MODELLING OF CONCRETE PERFORMANCE BASED ON QUALITY ATTRIBUTES OF DIFFERENT FINE AGGREGATES

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Modelling of Concrete Performance Based on Quality Attributes of Different Fine Aggregates

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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DEDICATION

To the built-environment professionals who are truthful to themselves and committed to high quality concrete.

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Maina Kiambigi

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

AAS	Atomic Absorption Spectrometry
ACI	American Concrete Institute
ACV	Aggregate Crushing Value
BS	British Standards
COD	Coefficient of Determination
D.O.E.	Department of Environment
EAS	East African Standards
GPS	Global Positioning System
KS EAS	Kenyan Standards
OPC	Ordinary Portland Cement
UTM	Universal Testing Machine
VSI	Vertical Shaft Impact (VSI)
XRD	X-ray Diffraction
XRF	X-ray Fluorescence

ABSTRACT

Fine aggregate has extensively been used in the construction industry as a key component in concrete production. One of the major sources of fine aggregates is river sand. The use of river sand as the primary source of fine aggregate has resulted in over-exploitation leading to diminution and environmental degradation. This has led to exploration of other sources to safeguard depletion and reduce the negative impacts on the environment. This research was conducted on a variety of river sands and other fine aggregates used in Nairobi Metropolitan to assess their suitability for use in concrete manufacture. The fine aggregates were sourced from six locations that popularly supply the Nairobi Metropolitan area; natural river sands from Mwingi (S2), Kajiado (S3) and Machakos (S5); rock sand and quarry dust (S4 and S7) from Mlolongo and Sand from Naivasha quarry (S6). An experimental approach was adopted to test the physical, chemical and mineralogical properties of the fine aggregates and the resultant concrete strength after 7, 14, 28, 56, 112, 180 and 360 days was recorded. The physical properties were established in accordance with the British Standards test methods while chemical properties were obtained using Atomic Absorption Spectrometry (AAS) and validated using X-Ray Fluoresce (XRF) method. The mineralogical properties were determined using the X-Ray diffraction (XRD) method and counter checked with the secondary data on the geological formation of the catchment areas. Concrete mix design using the different samples was done for C30/37 concrete using Department of Environment (D.O.E.) /British method. A universal testing machine (UTM) was used to determine the compressive strength of the concrete. To achieve reliability, three cubes for each sample were crushed and the mean of the values taken as the compressive strength for that particular batch. All the fine aggregates not only had different physical and chemical properties but also failed to meet permissible limits for concrete production. The target mean strength of concrete 30/37 was achieved at different ages due to the variation in properties. Mlolongo rock sand (S4), Naivasha sand (S6) and Mlolongo quarry dust (S7) took longer to achieve the strength with S7 taking 180 days. A multiple linear regression analysis was conducted with the inclusion of Physical and chemical properties on the data sets to predict the compressive strength of concrete at 7, 14, 28, 56, 112, 180 and 360 days. The model yielded satisfactory coefficient of determination and curves were comparable to ACI and BS model.

CHAPTER ONE

INTRODUCTION

1.1 Overview

Global production and consumption of cement has been on the rise over the recent past commensurate to the high demand for housing and infrastructural developments. It is estimated that 66% of the world population will be living in the urban areas by 2050 (UN, 2014). This, together with the desire for improved living standards will ensure that cement remains an extremely important commodity for construction (Global Cement Magazine, 2011).

In Kenya, the production and consumption of cement has experienced a steady incline. From 2011 to 2012, cement production rose from 4,478.4 to 4,693.7 thousand tonnes and consumption rose from 3,870.9 to 3,991.2 thousand tonnes (KNBS, 2013- 2018). In 2013, the production increased to 5059.1 thousand tonnes while consumption increased to 4266.5 thousand tonnes (KNBS, 2013- 2018). From 2014 to 2015, cement production further went up by 8% from 5,882.5 to 6,352.9 thousand tonnes, while the consumption and stocks rose from 5,196.7 to 5,708.8 thousand tonnes. In 2016, the cement production went up by 5.6% to 6,707.2 thousand tonnes and consumption and stocks rose to 6302.0 thousand tonnes (KNBS, 2013- 2018). The continual increase in demand of cement indicates a growth in concrete production for use in building and infrastructural services.

The high consumption of cement has concomitantly resulted in increased demand for fine aggregate material which has been extensively used as a key component in concrete and Mortar production. In Kenya, the primary source of fine aggregates has been natural river sand. The rise in demand for fine aggregates has not only resulted in overexploitation of river sand leading to depletion and environmental degradation but also evoked the need to explore other sources of fine aggregate.

In Nairobi Metropolitan, the sources of fine aggregates commonly in use and which this study seeks to investigate include natural river sands from Mwingi, Kajiado and

Machakos, and other fine aggregates from Naivasha, quarry dust and rock sand from Mlolongo.

This study aims to examine the effects of using different fine aggregates on the strength of concrete, with a view to advise on their suitability for concrete production and model their performance using strength development curves.

1.2 Background to the Problem

The worldwide consumption of sand as fine aggregate in concrete production is very high and several developing countries have encountered some strain in meeting supply of the increased demand in the recent years (Manasseh, 2010). The fact that river sand has been subjected to years of abrasion and washing makes it smooth, rounded and low in silt & clay making it suitable for quality concrete (Kwan, 2013). Further, an increase in demand for these fine aggregates has resulted in increased prices and therefore high concrete cost (Raman, Safiuddin, & Zain, 2007). Since the global urbanisation will continue to rise, the demand for housing and infrastructure development will continue in the same trend depicting a gloomy picture in the extent of exploitation of river sand and consequences on the concrete cost and quality.

This high demand for fine aggregate has resulted in the exploration of other sources to satisfy the rising need in the construction industry. In Kenya, these include quarry dust, rock sand and Sand from Naivasha. This not only reduces the demand for river sand but also the burden on the environment (Nagaraj & Banu, 1996). Unfortunately, there is inadequate research done on these fine aggregates making the adoption and acceptability to lag behind those of the developed countries. Unfortunately, the rush to build quickly and cheaply with whatever materials can result in severe consequences.

Several studies have been done on various fine aggregate materials thought to possess almost similar characteristics to sand and which could be used in full or partially as a substitute to river sand. Manufactured sand has been produced in Scandinavian countries (such as Finland) with varying properties for use in specialized concrete and found to be a more economical alternative (Cepuritis, 2015).

Quarry dust has been utilized in concrete mixtures as a substitute for natural river sand giving maximum compressive strength only at 50% replacement (Raman, Zain, Mahmud, & Tan, 2005). However, Ukpata, Ephraim, & Akeke, (2012) found out that quarry dust reduces workability of concrete. Granite crusher dust has been accepted as a suitable replacement for river sand in western countries (Malagavelli & Rao, 2010). The fact however is; material properties vary from region to region due to varied geological formation of the parent rocks. While the fine aggregate in these case studies worked to some extent in their home countries, such information cannot be applied for the fine aggregates in Kenya.

In Kenya, it is observed that the various fine aggregates in use are applied in similar ratios without regard to their physical and chemical properties and the effect that they have on concrete strength. This study aims at establishing the Physical and chemical composition of these fine aggregates and their effect on concrete strength. It also aims at providing professionals with a guideline on their use and application in the construction industry.

