2}{100}(721.6) = 675.55 \\ &\cong 676.00\text{kg m}^3 \end{aligned}$$

2. Coarse Aggregate absorbs 1% water

$$\begin{aligned} \text{Weight of Coarse Aggregate} &= 1127.7 - \frac{1}{100}(1038.4) \\ &\cong 1139.00\text{kg m}^3 \end{aligned}$$

**j. Final design proportions**

**Table 3.2:** Final design mix proportions

<b>Ingredients</b>	<b>Water</b>	<b>Cement</b>	<b>Fine Aggregate</b>	<b>Coarse Aggregate</b>
Quantity ( $\text{kg m}^3$ )	205.0	410.0	676.0	1139.0
Ratio	0.50	1	1.65	2.78
1 Bag of Cement	25.0	50.0	82.5	139

Steps g to j is repeated for four other mix proportions and cement replaced with Rice Metakaolin (MK) from 0 to 20% respectively. The following results were obtained:

Where, SP = Sample points; MK = Metakaolin; FA = Fine aggregates, CA = Coarse aggregates.

**Table 3.3:** Mix design ratios for a (5, 2) component system

SP	Water	Cement	MK	FA	CA
1	0.50	1.00	0	1.65	2.78
2	0.48	0.95	0.05	1.54	2.64
3	0.46	0.90	0.10	1.46	2.50
4	0.52	0.85	0.15	1.69	2.91
5	0.54	0.8	0.20	1.77	3.05

### 3.3 Simplex Lattice Design Formulation for (5, 2) System

Scheffe's model can be adapted to represent a five-component concrete mix containing Water, Cement, Metakaolin (MK), Fine aggregate and Coarse aggregate, by the pentahedron simplex matrix shown in Figure 3.2. The modal coordinates are the pseudo components of the matrix (Scheffe, 1958).

#### 3.3.1 Simplex lattice method

In mathematical terms, a simplex lattice is a space of constituents' variables of  $x_1, x_2, x_3, \dots$  and  $x_i$  which obeys Equation (3.1). Lattice is an abstract space to achieve the desired strength of concrete, the essential factors lie on the adequate proportioning of ingredients needed to make the concrete. A polynomial of degree  $n$  in  $q$  variables has  $C_{q+n}^n$  coefficients. If a mixture has a total of  $q$  the components and  $x_i$  be the proportion of the  $i^{\text{th}}$  component in the mixture, (Equation 3.2).

#### 3.3.2 Actual and pseudo components

The requirements of the simplex are in line Equation (3.1) which makes it impossible to use the normal mix ratios such as 1:3, 1:5, at a given water/cement ratio. Hence a transformation of the actual components (Ingredients Proportions) to meet the above criterion is unavoidable. Such transformed ratios say  $x_1^1, x_2^1, \text{ and } x_3^1$ . For the  $i^{\text{th}}$

experimental point, the transformation computations are to be done by some multiplicative operations between the pseudo and the initially arbitrarily assumed actual variables.

The relationship between the actual components and the pseudo components is expressed by (Scheffe, 1958):

$$[S] = [A][X] \quad (3.23)$$

Where S, A and X, represent the actual mix ratios, coefficient of relation matrix, and pseudo mix ratios respectively. S and X are five component vectors and A is 5 x 5 matrix of coefficients. The value of matrix A was obtained from the first five mix ratios comprising the designed and modified mix ratios, (see Table 3.3).

In order to satisfy the requirement of a 5, 2 Scheffe's model, the following five mix ratios of Water: Cement: RHA: FA: CA were generated from a five-mix design in 3.3.2:

$$\begin{aligned} A_1 &= [0.50, 1.00, 0.00, 1.65, 2.78] \\ A_2 &= [0.48, 0.95, 0.05, 1.54, 2.64] \\ A_3 &= [0.46, 0.90, 0.10, 1.46, 2.50] \\ A_4 &= [0.52, 0.85, 0.15, 1.69, 2.91] \\ A_5 &= [0.54, 0.80, 0.20, 1.77, 3.05] \end{aligned} \quad (3.24)$$

The corresponding pseudo components are:

$$\begin{aligned} X_1 &= [1, 0, 0, 0, 0] \\ X_2 &= [0, 1, 0, 0, 0] \\ X_3 &= [0, 0, 1, 0, 0] \\ X_4 &= [0, 0, 0, 1, 0] \\ X_5 &= [0, 0, 0, 0, 1] \end{aligned} \quad (3.25)$$



Substituting  $X_i$  and  $S_i$  into equation 3.23 and transposing the values of A matrix were obtained as

$$[S] = \begin{bmatrix} 0.50 & 0.48 & 0.46 & 0.52 & 0.54 \\ 1.00 & 0.95 & 0.90 & 0.85 & 0.80 \\ 0.00 & 0.05 & 0.10 & 0.15 & 0.20 \\ 1.65 & 1.54 & 1.46 & 1.69 & 1.77 \\ 2.78 & 2.64 & 2.50 & 2.91 & 3.05 \end{bmatrix} \quad (3.26)$$

With the binary points or centre points

$$\begin{aligned} X_{12} &= [0.5, 0.5, 0, 0, 0] \\ X_{13} &= [0.5, 0, 0.5, 0, 0] \\ X_{14} &= [0.5, 0, 0, 0.5, 0] \\ X_{15} &= [0.5, 0, 0, 0, 0.5] \\ X_{23} &= [0, 0.5, 0.5, 0, 0] \\ X_{24} &= [0, 0.5, 0, 0.5, 0] \\ X_{25} &= [0, 0.5, 0, 0, 0.5] \\ X_{34} &= [0, 0, 0.5, 0.5, 0] \\ X_{35} &= [0, 0, 0.5, 0, 0.5] \\ X_{45} &= [0, 0, 0, 0.5, 0.5] \end{aligned} \quad (3.27)$$

According to Scheffe (1958),

$$S_{ij} = XS_i \quad (3.28)$$

Substituting,

$$\begin{bmatrix} S_{12} \\ S_{13} \\ S_{14} \\ S_{15} \\ S_{23} \end{bmatrix} = \begin{bmatrix} 0.5 & 0.5 & 0.0 & 0.0 & 0.0 \\ 0.5 & 0.0 & 0.5 & 0.0 & 0.0 \\ 0.5 & 0.0 & 0.0 & 0.5 & 0.0 \\ 0.5 & 0.0 & 0.0 & 0.0 & 0.5 \\ 0.0 & 0.5 & 0.5 & 0.0 & 0.0 \end{bmatrix} \begin{bmatrix} 0.50 \\ 0.48 \\ 0.46 \\ 0.52 \\ 0.54 \end{bmatrix} \quad (3.29)$$

This process is repeated for  $S_{24}$ ,  $S_{25}$ ,  $S_{34}$ ,  $S_{35}$  and  $S_{45}$ . Similarly, this process is repeated for an additional 15 control points that will be used for the verification of the formulated model.