1.3 Statement of the Problem

The use of fine aggregate in concrete manufacture has been predominant for many years in the construction industry. The growth in urbanization and infrastructural development has led to high demand of concrete and its constituent materials.

The research has established through visual observations that there are different types of sand used in the construction industry. Due to the variation in geology of the catchment areas, natural river sand properties differ and would thus have different effects on concrete quality. Although river sand has been the primary source of fine aggregate, various other options have emerged which include sand mined from quarries like Naivasha, use of manufactured sand from ballast and to some extent use of quarry dust as fine aggregates. Though many structures have been built using the other aggregates, there is inadequate data to establish the effects of performance and behavior of these materials on the concrete quality with some engineers rebuffing in full the use of such material. In all this confusion, structures built with such materials continue to sprout and the call to have some scientific research done can neither be underestimated nor postponed.

In Kenya, building collapse has been reported in various parts of the country with the Ministry of Metropolitan, in their study on the building safety and security in the built environment, attributing the same to, among others, poor quality of concrete constituent materials and poor-quality concrete (Ministry of Nairobi Metropolitan, 2013). There were 24 buildings which collapsed, killing 41 and injuring 47 people between 1996 and 2011 (Situma, 2013). Raul, in his study on ‘‘Strategies to Reduce the Risk of Building Collapse in Developing Countries’’, found that 75% of the buildings surveyed in Nairobi county had concrete that did not meet the standards specified by the structural engineers (Raul, 2014).

Of all the constituents, fine aggregate comes from different sources yet used in same proportions for the production of concrete despite contributing largely to the its volume and subsequently its quality. There is therefore need to understand the implications of using different fine aggregate material in concrete production. While the geological classification of aggregates gives insight into the properties of the material, the quality and suitability of a specific source of aggregates for a particular application requires testing and evaluation (Maina, 2010). This study, therefore, seeks to establish the performance of concrete produced from the different fine aggregates and hence their acceptability for use in the built environment. The research Posits that Concrete performance = (Quality attributes of fine aggregates); while Fine aggregate quality is a function of (Geological location, Physical composition, chemical properties and Mineralogical factors)

1.4 Research Objectives

The aim of this research is development of a Concrete Performance Model based on quality attributes of different fine aggregates. The specific objectives were:

1. To establish the relationship between physical, chemical and mineralogical properties of different fine aggregates used in Nairobi Metropolitan

2. Establish the Strength of concrete from the different materials and compare with existing strength prediction models.
3. To develop and validate the concrete performance model for the different fine aggregate

1.5 Hypothesis

The study research hypothesis is that the chemical properties of fine aggregates have no significant effect on concrete strength development.

The hypothesis can be stated mathematically as follows:

$$f = b1 + b2\,x1 + b3\,x2 + \dots + bnxn$$

where: f: compressive strength of concrete N/mm^2

$b1$: constant

$b2$, $b3 \dots b1-n$ coefficients

$x1$, $x2 \dots xn$: explanatory variables

The null hypothesis can be stated as follows:

$$Ho: b2 = b3 = \dots = bn-1 = 0$$

The Alternate hypothesis is that: -

$$H1: bj \neq 0 \quad For\ at\ least\ one\ j, j = 1, \dots, n-1$$

By rejecting the null hypothesis, it is implied that at least one of the explanatory variables, $x1$, $x2 \dots xn$, contributes significantly to concrete strength development. A generalization of the F-test in regression is used to test this hypothesis at level of significance α=0.05.

The research seeks to find out if the addition of certain independent variables of interest (chemical properties of fine aggregates) add significantly to the determination of concrete strength, *f*, obtained through other independent variables already in the model. In this study, the research seeks to establish the effect of the extra variables (Silicon dioxide, aluminum oxide) to the 'traditional' ones, (water-cement ratio, quantities of coarse and fine aggregates and physical properties of fine aggregates) on concrete strength.

1.6 Justification

The purpose of this research project is to examine effects of different fine aggregate being used in Nairobi Metropolitan on concrete strength. The study endeavors to solve the perennial river sand scarcity and restrictions owing to environmental degradation associated with its mining. Further, there has been numerous collapses of buildings associated with poor concrete and concrete materials. Investigating the quality of these different materials offers an opportunity to establishing their performance in concrete and application in the built environment.

While other developed countries have done several studies on the various fine aggregate materials thought to possess almost similar characteristics to sand and which could be used in full or partially as a substitute to river sand, there is inadequate research done on the same materials in the Nairobi Metropolitan. However, these materials have been used in construction within the Nairobi Metropolitan in the same batching ratios as river sand without consideration of their properties.

This research seeks to establish the suitability of the different fine aggregate materials for concrete production. It will therefore inform the built environment professionals and authorities on the range of fine aggregates suitable for use in construction projects.

1.7 Scope

This research is limited to Nairobi Metropolitan where most of the construction work occurs. The fine aggregate material was sourced from Machakos, Kitui, Nakuru and Kajiado counties which are the main suppliers for the region. The fine aggregates used in the research were Natural river sands from Mwingi (00^0 58’ 4.36” S, 38^0 03’ 35.66” E), Machakos (01^0 20’ 29.4” S, 37^0 26’ 15.2” E) and Kajiado (02^0 02’ 28.9” S, 37^0 06’ 43.7” E), quarry dust and rock sand from Mlolongo (01^0 23’ 11.1” S, 36^0 50’ 31.5” E) and Naivasha sand from Naivasha quarry (01^0 00’ 47.6” S, 36^0 21’ 19” E).

This study focused on the evaluation of the physical, chemical and mineralogical properties of fine aggregates. The fine aggregate properties were compared to predetermined material standards in the codes to ascertain their suitability for use as concrete aggregates. A desk study of the geological formation of the different catchment areas of the fine aggregates was done to determine the mineralogical properties which was validated by laboratory X-ray diffraction (XRD) tests. The fine aggregates were used to cast concrete cubes whose compressive strength were tested to determine their suitability for use in concrete manufacture.

A multi-staged evaluation of the existing strength prediction models was done, which included ACI, Bolomey’s, Abrams’, BS prediction factors and the German model. This was done by identification of the parameters used in the various models as the key determinants of strength development and the limitations associated with the same. This was used as the basis of formulation of a multi-linear regression model for strength prediction of the fine aggregates from the various catchment areas.

1.8 Limitations

1. Unavailability of testing equipment – The researcher had to outsource some equipment from the Ministry of Mining for testing of the samples.
2. Variation in environmental conditions – Changes in temperature and humidity might have caused variation in the rate of strength development over time.

3. Storage space was required to keep the cubes under water for 28 days and on the laboratory shelves for one year.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Fine aggregate materials have widely been used in manufacture of concrete for use in buildings and other infrastructural developments. The acceptability of concrete as the most versatile product in construction is hinged on the quality and availability of the respective material constituents, durability and the relative ease of its moulding to required shapes (Civil engineers forum, 2016). Concrete constitutes water, cement, fine and coarse aggregates (MacGinley & Choo, 2003). Aggregates form 75% of concrete by volume whose properties significantly affect the durability and structural performance of concrete (Neville, 2011). The fine and coarse aggregate proportions vary depending on the design mix required for construction. Quality assurance of building materials is essential in building strong, durable and cost-effective structures (Savitha, 2012). The need to use the right type and quality of aggregates in concrete manufacture cannot be underestimated; and the selection of the constituent materials should be made to the highest standard if the integrity of the structures is to be maintained (The Constructor, 2016).