**Table 3.4:** Actual and pseudo mix ratios of the model

S	Actual Components					Resp. ( $Y_{exp}$ )	Pseudo Components				
	W	C	MK	FA	CA		$X_1$	$X_2$	$X_3$	$X_4$	$X_5$
$N_1$	0.50	1.00	0	1.65	2.78	$Y_1$	1	0	0	0	0
$N_2$	0.48	0.95	0.05	1.54	2.64	$Y_2$	0	1	0	0	0
$N_3$	0.46	0.90	0.10	1.46	2.50	$Y_3$	0	0	1	0	0
$N_4$	0.52	0.85	0.15	1.69	2.91	$Y_4$	0	0	0	1	0
$N_5$	0.54	0.80	0.20	1.77	3.05	$Y_5$	0	0	0	0	1
$N_{12}$	0.49	0.975	0.025	1.595	2.71	$Y_{12}$	0.5	0.5	0	0	0
$N_{13}$	0.48	0.950	0.05	1.555	2.64	$Y_{13}$	0.5	0	0.5	0	0
$N_{14}$	0.51	0.925	0.070	1.67	2.845	$Y_{14}$	0.5	0	0	0.5	0
$N_{15}$	0.52	0.90	0.10	1.70	2.915	$Y_{15}$	0.5	0	0	0	0.5
$N_{23}$	0.47	0.925	0.075	1.50	2.57	$Y_{23}$	0	0.5	0.5	0	0
$N_{24}$	0.50	0.90	0.1	1.615	2.775	$Y_{24}$	0	0.5	0	0.5	0
$N_{25}$	0.51	0.875	0.125	1.655	2.845	$Y_{25}$	0	0.5	0	0	0.5
$N_{34}$	0.49	0.875	0.125	1.575	2.705	$Y_{34}$	0	0	0.5	0.5	0
$N_{35}$	0.50	0.850	0.15	1.615	2.775	$Y_{35}$	0	0	0.5	0	0.5
$N_{45}$	0.53	0.825	0.175	1.73	2.98	$Y_{45}$	0	0	0	0.5	0.5

**Table 3.5:** Actual and pseudo mix ratios of control observation points

S	Actual Components					Resp. (Y <sub>exp</sub> )	Pseudo Components				
	W	C	MK	FA	CA		X <sub>1</sub>	X <sub>2</sub>	X <sub>3</sub>	X <sub>4</sub>	X <sub>5</sub>
C <sub>1</sub>	0.514	0.895	0.105	1.678	2.871	Y <sub>1</sub>	0.3	0	0	0.7	0
C <sub>2</sub>	0.478	0.945	0.055	1.538	2.626	Y <sub>2</sub>	0.2	0.5	0.3	0	0
C <sub>3</sub>	0.476	0.940	0.06	1.536	2.612	Y <sub>3</sub>	0.4	0	0.6	0	0
C <sub>4</sub>	0.50	0.90	0.10	1.622	2.776	Y <sub>4</sub>	0.2	0.2	0.2	0.2	0.2
C <sub>5</sub>	0.49	0.935	0.065	1.587	2.708	Y <sub>5</sub>	0.3	0.3	0.2	0.2	0
C <sub>12</sub>	0.488	0.970	0.03	1.584	2.696	Y <sub>12</sub>	0.4	0.6	0	0	0
C <sub>13</sub>	0.486	0.915	0.085	1.565	2.68	Y <sub>13</sub>	0.1	0.4	0.3	0.1	0.1
C <sub>14</sub>	0.472	0.93	0.070	1.517	2.584	Y <sub>14</sub>	0.3	0	0.7	0	0
C <sub>15</sub>	0.464	0.91	0.09	1.476	2.528	Y <sub>15</sub>	0	0.2	0.8	0	0
C <sub>23</sub>	0.504	0.92	0.08	1.642	2.805	Y <sub>23</sub>	0.3	0.4	0	0	0.3
C <sub>24</sub>	0.496	0.99	0.01	1.631	2.752	Y <sub>24</sub>	0.9	0	0.1	0	0
C <sub>25</sub>	0.49	0.905	0.095	1.577	2.707	Y <sub>25</sub>	0	0.5	0.2	0.2	0.1
C <sub>34</sub>	0.496	0.97	0.03	1.624	2.751	Y <sub>34</sub>	0.7	0.1	0.1	0.1	0
C <sub>35</sub>	0.508	0.94	0.06	1.666	2.832	Y <sub>35</sub>	0.6	0	0	0.4	0
C <sub>45</sub>	0.496	0.91	0.09	1.61	2.749	Y <sub>45</sub>	0.3	0.1	0.3	0.1	0.2

### 3.4 Determination of the Physical Properties of Aggregates

The test carried out to determine the physical properties include;

#### 3.4.1 Sieve analysis test

These talks of fraction consisting particles of the same shape. In normal practice, each of these fractions consists of particles between the openings of the standard test sieves. The test sieves normally used for aggregates have square openings and usually described by the size of the openings in millimetre (mm). Coarser test sieves (4.0mm and larger) are made with wire cloth. It has a screening which varies between 34-53% of the gross area of the sieve.

Sieve analysis in simple terms can be defined as the process of partitioning aggregates sample into fractions of the same particle sizes. It is used to determine the grinding effect of the aggregate.

### ***Test Procedures***

Coarse aggregates are aggregates retained at the 12mm BS Sieve. For the purpose of this research work, the coarse aggregates to be used are granite. Fine aggregates are aggregates mainly passing the 4.75mm sieve. Sharp sand is the fine aggregate used here.

The sieve was thoroughly cleaned and weighed on an electronic weighing balance; the set of sieves were arranged in descending order according to their sizes from a maximum mesh opening to the minimum opening with a pan at the bottom. The sample was poured gradually into the topmost sieve of the set of the sieves. The set of sieves with the sample were shaken manually due to the absence of the mechanical shaker in the lab. The sieve was then removed from the shake and weighed. The weight of the samples retained on them after it was shaken was determined by subtracting the weight of sieves from the weight of sieve plus sample retained on the sieve.

$$\text{Coefficient of Uniformity } (C_u) = \frac{D_{60}}{D_{10}} \quad (3.30)$$

$$\text{Coefficient Curvature } (C_c) = \frac{(D_{30})^2}{(D_{10})(D_{60})} \quad (3.31)$$

### **3.4.2 Bulk density test**

This is defined as the weight of the aggregates needed to fill a given space of a given unit volume where the aggregates are said to be fully packed according to volume. Bulk density of a material depends on the packing of the material. The material can either be

loosely packed or well compacted. This test is being carried out to know the degree of void that an aggregate will have.

***Test Procedures for Compacted Bulk Density***

- a) Measure the volume of the mould
- b) Fill the mould to about one-third with the sample and tamp it for 25 times using the tamping rod.
- c) Again, add one third of the sample and tamp it again with the tamping rod for 25 times.
- d) Fill the mould with the sample for the final time and tamp it for another 25 times.
- e) Use the tamping rod as a straight edge to remove the surplus aggregates.
- f) Measure the weight of the material and record it as 'W' in Kg.
- g) Determine the bulk density by

$$\text{Bulk Density} = \frac{\text{Weight of material}}{\text{Volume of mould}} \quad (3.32)$$

***Test Procedures for Uncompacted Bulk Density***

- a) Measure the volume of the mould.
- b) Fill the mould with the sample to overflowing by means of a scoop.
- c) Level top surface of the aggregate.
- d) Measure the aggregate weight and record as 'W' in Kg.

**3.4.3 Specific gravity test**

According to the BS standard provided; the ratio of the mass of the material, to the mass of the same volume of free distilled water at a taken stated temperature is defined as

specific gravity. The objective of carrying out this test is so as to determine specific gravities of both the fine and coarse aggregates been specified.

***Test Procedures for Uncompacted Bulk Density***

- a) An empty cylinder was weighed and mass recorded.
- b) Aggregates were introduced into the cylinder, weighed and mass recorded.
- c) The cylinder in (2) above is then filled with water to gauge level, weighed and mass recorded.
- d) The cylinder was then emptied, filled with water to gauge level, weighed and mass recorded.
- e) The procedures were repeated for two more tests.

$$\text{Specific Gravity} = \frac{W_2 - W_1}{(W_4 - W_1) - (W_3 - W_2)} \quad (3.33)$$

Where;

$W_1$  = Weight of empty cylinder

$W_2$  = Weight of empty cylinder + sample

$W_3$  = Weight of empty cylinder + sample + water

$W_4$  = Weight of empty cylinder + water

**3.4.4 Water absorption test**

Water absorption test is used in determining the amount of water absorbed by a material under specified conditions. The factors that affect water absorption include additives used, type of plastics, length and temperature of exposure.

***Test Procedures for Water Absorption***

- a) The sample is dried in the oven for a specific period of time (24 hours) and then placed in the desiccator to cool

- b) After cooling the sample is then weighed.
- c) The material is merged in water at a particular condition often 23<sup>0</sup>C for 24 hours. The specimen is then removed, patted dry and the weighed.

$$\text{Water Absorption} = \frac{\text{Wet weight} - \text{Dry weight}}{\text{Dry weight}} \times 100 \quad (3.34)$$

### 3.4.5 Aggregate impact value (AIV) test

This test is carried out so as to evaluate the resistance of a material to mechanical degradation. Degradation may take place if the aggregate is weak and this leads to a change in grading, or production of excessive, and undesired fines.

#### *Test Procedures for AIV*

- a) The material used is the aggregate passing through the 28mm sieve and retained on the 20mm sieve. The mould is then cleaned.
- b) Place sample in the mould, and compact by a single tamping of 25 strokes.
- c) Subject the sample to 15 blows of the hammer dropping each being delivered at an interval not less than a second.
- d) The aggregate crushed is then sieved using the 2.36mm sieve. The portion passing through the 2.36mm sieve is then weighed.

$$\text{Aggregate Impact Value} = \frac{\text{Mass Passing 2.36mm}}{\text{Initial mass of dried sample}} \times 100 \quad (3.35)$$

### 3.5 Compressive Strength of Concrete

Three replicate concrete cubes were made for each of the thirty mix ratios using 150 x 150 x 150mm moulds. The cubes were removed after 24 hours from the mould and were soaked in water to cure for 28 days. The cubes were removed on the 28<sup>th</sup> day and

subjected to crushing with the help of a uniaxial compressive strength machine. The compressive strength was determined with Equation (3.36).

$$F_c = \frac{P}{A} \quad (3.36)$$

Where;

$F_c$  = compressive strength of concrete

P = the applied compressive load at failure (KN)

A = the cross-sectional area of the specimen ( $\text{mm}^2$ )



**Plate III:** Concrete cubes after casting



**Plate IV:** Concrete cubes after curing





**Plate V:** Crushing of concrete cubes

## CHAPTER FOUR

### 4.0

### RESULTS AND DISCUSSION

#### 4.1 Sieve Analysis

The sieve analysis results for the fine and coarse aggregates are presented in Table A1 and A2 in Appendix A.