The increased demand for housing and other infrastructure due to growth in population and urbanisation has resulted in high demand for concrete and subsequently its constituents. Globally, material mined every year amount to between 47-59 billion tonnes, with sand and gravel accounting for the largest percentage (about 68- 85%) of this, as well as the fastest increase in exploitation rate (Krausman, et al., 2009). River sand has been the most preferred choice of fine aggregate due to its availability, affordability and minimal or no processing requirements (Camp, 2018). A conservative estimate for world consumption of aggregates gives more than twice the amount of sediment carried by all of the rivers of the world (Milliman & Syvitski, 1992), resulting in man being the planet’s largest transforming agent with respect to aggregates (Radford, 2005). This level of exploitation has led to depletion of river s and which has resulted to increase in cost for concrete production and environmental degradation. There is considerable pressure in many countries to use other fine aggregates in construction to supplement or augment natural river sand to reduce the strain and environmental problems associated with production of the primary aggregates (Harrison & Steadman, 2003). These include rock sand, quarry dust and manufactured sand.

Fine aggregates are often manufactured by crushing and processing hard rocks to produce fine-grained materials. The degree to which the crushed rock sand can be used as fine aggregate varies with rock type, the degree of quarry processing and the end use. In some quarries, the sand is washed to remove fines thereby significantly improving the quality (Harrison & Steadman, 2003). Most developed countries use manufactured sand produced from crushing and processing of hard rock like limestone, sandstone and igneous rocks, whose aggregate properties are well researched. However due to the variance in geological processes that led to the formation of the parent rocks, the research findings cannot be applied to other areas because of the variation in rock mineral compositions.

2.2 Concrete Production

Concrete is a composite material composed of aggregates (both coarse and fine) and a cementitious paste, made by mixing water and cement. The nature of concrete lies in the way the various materials are mixed, moulded and shaped to form a product that can withstand high load carrying capacity over the lifetime of the structure without failure. Concrete volume is made up of 60-75% coarse and fine aggregates which significantly influence the fresh and hardened properties of concrete (Camp, 2018). The water-cement paste typically surrounds all the particles of aggregates to make a plastic mixture which gradually changes to a solid state in the process of hydration. The mixing should ensure that the mass becomes homogeneous, uniform in colour and consistent (Shetty, 2006).

2.2.1 Cement

Cement is the bonding material used with stones, sand, bricks and building blocks in construction. In concrete manufacture, hydraulic cement consisting of silicates and aluminates of lime, are used by virtue of chemical reactions that results in setting and hardening under water. Hydraulic cement is classified into natural cement, Portland cement and high-alumina cement. For practical purposes of selection of an appropriate Portland cement or blended cement, it is useful to consider a classification based on the relevant physical or chemical properties, such as a rapid gain of strength, low rate heat of hydration, or resistance to sulphate attack (Neville, 2011). The different types of cement, according to (EAS-KS, 2001) are as given in Table 2.1.

Table 2.1: Main types of common cement (EAS-KS, 2001)

Main Types	Notation of the 27 products(types of common cement)		Composition (percentage by mass [a]) Main constituents: Clinker K	ballast furnace S	silica fume D [a]	pozzolana Natural P	pozzolana Natural calcined Q	fly ash Siliceous v	fly ash calcareous w	burnt shale t	lime stone L	lime stone LL	Minor additional
CEM 1	Portland cement	CEM 1	95-100		-	-	-	-	-	-	-	-	0 to 5
CEM II	Portland slag cement	CEM II/A-S	80-94	6 to 20	-	-	-	-	-	-	-	-	0 to 5
		CEM II/B-S	65-79	21 to 35	-	-	-	-	-	-	-	-	0 to 5
	Portlandsilica fume cement	CEM I/A-D	90 to 94	-	6 to 10	-	-	-	-	-	-	-	0 to 5
	Portland-pozzollana	CEM II/A-P	80 to 94	-	-	6 to 20	-	-	-	-	-	-	0 to 5
		CEM II/B-P	65 to 79	-	-	21 to 35	-	-	-	-	-	-	0 to 5
		CEM II/ A-Q	80 to 94	-	-	-	6 to 20	-	-	-	-	-	0 to 5
		CEM II/B-Q	65 to 79	-	-	-	21 to 35	-	-	-	-	-	0 to 5
	Portland fly ash cement	CEM II/A-V	80 to 94	-	-	-	-	6 to 20	-	-	-	-	0 to 5
		CEM II/B-V	65 to 79	-	-	-	-	21 to 35	-	-	-	-	0 to 5
		CEM II/A-W	80-94	-	-	-	-	-	6 to 20 -	-	-	-	0 to 5
		CEM II/B-V	65 to 79	-	-	-	-	-	21 to 35	-	--	-	0 to 5
		CEM II/A-W	80-94	-	-	-	--	-	-	6 to 20	-	-	0 to 5
		CEM II/B-W	65 to 79	-	-	-	-	-	-	21 to 35	-	-	0-5
	Portland burnt shale cement	CEM II/A-T	80-94	-	-	-	-	-	-	-	6 to 20	-	
		CEM II/B-T	65 to 79	-	-	-	-	-	-	-	21 to 35	-	0 to 5
	Portland limestone cement	CEM II/A-L	80 to 94	-	-	-	-	-	-	-	-	6 to 20	0 to 5
		CEM II/A-L	65 to 79	-	-	-	-	-	-	-	-	21 to 35	0 to 5
		CEM II/A-LL		-	-	-	-	-	-	-	-	-	0 to 5
		CEM II/B-LL	65 to 79	-	-	-	-	-	-	-	-	-	0 to 5
	Portland composite cement [c]	CEM II/A-M	80-94			6 to 20							0 to 5
		CEM II/B-M	65 to 79			31 to 35							0 to 5
CEM III	Ballast-Furnace cement	CEM III/A	35 to 64	36 to 65	-	-	-	-	-	-	-	-	0 to 5
		CEM III/B	20 to 34	66 to 80	-	-	-	-	-	-	-	-	0 to 5
		CEM III/C	5 to 19	81 to 95	-	-	-	-	-	-	-	-	0 to 5
CEM IV	Pozzollanic cement [c]	CEM IV/A	65 to 89	-			11 to 35			-			0 to 5
		CEM IV/B	45 to 64	-	35 to 55				-				0 to 5
CEN V	Composite cement [c]	CEM V/A	40 to 64	18 to 30		18 to 30			-	-			0 to 5
		CEM V/B	20 to 38	31 to 50		31 to 50			-				0 to 5

a) The values in the table refer to the sum of the main and minor additional constituents

b) The proportion of silica fume is limited to 10%

c) In Portland-composite cements CEMII/A-M and CEM II/B-M, In pozzolanic cements CEM IV/A and in composite cements CEM V/A and CEM V/B the main constituents other than clinker shall be declared by designation of the cement

Portland cement is obtained by intimately mixing raw materials (calcareous and argillaceous or other silica-alumina and iron oxide bearing materials) and melting them at temperatures of 1400^0 C to 1650^0 C to form cement clinker which is cooled and pulverised into fine powder (Mamlouk & Zaniewski, 1999).