Percentage gravel (%) = 0.04

Percentage sand (%) = 95.06

Percentage fines (%) = 4.88

Diameter passing @ sieve size 60 (D60) = 0.56

Diameter passing @ sieve size 30 (D30) = 0.27

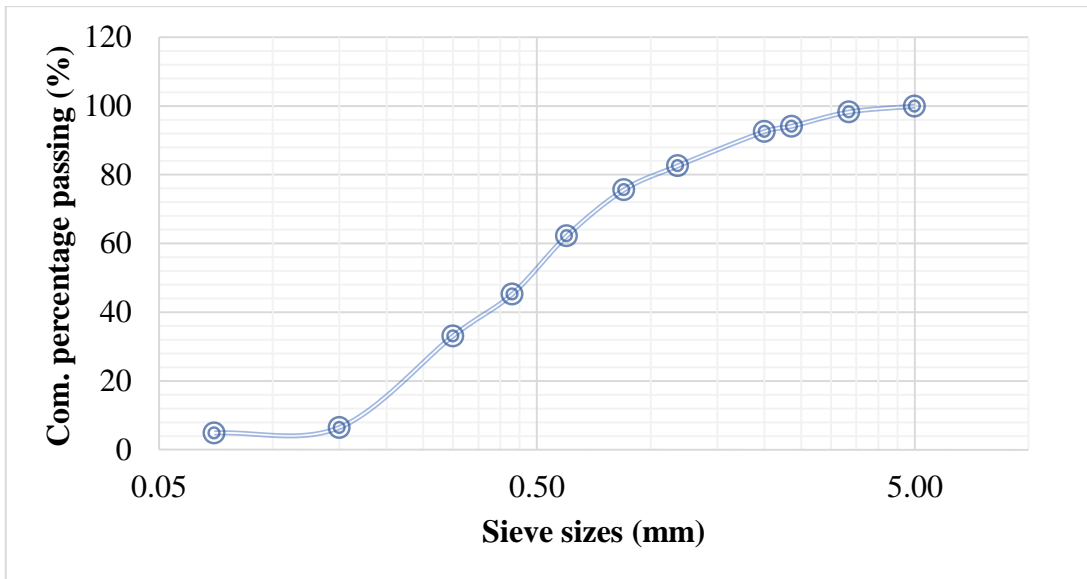
Diameter passing @ sieve size 10 (D10) = 0.17

Coefficient of uniformity (Cu) = 3.29

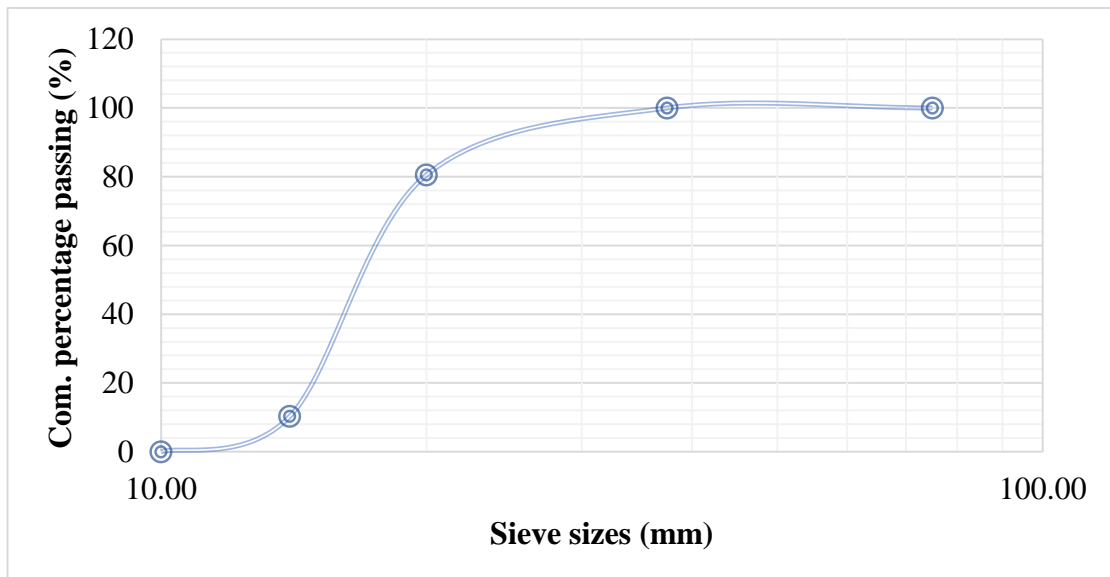
Coefficient of curvature (Cc) = 0.76

Fineness Modulus Fm for fine aggregates = 2.216

From particle distribution curve, the fine aggregate is well-graded



**Figure 4.1:** Sieve analysis curve for fine aggregates



**Figure 4.2:** Sieve analysis curve for coarse aggregates

#### 4.2 Water Absorption

#### 4.3 Specific Gravity

#### 4.4 Bulk Density

##### Bulk Density for Fine Aggregate

Volume of Mould= 3258.9cm<sup>3</sup>

Weight of Sand=2661.3g

Bulk Density= 0.82g/cm<sup>3</sup>

### **Bulk Density for Coarse Aggregate**

Volume of Mould= 3258.9cm<sup>3</sup>

Weight of Sand=2709.3g

Bulk Density= 0.83g/cm<sup>3</sup>

### **4.5 Aggregates Impact Value (AIV)**

### **4.6 Compressive strength**

The compressive strength test result for the thirty-mix ratios is presented inTable C1, C2, C3 and C4 in Appendix C.

### **4.7 Scheffe's model for 28 days compressive strength**

The coefficients of polynomials from Table C1, Equation (3.16) and Equation (3.18) are:

$$\beta_1 = 29.51, \quad \beta_2 = 32.66, \quad \beta_3 = 33.39, \quad \beta_4 = 32.11, \quad \beta_5 = 31.40$$

Recall from equation 3.18 that,  $\beta_{ij} = 4 Y_{ij} - 2 Y_i - 2 Y_j$

$$\beta_{12} = 4 Y_{12} - 2 Y_1 - 2 Y_2$$

$$\beta_{12} = 4(30.6) - 2(29.51) - 2(32.66) = -1.94$$

Similarly,  $\beta_{13} = -1.4$ ,  $\beta_{14} = -15.84$ ,  $\beta_{15} = 6.1$ ,  $\beta_{23} = -19.3$ ,  $\beta_{24} = 0.74$ ,

$$\beta_{25} = 1.72, \quad \beta_{34} = 3.84, \quad \beta_{35} = 1.62, \quad \beta_{24} = 4.94$$

Substituting the above coefficients into equation(3.12)

$$\begin{aligned} Y = & 29.51x_1 + 32.66x_2 + 33.99x_3 + 32.11x_4 + 31.40x_5 - 1.94x_1 x_2 - 1.4x_1 x_3 \\ & - 15.84x_1 x_4 + 6.1x_1 x_5 - 19.3x_2 x_3 + 0.74x_2 x_4 + 1.72x_2 x_5 \\ & + 3.84x_3 x_4 + 1.62x_3 x_5 + 4.94x_4 x_5 \quad (4.1) \end{aligned}$$

Equation (4.1) above is the mathematical model to predict the 28 days compressive strength of concrete using MK to replace 0-20% of cement.

The predicted compressive strength is gotten when the Pseudo points from table 3.4 are substituted into Equation (4.1).

#### 4.8 Test of Adequacy of the model

To do the test of adequacy of the model, the Fischer test (Fischer, 1938) at 95% of confidence level is applied on the compressive strength of control points was used. Two hypotheses were formulated.

##### a. Null hypothesis

This is when there is no significant difference between the laboratory compressive strength and the predicted compressive strength of the concrete cubes

##### b. Alternative hypothesis

There is a significant difference between the laboratory compressive strength and the predicted compressive strength of the concrete cubes.

The test was carried out as shown in the appendix Table D1.

#### Note:

$Y_{exp}$  = Experimental Compressive strength from Laboratory

$Y_{pred}$  = Predicted Compressive strength from the model

$$\bar{Y}_{exp} (\text{Mean}) = \frac{\sum Y_{exp}}{N} = \frac{439.59}{15} = 29.31$$

$$\bar{Y}_{pred} (\text{Mean}) = \frac{\sum Y_{pred}}{N} = \frac{454.28}{15} = 30.29$$

$$S_{exp}^2 = \frac{\sum (y_{exp} - \bar{y}_{exp})^2}{N - 1} = \frac{22.71}{14} = 1.62$$

$$S_{pred}^2 = \frac{\sum (y_{pred} - \bar{y}_{pred})^2}{N - 1} = \frac{33.10}{14} = 2.36$$

$$F_{calculated} = \frac{S_1^2}{S_2^2}$$

Where  $S_1^2$  is the greater of  $S_{exp}^2$  and  $S_{pred}^2$  and  $S_2^2$  is the smaller of the two.

Hence,  $S_1^2 = S_{pred}^2 = 2.36$  and  $S_2^2 = S_{exp}^2 = 1.62$

$$F_{calculated} = \frac{2.36}{1.62} = 1.46$$

The model is acceptable at 95% confidence level if

$$\frac{1}{F_{\alpha}(V_1, V_2)} < \frac{S_1^2}{S_2^2} < F_{\alpha}(V_1, V_2)$$

Where, significant level,  $\alpha = 1 - 0.95 = 0.05$

Degree of freedom,

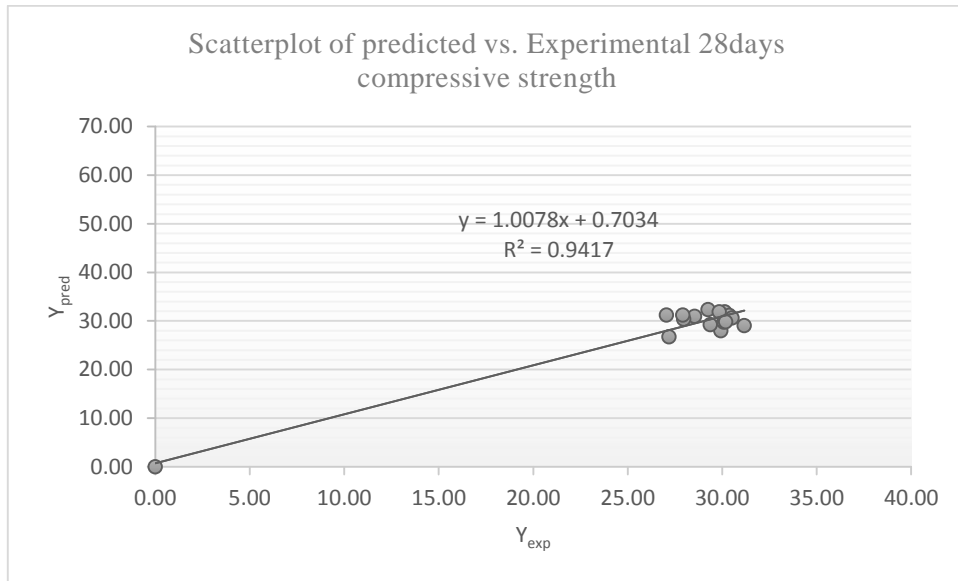
$$V_1 = V_2 = N - 1 = 15 - 1 = 14$$

From Standard F-statistic table,  $F_{\alpha}(V_1, V_2) = 2.48$  and  $\frac{1}{F_{\alpha}(V_1, V_2)} = \frac{1}{2.48} = 0.4032$

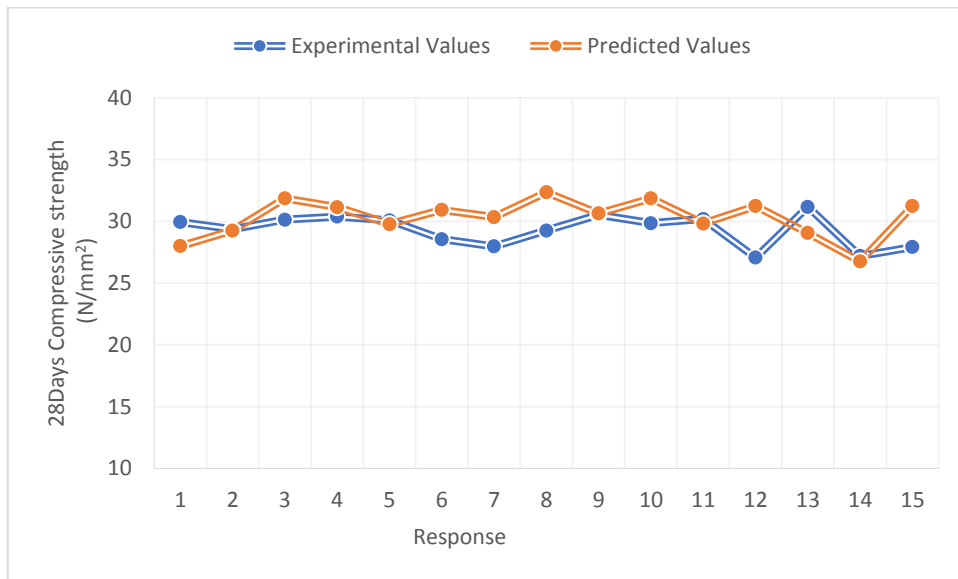
Hence, the condition  $\frac{1}{F_{\alpha}(V_1, V_2)} < \frac{S_1^2}{S_2^2} < F_{\alpha}(14, 14) = 0.40 < 1.46 < 2.48$  is satisfied.