There are two main types of Portland cement used in concrete manufacture in Kenya; Portland cement and Pozzolana Portland cement. Concrete made from Portland cement is usually prone to chloride and sulphate attacks unlike Pozzolana which inhibits the attack by the formation of calcium silicate hydrate (CSH) (Mwiti, 2013). Such cementitious characteristics of Pozzolana results to increased strength and durability of concrete over time (Agarwal, 2006).

2.2.1.1 Chemical Properties of Portland cement

Portland cement is manufactured from lime, Silica, Alumina and Iron oxide reacting to form a series of more complex products resulting in a state of chemical equilibrium. The main compounds constituting Portland cement are lime/ calcium oxide (CaO) silica/silicon (IV) oxide (SiO_2), alumina/aluminium (III) oxide (Al_2O_3) and iron (III) oxide (Fe_2O_3). The trace compounds include magnesia/magnesium oxide (MgO), potash/potassium oxide (K_2O), soda/sodium oxide (Na_2O), manganese oxide (Mn_2O_3) and titanium oxide (TiO_2). The actual proportioning of various compounds varies from cement to cement.

The chemical constituents of Portland cement are as shown in Table 2.2.

Table 2.2: Approximate specifications limits of Portland cement (Neville, 2011)

Constituent	Percentage Content
Lime/calcium oxide (CaO)	60 – 67 %
Silica/silicon (IV) oxide (SiO_2)	17 – 25 %
Alumina/aluminium (III) oxide (Al_2O_3)	3 – 8 %
Iron (III) oxide (Fe_2O_3)	0.5 – 6 %
Magnesia/ magnesium oxide (MgO)	0.5 – 4 %
Sulphur trioxide (SO_3)	2.0 – 3.5 %
Soda/sodium oxide (Na_2O)	0.3 – 1.2 %

Each of the constituents has a contribution towards the performance as captured below (Penn State University, 2000).

Lime/calcium oxide (CaO): High calcium oxide increases the setting time of freshly mixed concrete but gives an early strength. A reduced concentration of this reduces the strength of the cement unduly.

Silica/silicon (IV) oxide (SiO_2) and alumina/aluminium (III) oxide (Al_2O_3): These are complementary, a reduction of one usually being accompanied by an increase of the other. High silica prolongs the setting time but increases the strength.

Alumina/aluminium (III) oxide (Al_2O_3): It tends to reduce the setting time but also increase the strength. Iron (III) oxide (Fe_2O_3): This is not a very active constituent of cement but it is due to its presence that Portland cement derives its characteristic grey colour. Iron oxide also combines with lime and silica.

Soda/sodium oxide (Na_2O) and potash/potassium oxide (K_2O): These have little or no value.

Calcium sulphate or gypsum: This is added in amounts of 2-3% at grinding stage to prevent excessively rapid setting of cement.

2.2.1.2 Ordinary Portland cement

Portland cement is commonly used due to its suitability for use in general construction with no exposure to sulphates in the soil and groundwater. British Standard (BSI, 1996) classifies Portland cement according to their compressive strength, as shown in Table 2.3.

Table 2.3: Compressive strength requirements of cement (BSI, 1996)

Class	Maximum strength, MPa at the age of			Maximum strength, MPa at the age of 28 days
	2days	**7 days**	**28 days**	
32.5N	-	16	32.5	52.5
32.5N	10	-		
42.5N	10	-	42.5	62.5
42.5N	20	-		
52.5N	20	-	52.5	
62.5N	20	-	62.5	

The minimum strength in MPa at 28 days gives the name of the class of cement; 32.5, 42.5, 52.5 and 62.5. The strengths at 28 days of cement class 32.5 and 42.5 are determined by a range of maximum and minimum values of strength. The two classes are further divided into ordinary early strength and high early strength (R). The latter is rapid hardening cement.

2.2.2 Coarse Aggregate

Mining suitable rock deposits produces crushed stone or angular rocks. These are broken down to the desired size using crushers and used as coarse aggregates. Additionally, natural processes of weathering and erosion also produce gravel used as coarse aggregates, which typically has a more rounded shape.

Various types of rocks when crushed are suitable for use as aggregates in concrete.

1) **Limestones are sedimentary rocks** composed chiefly of calcium carbonate. The harder and denser types of limestone, particularly the carboniferous types are very suitable for concrete.
2) **Igneous rocks** - These include granites, basalts (trap-rock), dolerites, gabbros and porphyries. Granite is hard, tough and dense and is an excellent aggregate for concrete. Basalts are igneous rocks similar to granite, but with a much finer grain structure due to more rapid cooling when they are formed. They

are excellent aggregates. Dolerites have a finer crystalline grain structure and when used as aggregate for concrete, may cause cracking and disruption of the concrete.

3) **Sandstones**. When hard and dense, most sandstone are suitable for aggregates. The best are those which are composed of quartz grains cemented with hydrated iron oxide or amorphous silica, known geologically as ferruginous and siliceous sandstones. Imperfect cementation of the constituent grains makes some sandstones friable and more porous and they are then unsuitable aggregates.
4) **Shales** are usually poor aggregates, being soft, weak, laminated and absorptive. Also, the flat shape of the particles makes compaction of any concrete in which they are used to be very difficult.
5) **Metamorphic rocks** are variable in properties. Marbles and quartzites are usually massive, dense and adequately tough and strong, providing excellent aggregates. However, some schist and slates are often thinly laminated and, therefore, unsuitable for aggregates.

2.2.2.1 Properties of Coarse Aggregate

Some of the important parameters of coarse aggregate include the shape, surface texture, grading, cleanliness and nominal maximum size. Aggregate properties such as surface texture and mineralogy significantly affect the interfacial paste aggregate bond and the level of stress at which interfacial cracking commences (Reynolds & Steedman, 1999). The total surface area of rough textured angular aggregate is more than smooth rounded aggregate for the given volume. By having greater surface area, the angular aggregate may show higher bond strength than rounded aggregates (Shetty, 2006).

2.2.3 Fine Aggregate

Fine aggregates are made of natural sand or crushed stone in which most particles are smaller than 5mm (Dayaratnam, 1998). Naturally occurring aggregates consist of gravel and sand, usually dredged or dug from pits, rivers, lakes or sea-bed that can readily be used with minimum processing. Crushed stone is obtained from crushed quarry rocks, boulder cobbles or large sized gravel. Crushed air-cooled blast-furnace slag can also be used as fine aggregate (PCA, 2011).

Aggregates are constituted of rocks and minerals. A mineral refers to a naturally occurring solid substance with an orderly internal structure (Camp, 2018). Rocks, whether igneous, metamorphic or sedimentary depending on their origin, contain several minerals. Weathering and rock erosion produce particles of stone, gravel, sand, silt and clay.

The suitability of aggregates from a given source must be evaluated by a combination of tests to check physical, chemical, and mechanical properties, and must be supplemented by mineralogical examination. The best possible prediction of aggregate suitability for a given application is that based on historical performance in a similar design (Michael & John, 1999). Concrete aggregates are required to conform to specific standards for optimum use; they should be clean, hard, strong, durable, with controlled amounts of chemical absorbed, clay coatings and other fine materials that affect hydration and bond of the cement paste (Camp, 2018). Aggregate particles are undesirable if they are friable or capable of being split, if they contain substantial amounts of shale, soft and porous materials or certain types of chert that have low resistance to weathering causing pop outs. Aggregates should meet the requirements on the permissible amounts of deleterious substances. Compliance to this, however, does not assure defect-free concrete.