Therefore, the null hypothesis which says there is no significant difference between the experimental results and the model expected result is acceptable. This means that the compressive strength model equation for 28 days is adequate for the prediction of compressive strength of concrete containing water, cement, Metakaolin, fine aggregates (sharp sand) and coarse aggregate (granite).

## 4.9 Discussion of results



**Figure 4.3:** Scatter plot of predicted vs. Experimental 28days compressive Strength



**Figure 4.4:** Comparison between Experimental and predicted 28 days compressive strength

Replacement of cement with Metakaolin from 0 to 20% shows a general increase in the strength of the 28 days compressive strength. This has resulted in an acceptable experimental compressive strength (between 27.06 to 31.17  $N/mm^2$ ). With concrete mix ratios resulting from 15 different design mix.

A regression model has been generated from the resulting laboratory experiments using Scheffe's simplex theory. A F-Statistical test (Fisher) was carried out, which confirmed the adequacy of the derived model and the null hypothesis says there is no significant difference between the experimental results and the model expected results. A scatter plot of predicted against experimental 28 days compressive strengths was plotted and the  $R^2$  value of 0.9417 shows that the predicted values is close to the experimental value and hence the model is adequate to predict the 28 days compressive strength for 0 to 20% partial replacement of cement with Metakaolin.



## CHAPTER FIVE

### 5.0 CONCLUSION AND RECOMMENDATIONS

#### 5.1 Conclusion

Results of this research work have been collected within the limits of experimental accuracy, upon which various deductions have been made, these deductions include;

The compressive strength of concrete increases on the progressive replacement of cement with Metakaolin (MK)

Using Scheffe's (5, 2) polynomial equation, mix design mathematical model for a five component MK blended cement concrete was developed. The model could predict the compressive strength of MK blended concrete when the mix ratios are known and vice versa.

The predictions from the model were tested at 95% accuracy level using statistical Fisher test and found to be adequate. The maximum strength predicted by this model was 33.71 N/mm<sup>2</sup> derived from a mix ratio of 0.490:0.875:0.125:1.575:2.705 for Water: Cement: MK: FA (Sharp sand): CA (Granite) respectively.

#### 5.2 Recommendations

From the results obtained in this research, with the conclusion made on the model developed,

the following are hereby recommended

1. Replacement level 12.5% of cement with Metakaolin will have the highest increase in concrete strength.
2. A higher polynomial equation can be used in other research to increase the accuracy of model.

### **5.3 Contributions to Knowledge**

The Scheffe's regression model, developed within this study, was rigorously assessed using the F-statistical (Fisher) method at a 95% confidence level. This model serves as a valuable tool for predicting the compressive strength of concrete after 28 days, with varying replacement levels of Metakaolin in lieu of cement, ranging from 0% to 20%.

Furthermore, this study revealed that an optimal strength gain of 33.71 N/mm<sup>2</sup> can be achieved when cement is replaced with Metakaolin at a specific concentration of 12.5%. This optimal composition corresponds to a mix ratio of 0.490:0.875:0.125:1.575:2.705 for Water: Cement: Metakaolin: Fly Ash (FA): Coarse Aggregate (CA), respectively. These findings contribute valuable insights into enhancing the performance of concrete formulations, offering potential applications in the construction industry.

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## APPENDICES

### Appendix A: Physical Properties of Concrete Constituents

**Table A1: Sieve analysis results for fine aggregates. Weight of sample = 500g**

Sieve sizes (mm)	Weight of empty sieve (g)	Weight of sieve +sample (g)	Weight of sample retained (g)	Percentage weight retained (%)	Cumulative percentage retained (%)	Cumulative percentage passing (%)
5.00	475.00	475.20	0.20	0.04	0.04	99.96
3.35	468.00	476.60	8.60	1.72	1.76	98.24
2.36	433.2	454.00	20.8	4.16	5.92	94.08
2.00	416.60	424.80	7.70	1.54	7.46	92.54
1.18	358.00	434.80	49.80	9.96	17.42	82.58
0.85	354.80	389.70	34.90	6.98	24.40	75.60
0.60	468.50	535.40	66.90	13.38	37.78	62.22
0.43	435.00	519.90	84.90	16.98	54.76	45.24
0.3	382.10	442.80	60.70	12.14	66.90	33.10
0.15	420.60	553.80	133.20	26.64	93.54	6.46
0.07	332.40	340.30	7.90	1.58	95.12	4.88
pan	286.00	310.40	24.40	4.88	100.00	0.00
	4857.20	5357.20	500.00			

**Table A2: Sieve analysis results for coarse aggregates**

<b>Sieve Sizes (mm)</b>	<b>Weight of empty sieves (g)</b>	<b>Weight of Sieves + Samples (g)</b>	<b>Weight of Samples retained (g)</b>	<b>Percentage Weight retained (%)</b>	<b>Cumulative Percentage retained (%)</b>	<b>Cumulative Percentage passing (%)</b>
75.00	1000.00	1000.00	0.00	0.00	0.00	100.00
37.50	1535.00	1535.00	0.00	0.00	0.00	100.00
20.00	1416.00	1611.00	195.00	19.50	19.50	80.50
14.00	1363.00	2065.00	702.00	70.20	89.70	10.30
10,00	1318.00	1421.00	103.00	10.30	100.00	0.00
pan	1000.00	1000.00	0.00	0.00	0.00	0.00
	7632.00	8632.00	1000.00			

**Table A3: Water absorption results for fine aggregates**

<b>Can/Trial No.</b>	<b>Weight of Can</b>	<b>Weight of Can+wet Soil</b>	<b>Weight of Can+dry Soil</b>	<b>Moisture Content</b>	<b>Percentage moisture Content</b>	<b>Average moisture Content</b>
Trial	21.60	98.20	82.30	0.26	26.19	26.03
Tria2	22.10	113.60	94.80	0.26	25.86	

**Table A4: Water absorption results for coarse aggregates**

<b>Can/Trial No.</b>	<b>Weight of Can</b>	<b>Weight of Can+wet Soil</b>	<b>Weight of Can+dry Soil</b>	<b>Moisture Content</b>	<b>Percentage moisture Content</b>	<b>Average moisture Content</b>
Trial	41.00	294.4	286.50	0.03	3.22	2.69
Tria2	44.80	286.30	281.20	0.02	2.16	

**Table A5: Specific gravity results for fine aggregates**

<b>Trial Number</b>	<b>1</b>	<b>2</b>	<b>3</b>
Weight of empty Pycnometer bottle	117.20	155.60	149.00
Weight of empty Pycnometer bottle + Sample	321.90	387.10	380.10
Weight of empty pycnometer bottle + sample + Water	563.50	781.70	785.10
Weight of empty pycnometer bottle + Sample	436.10	638.00	638.00
Specific Gravity	2.65	2.64	2.75
Average Specific gravity		2.68	

**Table A6: Specific gravity results for coarse aggregates**

<b>Trial Number</b>	<b>1</b>	<b>2</b>	<b>3</b>
Weight of empty Pycnometer bottle	46.00	43.60	69.00
Weight of empty Pycnometer bottle + Sample	119.90	105.60	133.50
Weight of empty pycnometer bottle + sample + Water	198.90	187.10	215.20
Weight of empty pycnometer bottle + Sample	153.30	149.20	176.10
Specific Gravity	2.61	2.57	2.54
Average Specific gravity		2.57	

**Table A7: Aggregates impact value results**

<b>Aggregate Impact Value</b>	
% Retain on sieve 10mm	683
% Passing sieve 2.35mm	93
AIV	13.6164
< 20 signifies Strong Aggregate	

## Appendix B: Concrete Mix design by Weight

**Table B1: Model concrete mix by weight**

sample	Quantity				
	W(kg)	C (kg)	MK(kg)	Fa(kg)	Ca(kg)
N <sub>1</sub>	2.076	4.151	0.000	6.850	11.540
N <sub>2</sub>	2.076	4.324	0.216	6.659	11.416
N <sub>3</sub>	2.076	4.512	0.451	6.588	11.281
N <sub>4</sub>	2.076	3.992	0.599	6.746	11.616
N <sub>5</sub>	2.076	3.844	0.769	6.803	11.723
N <sub>12</sub>	2.076	4.236	0.106	6.756	11.479
N <sub>13</sub>	2.076	4.324	0.216	6.724	11.416
N <sub>14</sub>	2.076	4.070	0.285	6.797	11.579
N <sub>15</sub>	2.076	3.992	0.399	6.786	11.635
N <sub>23</sub>	2.076	4.416	0.331	6.624	11.350
N <sub>24</sub>	2.076	4.151	0.415	6.704	11.520
N <sub>25</sub>	2.076	4.070	0.509	6.736	11.579
N <sub>34</sub>	2.076	4.236	0.529	6.672	11.458
N <sub>35</sub>	2.076	4.151	0.623	6.704	11.520
N <sub>45</sub>	2.076	3.916	0.685	6.775	11.670
	31.134	62.385	6.134	100.924	172.782
allow 10% for wastage	3.113	6.239	0.613	10.092	17.278
Sum	34.248	68.624	6.747	111.017	190.060

**Table B2: Model concrete mix by weight**

	<b>Quantity</b>				
sample points	W(kg)	C (kg)	MK	Fa	Ca
C <sub>1</sub>	2.076	4.038	0.424	6.776	11.594
C <sub>2</sub>	2.076	4.342	0.239	6.678	11.403
C <sub>3</sub>	2.076	4.361	0.262	6.698	11.390
C <sub>4</sub>	2.076	4.151	0.415	6.733	11.524
C <sub>5</sub>	2.076	4.236	0.275	6.722	11.471
C <sub>12</sub>	2.076	4.253	0.128	6.737	11.467
C <sub>13</sub>	2.076	4.271	0.363	6.684	11.446
C <sub>14</sub>	2.076	4.398	0.308	6.671	11.363
C <sub>15</sub>	2.076	4.473	0.403	6.603	11.309
C <sub>23</sub>	2.076	4.118	0.329	6.762	11.552
C <sub>24</sub>	2.076	4.185	0.042	6.825	11.516
C <sub>25</sub>	2.076	4.236	0.402	6.680	11.467
C <sub>34</sub>	2.076	4.185	0.126	6.796	11.512
C <sub>35</sub>	2.076	4.086	0.245	6.807	11.571
C <sub>45</sub>	2.076	4.185	0.377	6.737	11.504
	31.134	63.518	4.337	100.911	172.088
allow 10% for wastage	3.113	6.352	0.434	10.091	17.209
<b>Sum</b>	<b>34.248</b>	<b>69.869</b>	<b>4.771</b>	<b>111.002</b>	<b>189.297</b>



## Appendix C: Compressive strength of concrete cubes

**Table C1: Compressive strength for the model mix**

Sample point	Failure Loads(kN)			Average Load(kN)	Area (mm <sup>2</sup> )	compressive strength (N/mm <sup>2</sup> )
	A	B	C			
N1	661.2	669.8	661	664.00	22500	29.51
N2	735.3	731.2	738.2	734.90	22500	32.66
N3	748	747.2	758.3	751.17	22500	33.39
N4	723.9	725.1	718.1	722.37	22500	32.11
N5	706.6	707.9	705.1	706.53	22500	31.40
N12	686.4	687.2	691.8	688.47	22500	30.60
N13	707.1	708	684.1	699.73	22500	31.10
N14	620.5	631.5	560.5	604.17	22500	26.85
N15	723.2	720	715.3	719.50	22500	31.98
N23	572.5	661.8	669.1	634.47	22500	28.20
N24	725.3	723.1	724.9	724.43	22500	32.20
N25	731.1	735.1	725.1	730.43	22500	32.46
N34	755.1	758.9	761.1	758.37	22500	33.71
N35	736.7	741.7	735.3	737.90	22500	32.80
N45	742.1	742.9	741.8	742.27	22500	32.99