2.2.3.1 Physical properties of fine Aggregates-Grading

Physical properties of aggregates refer to the physical structure of the particles that make up the aggregates.

Grading refers to the process that determines the particle size distribution of a representative sample of an aggregate (Somayaji, 2001). There are several reasons for specifying grading limits and nominal maximum aggregate size which include; their effect on relative aggregate proportions as well as cement and water requirements, workability, pumpability, economy, porosity, shrinkage, and durability of concrete. Significant variations in grading can have an adverse effect on the uniformity of concrete from batch to batch. Aggregates without a large deficiency or excess of any size and give a smooth grading curve will produce the most satisfactory results. The type of work, the richness of mixture and maximum size of coarse aggregate determines the most desirable fine aggregate grading. The best economy is achieved by adjusting the concrete mixture to suit the gradation of the local aggregates (Camp, 2018). The variation in gradation of samples can be attributed to the formation processes of the aggregates. For natural aggregates, the degree of friction and abrasion determines the sizes of particles. For manufactured aggregates, the crushing reduction ratio of the machine used in the quarry determine the gradation (Harrison & Steadman, 2003). When determined in accordance with (BSI, 1992), the grading of the sand shall comply with the overall limits given in Table 2.4.

Table 2.4: Grading limits for fine aggregates (BSI, 1992)

Sievesize	Percentage by mass passing BS sieve			
	Overall limits	Additional limits for grading C	M	F
10.00mm	100	_ _ _	_ _ _	_ _ _
5.00mm	89 to 100	_ _ _	_ _ _	_ _ _
2.36mm	60 to 100	60 to 100	65 to 100	80 to 100
1.18mm	30 to 100	30 to 90	45 to 100	70 to 100
600 µm	15 to 100	15 to 54	25 to 80	55 to 100
300 µm	5 to 70	5 to 40	5 to 48	5 to 70
150 µm	0 to 15a	_ _ _	_ _ _	_ _ _

NOTE: Individual sands may comply with the requirements for more than one grading. Alternatively, may satisfy the overall limits but nay not fall within any of the additional limits C.M or F. In this case and where sands do not comply with Table 4 an agreed grading envelope may also be used provided that the supplier can satisfy the purchaser that such material can produce concrete of the required quality.

- Increased 20% for crushed rock fines, expect when they are used for heavy duty floors.

Source: Grading limits for fine aggregates (BSI 1992), Table 4

2.2.3.2 Particle Shape and Texture

In addition to the petrological character of aggregate, its external characteristics are of importance, in particular the particle shape and surface texture. The shape and surface texture of the individual aggregate particles determine how the material will pack into a dense configuration and also determines the mobility of the stones within a mix (Michael & John, 1999). Surface texture, defined as the pattern and relative roughness or smoothness of an aggregate, greatly contributes to the development of bond between the aggregate particles and the cement paste. Generally, angular and rough-textured aggregates produce bulk materials with higher stability than rounded, smooth-textured aggregates.

The rougher the texture the greater the bond resulting in stronger cement concrete (Michael & John, 1999). The surface texture of aggregates also affects the water requirement in concrete manufacture and the workability of fresh concrete. The higher surface area of angular aggregate with rough texture requires more water for a given workability than rounded aggregates (Shetty, 2006).

The shape of the aggregates is determined by certain geometrical characteristics of such bodies. Aggregate shape affects the cement demands, the workability and strength of concrete. Crushed stone and crushed gravel are the best aggregates for use to attain the highest strength due to their irregular, angular shape that interlocks when compacted. However, crushed stone makes the concrete mix difficult to place, therefore to improve workability, many mixes contain both angular and round particles. Roundness measures the relative sharpness or angularity of the edges and corners of a particle (Neville, 2011). This is controlled by the strength and the ability of the parent rock to resist abrasion by wear subjected to the particles. In crushed aggregates, the shape is determined by the nature of parent rocks, type of crusher and its reduction ratio. Roundness can be classified in accordance to (BS, 1975) as shown in Table 2.5.

Table 2.5: Particle shape classification (BS, 1975)

Classification	Description	Examples
Rounded	Fully water worn or completely shaped by attrition	River or seashore gravel; desert, seashore and windblown sand
Irregular	Naturally irregular, or partly shaped by attrition or having rounded edges	Other gravels; land or dug flint
Flaky	Materials of which the thickness is small relative to the other two dimensions	Laminated rock
Angular	Possessing well defined edges formed at the intersection of roughly planer faces	Crushed rocks of all types; talus; crushed slag
Elongated	Materials, usually angular, in which the length is considerably larger than the other two dimensions	_
Flaky and elongated	Materials having the length considerably larger than the width, and the width considerably larger than the thickness	_

Source: Particle Shape classification (BS 812-1:1975), table 3.3

2.2.3.3 Absorption, Porosity and Permeability.

One of the most important properties of fine aggregates is their internal pore characteristics. The strength, surface texture, resistance to freezing and thawing action, bonding capabilities, abrasion resistance and specific gravity are affected by the size, number and continuity of the pores through an aggregate (Arumugam, 2014). Absorption is the particles ability to take in liquid. It is determined in order to control the total water content in concrete and to ensure correct weight batching. The absorption and surface moisture of aggregates should be determined according to

(BSI, 1990). The aggregate internal structure is made of solid matter and voids, which may or may not contain water. The moisture conditions of aggregates can be designated as;

- Oven-dry – when the aggregate is fully absorbent;
- Air dry – when the aggregate is dry at the particle surface but still contains some interior moisture;
- Saturated surface dry (SSD) – when the aggregate is neither absorbing water from nor contributing water to the concrete mixture;
- Damp or wet – when the aggregates contain an excess of moisture on the surface (free water).

Porosity refers to the ratio of the volume of the pores to the total volume of the particle. Permeability is the particles' ability to allow liquids to pass through.

2.2.3.4 Density and Specific Gravity

Density is the weight per unit volume of a substance while specific gravity is the ratio of the weight in air of a unit volume of a material to the weight of an equal volume of water (Somayaji, 2001). The density and specific gravity of aggregate particles depend on the density and specific gravity of the minerals making up the particles and the porosity of the particles (Camp, 2018). There are different types of density;

- Bulk density- density of the aggregate including all the pore space;
- Effective density- density of the aggregate including some of the pore space;
- Apparent density- density of the aggregates excluding all the pore space.

There are different types of specific gravity;

- Absolute specific gravity- refers to the volume of solid material excluding all pores;
- Apparent specific gravity- refers to the volume of material including impermeable pores but no the capillary ones.

2.2.3.5 Soundness of aggregate

Soundness refers to the ability of aggregate to resist excessive changes in volume as a result of changes in physical conditions. Lack of soundness is evident by the chemical reactions between the aggregates and alkalis in cement. The physical causes of large or permanent volume changes of aggregate are freezing and thawing, thermal changes at temperatures above freezing and alternating wetting and drying (Neville, 2011). Unsound aggregate refers to aggregate in which the volume changes result in deterioration of the concrete.

2.2.3.6 Fineness Modulus

The fineness modulus is a measure of the fineness of aggregates and is useful in determining the proportions of fine and coarse aggregates to be used in concrete mixtures. A higher fineness modulus implies a coarser aggregate hence requires more water to produce workable concrete (Neville, 2011). Fine aggregate used in concrete production, usually natural river sand, has the following properties that influence the properties of the finished concrete mix (Penn State University, 2000);

Table 2.6: Physical properties of fine aggregates (Penn State University, 2000)

Parameter	Approximate volume	Effect of concrete mix
Bulk density	1520-1680 kg/m^3	It is required in concrete mixture proportioning, especially volume batching (prof. Nemati, 2015)
Specific gravity	2.4-3	It is determined to meet minimum density requirements; has no direct relationship on concrete performance
Particle density		It required in mixture proporting to establish weight- volume relationships
Water absorption		It determines the proper water / cementitious material ratio for the desired strength
Particle size distribution		It determines the paste requirements for adequately workable concrete larger aggregate sizes result in weaker concrete mixes.
Soundness	6-10	It affects the durability of concrete due to the alternating expansion and contraction caused by freeze and thaw action.
Shell content		It affect the workability of concrete thus water and cement ratio; It has no adverse effect on concrete strength, (dolage, dias & Ariyawansa, 2013)
Fines Quality	5-10	It affects the bonding between the concrete constituents and steel reinforcement, reducing the concrete strength, (Ngugi, Mutuku & Gariy
Moisture content	5-20%	It determines the proper water/ cementitious materials ratio for the desired strength
Organic materials	<5%	It affects the bonding between the concrete constituents and steel reinforcement, reducing the concrete strength

2.2.4 Chemical properties of fine aggregates

The chemical properties of aggregates have an influence on strength development of concrete (Neville, 2011). The main chemical constituents are Silicon IV oxide, Aluminum III oxide and calcium oxide which influence the setting time, early strength and final concrete strength (Penn State University, 2000). Iron III oxide provides concrete with its grey color while magnesium oxide helps in minimizing crack development due to its ability for long term expansion which compensates for shrinkage in mass concrete (Du, 2005). Presence of Sulphur trioxide concentration of beyond 2% reduces strength in concrete by increasing the drying shrinkage due to expansion of lime and sulphate. Chlorides, because of their accelerated effect on corrosion affect the durability of structures. Sodium oxide and potassium oxide have no significant effect on the finished concrete mix. Table 2.7 shows the recommended ranges of chemical concentrations in fine aggregates for concrete production.

Table 2.7: Chemical properties of fine aggregates (Penn State University, 2000)

CHEMICAL PROPERTIES		
Parameter	**Approximate Value**	**Effect on concrete mix**
Calcium Oxide (CaO)	2-5%	High calcium oxide (lime) content Increases setting time but gives a nearly strength. Too little lime will reduce the strength of the cement unduly
Silicon IV oxide (SiO_2)	70-90%	High silcon dioxide (Silica) content prolongs the setting time but increase the final concrete mix strength
Aluminium III Oxide (Al_2O_2)	8-12%	High aluminium oxide (alumina) content tends to reduce the setting time but also increases the concrete strength
Iron III oxide Fe_2O_3		It is not an active constituent of concrete; it provides concrete with its characteristic grey colour
Magnesium Oxide (MgO)	0.5-1%	It exhibits long term expression to compensate for shrinking of mass concrete as it cools; It minimizes crack development (Du, 2005)
Sulphur Trioxide (SO3)	Ni1-2%	It increases the expansion in lime and sulphate, it increases drying shrinking; It reduces the strength of the concrete mix (Zayed, Brown & Hanhan, 2004)
Sodium Oxide (Na2O)	0.9-2%	It has no significant effect on the properties of the finished concrete mix
Potassium Oxide (K2O)	0.7-1.9%	It has no significant effect on the properties of the finished concrete mix
Potential reactivity		High levels of reactivity is harmful if it increases the expansion of the concrete mix significantly (Farryn & Kerkhoff, 2007)
Chlorides		Affect the durability of concrete due to their acceleration effect on corrosion

2.2.5 Mineral Composition of Aggregates

All-natural aggregate particles originate from larger parent mass that has undergone natural processes of weathering and abrasion or artificial means of crushing. Consequently, many properties of the aggregates such as aggregate physiochemical properties and petrological character depend entirely on the mineral composition of the original rock (Neville, 2011).

Mineralogical classification helps in recognizing properties of aggregate but cannot provide a basis for predicting its performance in concrete as there are no minerals universally desirable.

The geological examination of aggregates is a crucial aid in assessing quality, particularly comparing new aggregates with one for which research data already exists. Unfavourable properties such as the presence of some unstable forms of silica or rocks may affect aggregate quality (Neville, 2011).

2.26 Use of Fine Aggregates in Concrete

2.2.6.1 River Sand

Natural river sand remains the most preferred source of fine aggregate for concrete production as it requires less processing, is relatively cheap and produces high-quality material (Kondolf, 1997). This can be attributed to the natural river sand having more or less optimum properties as described by building standards.

River sand also has some unfavorable properties, such as inconsistent grading, which is as a result of the varying time the sand was exposed to the elements of weathering. It also has a significant composition of clay, silt and organic material, as well as other impurities whose decay, due to weathering effect, shortens the life of concrete (NBM Ltd, 2016).

However, the use of river sand has been rendered very expensive, almost uneconomical over time. This is due to the depletion of the few available reserves from unsustainable mining; meaning significant transport costs have to be incurred to ferry it from the few available sources (NBM Ltd, 2016). All these extractions have a significant impact on the environment (Sonak, Pangam, Sonak, & Mayekar, 2006). The dredging of creeks, riverbeds and lake basins has resulted in ecological imbalance affecting bio-diversity and landscape, as well as having socio-economic, cultural and political consequences (Sonak, Pangam, Sonak, & Mayekar, 2006). In extreme cases, it has even led to change in international boundaries, as evidenced by the disappearance of the sand islands in Indonesia (The New York Times, March 2010), where it's suspected most of it was exported to Singapore for land reclamation (Peduzzi, 2014).

Mining of sand results in the lowering of the water table, propagating drought conditions (Sreebha, 2008). In essence, sand abstraction is done at the expense of other economic activities that would be more beneficial to the surrounding community, such as agriculture, fishing or provision of social amenities (Peduzzi, Mar 2014). Of most importance in Kenya is agriculture, which is affected by the loss of agricultural land due to erosion (John, 2009). Riverbed mining causes erosion and leaves the river plains much more vulnerable to flooding, as it allows loose landmass to be washed downstream. A decrease in the bed load may induce bed erosion, causing undercutting of engineering structures constructed along the water channel, such as bridges, side protection walls and water supply structures (Padmalal, Maya, Sreebha, & Streeja, 2008).

In Kenya, National Environment Management Authority (NEMA) ordered the closure of several mines in Nakuru due to their negative impacts on the environment. Those wishing to continue with the business were required to apply for an environmental impact assessment license from NEMA, at a cost of 0.1% of the project cost (Kibet, 2014). In Machakos County, a by-law was passed to ban all sand harvesting along riverbanks to limit environmental degradation, with only licensed groups allowed to mine at designated spots about 50m from the river. NEMA has issued restoration orders and prosecuted a number of illegal sand harvesters.