**Table C2: Compressive strength for the control mix**

Sample point	Failure Loads(kN)			Average Load(kN)	Area (mm <sup>2</sup> )	compressive strength (N/mm <sup>2</sup> )
	A	B	C			
C1	609.4	720	691.3	673.57	22500	29.94
C2	645.1	682.3	655.1	660.83	22500	29.37
C3	733.4	664.4	636.8	678.20	22500	30.14
C4	668.3	710.8	671.7	683.60	22500	30.38
C5	708.9	638.3	682.9	676.70	22500	30.08
C12	679.4	654.3	593.7	642.47	22500	28.55
C13	698.4	593.8	595.5	629.23	22500	27.97
C14	679	603.7	691.7	658.13	22500	29.25
C15	720.5	643	697.2	686.90	22500	30.53
C23	679.9	646.8	688	671.57	22500	29.85
C24	651.2	701.8	685.1	679.37	22500	30.19
C25	570.3	633.9	622.1	608.77	22500	27.06
C34	733.6	740.6	629.8	701.33	22500	31.17
C35	617.5	611.2	606.3	611.67	22500	27.19
C45	621.6	633.8	629	628.13	22500	27.92

**Table C3: Experimental and predicted values of 28 days compressive strength for the model mix**

Sample Points	Response Y	PSUEDO COMPONENTS					comp. strength	comp. strength
		W/C	C	MK	F. A	C. A	Y <sub>exp.</sub> (N/mm <sup>2</sup> )	Y <sub>pred.</sub> (N/mm <sup>2</sup> )
		X <sub>1</sub>	X <sub>2</sub>	X <sub>3</sub>	X <sub>4</sub>	X <sub>5</sub>		
N1	Y1	1.0	0.0	0.0	0.0	0.0	29.51	29.51
N2	Y2	0.0	1.0	0.0	0.0	0.0	32.66	32.66
N3	Y3	0.0	0.0	1.0	0.0	0.0	33.99	33.39
N4	Y4	0.0	0.0	0.0	1.0	0.0	32.11	32.11
N5	Y5	0.0	0.0	0.0	0.0	1.0	31.40	31.40
N12	Y6	0.5	0.5	0.0	0.0	0.0	30.60	30.60
N13	Y7	0.5	0.0	0.5	0.0	0.0	31.40	31.10
N14	Y8	0.5	0.0	0.0	0.5	0.0	26.85	26.85
N15	Y9	0.5	0.0	0.0	0.0	0.5	31.98	31.98
N23	Y10	0.0	0.5	0.5	0.0	0.0	28.50	28.20
N24	Y11	0.0	0.5	0.0	0.5	0.0	32.57	32.20
N25	Y12	0.0	0.5	0.0	0.0	0.5	32.46	32.46
N34	Y13	0.0	0.0	0.5	0.5	0.0	34.42	33.71
N35	Y14	0.0	0.0	0.5	0.0	0.5	32.70	32.80
N45	Y15	0.0	0.0	0.0	0.5	0.5	32.99	32.99

**Table C4: Experimental and predicted values of 28 days compressive strength for the control mix**

Sample Points	Response Y	PSUEDO COMPONENTS					comp. strength	comp. strength
		W/C	C	MK	F. A	C. A	Y <sub>exp.</sub> (N/mm <sup>2</sup> )	Y <sub>pred.</sub> (N/mm <sup>2</sup> )
		X1	X2	X3	X4	X5		
C1	Y1	0.3	0.0	0.0	0.7	0.0	29.94	28.00
C2	Y2	0.2	0.5	0.3	0.0	0.0	29.37	29.26
C3	Y3	0.4	0.0	0.6	0.0	0.0	30.14	31.86
C4	Y4	0.2	0.2	0.2	0.2	0.2	30.38	31.15
C5	Y5	0.3	0.3	0.2	0.2	0.0	30.08	29.77
C12	Y6	0.4	0.6	0.0	0.0	0.0	28.55	30.93
C13	Y7	0.1	0.4	0.3	0.1	0.1	27.97	30.34
C14	Y8	0.3	0.0	0.7	0.0	0.0	29.25	32.35
C15	Y9	0.0	0.2	0.8	0.0	0.0	30.53	30.64
C23	Y10	0.3	0.4	0.0	0.0	0.3	29.85	31.86
C24	Y11	0.9	0.0	0.1	0.0	0.0	30.19	29.83
C25	Y12	0.0	0.5	0.2	0.2	0.1	27.06	31.24
C34	Y13	0.7	0.1	0.1	0.1	0.0	31.17	29.06
C35	Y14	0.6	0.0	0.0	0.4	0.0	27.19	26.75
C45	Y15	0.3	0.1	0.3	0.1	0.2	27.92	31.24

## Appendix D: Fisher Statistical Test Computations

**Table D1: Fisher statistical test computations for the model**

Control Points	Yexp.	Ypred	Yexp. - $\bar{Y}_{exp}$	Ypred. - $\bar{Y}_{pred.}$	(Yexp. - $\bar{Y}_{exp}$ ) <sup>2</sup>	(Ypred. - $\bar{Y}_{pred.}$ ) <sup>2</sup>
C1	29.94	28.00	0.63	-2.29	0.40	5.23
C2	29.37	29.26	0.06	-1.03	0.00	1.07
C3	30.14	31.86	0.83	1.57	0.69	2.47
C4	30.38	31.15	1.07	0.86	1.14	0.75
C5	30.08	29.77	0.77	-0.52	0.59	0.27
C12	28.55	30.93	-0.76	0.64	0.58	0.42
C13	27.97	30.34	-1.34	0.05	1.80	0.00
C14	29.25	32.35	-0.06	2.06	0.00	4.25
C15	30.53	30.64	1.22	0.35	1.49	0.12
C23	29.85	31.86	0.54	1.57	0.29	2.46
C24	30.19	29.83	0.88	-0.46	0.77	0.21
C25	27.06	31.24	-2.25	0.95	5.06	0.90
C34	31.17	29.06	1.86	-1.23	3.46	1.51
C35	27.19	26.75	-2.12	-3.54	4.49	12.54
C45	27.92	31.24	-1.39	0.95	1.93	0.90
Sum	439.59	454.28			22.71	33.10
Mean	29.31	30.29			1.62	2.36