Figure 2.1: Sand mining

Figure 2.2: Sand collection from source

2.2.6.2 Manufactured Sand

Manufactured sand is fine aggregate used for construction purposes, produced from hard granite stone by crushing, using the jaw, cone and vertical shaft impact (VSI) crushers (The Constructor, 2016). The VSI crusher has a unique design and action of attrition that produces particles that are cubical and angular in shape (Venkatarama, 2011). This process of attrition reduces the roughness of the fine aggregate particles to some extent. The size specification for manufactured sand is that it should pass completely through a 3/8-inch sieve. The crushed sand is washed and graded to the specifications of construction materials. The washing ensures the micro-fines (particles passing the 75um sieve) are controlled below 15% by weight. It is a popular alternative due to its availability and relatively cheaper transportation costs.

It offers an alternative that the manufacturer can customize to the requirements of the client, depending on the final concrete desired *(*Morrow, 2011). Depending on the equipment used, different types of manufactured sand are produced, with varying properties for use in specialized construction. Manufactured sand has also been observed to be an economical alternative as it prepared from waste stockpiles at aggregate crushing areas (Cepuritis, 2015).

Granite crusher dust, better known as robo sand, has been accepted as a suitable replacement for river sand in western countries (Malagavelli & Rao, 2010). Robo sand shows relatively positive results when used as a fine aggregate in concrete, with the compressive strength of concrete having constant slump decreasing linearly with increase in the percentage of fines (Misra, 1984). It is being promoted in India as a suitable replacement for natural sand to prevent its indiscriminate use (Common Floor, 2012).

The main problem with this aggregate is that it contains a large proportion of fines, leading to the general building contractors' association insisting that crushed rock sand is not a suitable replacement for natural river sand (Kwan, 2013). However, crushed rock fine can be processed with improved particle shape and size distribution, resulting in a better substitute for both natural river sand and crushed rock fines. Table 2.8 gives a comparison of natural river sand and manufactured sand.

Table 2.8: Comparison between Natural River sand and manufactured sand (Venkatarama, 2011)

Properties	River sand	M-sand	Advantages of- M sand
Shape	Spherical shape	Cubical shape	Higher cohesion and compressive strength
Gradation	Can't be controlled	Can be controlled	Reduction in voids and higher strength
Particles passing 75µm	Up to 3%	Up to 15%	Adjust water- cement ratio for higher limit
Clay and Organic Impurities	Likely to be present (retard setting and compressive strength)	Absent	Better concrete quality

These disadvantages can be reduced/corrected by ensuring the fine crushing and separation is done with specialist knowledge and technology. The end product should also be put through various rigorous tests to ensure it conforms to the required standards. The proper choice of raw material goes a long way in reducing the negative effects of manufactured sand and also helps in producing quality fine aggregate for concrete and mortar production.

2.2.6.3 Quarry Dust

Quarry dust is a by-product generated from quarrying activities involved in the production of crushed aggregates and has been suggested as a possible supplement for natural river sand, in order to help satisfy the construction industry's demand. (Balamurugan & Perumal, 2013) found that the defective grading and excessive flakiness of quarry dust reduced the 28-day compressive strength of concrete. Furthermore, (Raman, Zain, Mahmud, & Tan, 2005) says that incorporation of quarry dust as a partial replacement reduces the 28-day compressive strength of the concrete, while (Ukpata, Ephraim, & Akeke, 2012) says that quarry dust reduces the workability of concrete.

Quarry dust (waste fine) was found to enhance the slump and slump flow of fresh concrete, without affecting the unit weight or air content, but reduced the 28-day compressive strength of the hardened concrete (Safiuddin, Raman, & Zain, 2007). The use of quarry rock fine decreased the concrete's resistance to water penetration, but the initial surface absorption was below the maximum absorptivity of low absorptive concrete. The best performance for quarry dust was when it was used within the presence of silica fume due to its efficient micro- filling ability and pozzolanic activity. The strength properties (compressive strength, split tensile strength and flexural strength) of concrete are all maximum at 50% replacement of natural sand with quarry dust (Balamurugan & Perumal, 2013).

Quarry rock dust, when used as a partial or full replacement of natural sand may sometimes give equal or better results in concrete than natural sand, with regard to compressive and flexural strength (Ilangovana, Mahendrana, & Nagamanib, 2008). The strength of quarry rock dust is comparatively $10\% - 12\%$ more than that of similar conventional concrete (Nagaraj & Banu, 1996).

The discrepancy in the results obtained by the various researchers could be attributed to the different properties of the rocks available close to their locations. The use of quarry dust in Kenya is very scarce, if any, and there is no previous research done on the properties of locally available quarry dust and its effects on concrete production. This underscores the importance of conducting a study on the properties of quarry dust to determine its suitability for use as fine aggregate.

2.2.7 Concrete manufacture

2.2.7.1 Concrete mix design

The quantities of the constituents of concrete are determined using a mix design. Concrete mix design consists selecting and proportioning the constituents to give the required strength, workability and durability. The mix is designed for the 'target mean strength'which is the characteristic strength required for design plus the 'current margin' which is determined either statistically or specified depending on degree of quality control exercised in the production.

The British standards (BSI, 2001) have the following main controlling parameters; grade designation, type of cement, maximum nominal size of aggregate, maximum water-cement ratio, minimum cement content, slump, type of aggregate and use of admixture.

There are different types of concrete mix designs (MacGinley & Choo, 2003);

1) Designed mix, where strength testing forms an essential part of the requirements for compliance and
2) Prescribed mix, in which proportions of the constituents to give the required strength and workability are specified; strength testing is not required.

The single most important factor affecting concrete strength is water-to-cement ratio. For full hydration cement absorbs 0.23 of its weight of water in normal conditions. This amount of water gives a very dry mix and extra water is added to give the required workability. The actual water-to-cement ratio used generally ranges from 0.45 to 0.6 (MacGinley & Choo, 2003).

2.2.7.2 Concrete Handling, Placement and Curing

Handling of concrete should be done with care to prevent segregation and contamination by other aggregates or by deleterious materials. Coarse aggregates should be split into size fractions approximately 5 to 10, 10 to 20, 20 to 40 etc. These should be handled and stockpiled separately and remixed only when being fed into the mixer in the desired proportions. Care should be taken to prevent the breakage of the aggregates; particles greater than 40mm should be lowered into bins using ladders and not dropped from a height (Neville, 2011).

Concrete mixing can be done by hand mixing for small quantities and by use of a mixer for large quantities. Using a concrete mixer ensures uniformity in the mix by sufficient interchange of materials between different parts of the chamber. The number of revolutions determines the criterion for adequate mixing, about 20 revolutions are adequate. It is paramount that disturbance of the mix during discharge is minimal for uniformity. The efficiency of a concrete mixer is determined by the variability of the mix discharged without interrupting the flow of concrete. The method of discharge determines the concrete mixers; tilting mixer, non-tilting mixers and pan type mixers (Neville, 2011).

For small quantities of concrete, hand mixing is used where the aggregate is spread in a uniform layer on a hard, clean, non-porous base. Cement is then spread over the aggregate and the dry materials are mixed by turning over in the tray three times from end to end and cutting by shovel till the mix appears uniform. Clean water is then added gradually, mix turned over again three times till it appears uniform in colour and consistency (Neville, 2011).

To achieve the highest possible density of concrete the mix is compacted by vibration. Vibration is applied uniformly to the entire concrete mass to ensure all parts are fully compacted and prevent segregation due to over vibration. Upon vibration, the resulting concrete should be as workable as possible. Workability of concrete is the ease with which concrete can be handled to its finally compacted shape and is very vital in freshly mixed concrete. It is affected by the water-cement content and the aggregate size distribution (Neville, 2011). The three main characteristics of workability are consistency, mobility and compactibility. Consistency refers to the wetness or fluidity of concrete. Mobility refers to the ease with which the concrete mix can flow into and fill the formwork. Compactibility is the ease with which a given mix can be fully compacted, all the entrapped air being removed (Dhir & Jackson, 1996).

Concrete strength increases with age. The characteristic strength is determined within the first 28 days of curing, beyond which the strength increases slowly. Curing refers to the procedures used for promoting the hydration of cement and involves control of temperature and moisture movement from and into the concrete. Curing can be achieved by keeping the concrete element completely saturated or as saturated as possible until the water-filled spaces are substantially reduced by hydration products (Cabrera, Cussens, & J, 1992). Curing water should generally satisfy the requirements for mixing water, but it should be free from substances that attack hardened concrete (Neville, 2011). The relative humidity in the concrete has to be maintained at a minimum of 80%, to ensure minimum movement of water between the concrete and the ambient air. Loss of water in concrete leads to effects on strength development, increased permeability, plastic shrinkage and reduced resistance to abrasion (Neville, 2011).

Poor curing has a significant effect on concrete with higher water-cement ratio and concrete made from cement with a lower rate of strength development such as Ordinary Portland Cement (OPC). There are two methods of curing; wet curing and membrane curing depending on the conditions on site, size, shape and position of the concrete member. The period of curing depends on the severity of the drying conditions and the expected durability requirements (Neville, 2011). Minimum periods of curing are given in BS EN 206-1: 2007 and shown in Table 2.9.

Table 2.9: Minimum curing times (in days) (BSI, 2007)

Rate of gain of strength of concrete	**Rapid***			**Medium**			**Slow**		
Temperature of concrete, ◦C	5	10	15	5	10	15	5	10	15
Ambient conditions during curing									
No sun, rh≥80	2	2	1	3	3	2	3	3	2
Medium sun or medium wind or rh≥50	4	3	2	6	4	3	8	5	4
Strong sun or high wind or rh<50	4	3	2	8	6	5	10	8	5

Rh=relative humidity in per cent.

*Low water/cement ratio and rapid-hardening cement.

2.3 Concrete Use in the Construction Industry in Kenya

Kenya has in the recent past enjoyed a sustained and continuous economic growth; recording a growth of 4.4 % in 2011, 4.6% in 2012, 5.8% in 2013, 6.2% in 2014, 5.7% in 2015, 5.8% in 2016 and 3.1% in 2017 (KNBS, 2013- 2018).

This growth saw a parallel growth in the construction sector with increased cement consumption of 3.085 million tonnes in 2010 , 4.600 million tonnes in 2013, 5.197 million tonnes in 2014 , 6.353 million tonnes in 2015, 6.707 million tonnes in 2016 and 6.157 million tonnes in 2017 as shown in Figure 2.2 (KNBS, 2013- 2018).

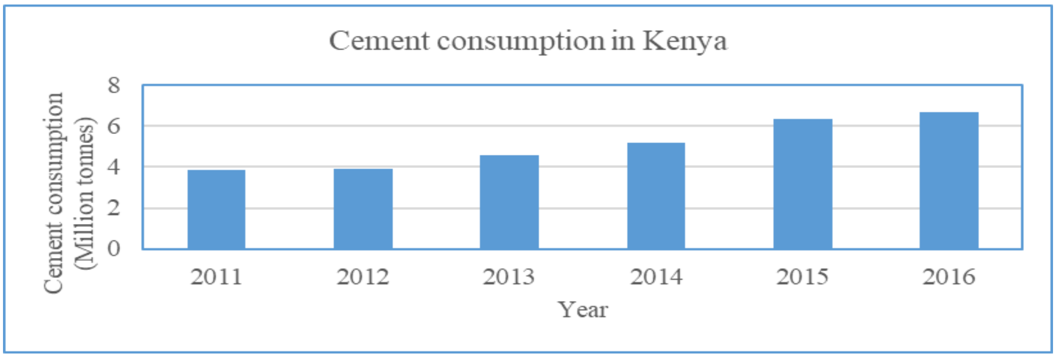


Figure 2.3: Cement consumption in Kenya

This huge consumption has been registered in the market by vibrant construction projects that are observed currently in the Nairobi metropolitan zone including other urban areas.

At the same time, the demand for other constituents of concrete production interalia, coarse aggregate and fine aggregate has continued in the same trend. In Kenya, continued mining of natural river sand has attracted attention from NEMA due to the extensive environmental degradation, especially in the semi-arid areas. This is echoed by (Ilangovana, Mahendrana, & Nagamanib, 2008), who underscore that large-scale depletion of natural river sand creates environmental problems besides being expensive due to excessive cost of transportation. In response to this, NEMA has sensitized the communities on the importance of safeguarding the environment and also created strict control measures with a view to ensuring sustainability in the sector. This has encouraged those in the construction industry to use alternative fine aggregate material in the production of concrete.

Many different types of fine aggregates have been explored for use globally including the possibility of replacing in full or partially the natural river sand. Ilangovana, cited in (Nisnevich, Sirotin, & Eshel, 2003), argues that quarry rock dust has been widely used in the developed countries of the west with limited use in India. In his study on the concrete produced with quarry rock dust in India, he established a 10% increase in performance than conventional concrete. Though this has been established elsewhere, its outcome cannot be assumed to be applicable locally since the composition of the physical and chemical properties of the material might be different.

(Koteng', 2013), in his study on concrete use for sustainable development noted that the stone dust from stone crushing quarries has not been widely used as fine aggregate. This study indicated that quarry dust could be used in the construction sites but what hinders its widespread use has not been established.

(Kuta & Nyaanga, 2014) in their research on the 'Effect of Quality of Engineering Materials on Construction and Quality Buildings' found out that the causes of failure are attributed to low quality materials and lack of quality assurance mechanisms. The study established that low quality sand contributed to the poor-quality concrete but did not define the sand type or qualifier parameters for low quality sand.

Hannah (2014) conducted a research on the effects of river sand quality on the compressive strength of concrete and established strength reduction due to silt opening a discussion for alternative sources for fine aggregates.

2.4 Concrete Quality in Construction

Quality is one of the critical factors in the success of construction projects. Project quality management are the processes and activities of the performing organization to determine quality policies, objectives and responsibilities so that the project satisfies the need for which it was undertaken. The major project quality management processes are quality assurance and quality control. Quality assurance is the process of auditing the quality requirements and the results from quality control measures to ensure appropriate quality standards and operational definitions are used. Quality control is the process of monitoring and recording results of executing the quality activities to assess performance and recommend necessary changes (PMI, 2008). The tools and techniques for quality monitoring include (Duncan, 1996);

1. Inspection – This involves measuring, examining and testing undertaken to determine whether results conform to requirements;
2. Control charts – These are graphic display of the results, over time, of a process and are used to determine if the process is under control. Control charts may be used to monitor any type of output variable;
3. Statistical sampling – Statistical sampling involves choosing a part of a population of interest for inspection. Appropriate sampling can often reduce the cost of quality control;
4. Trend analysis – Trend analysis involves using mathematical techniques to forecast future outcomes based on historical results. Trend analysis is often used to monitor;
    a. Technical performance – How many errors or defects have been identified, how many remain uncorrected and
    b. Cost and schedule performance – How many activities per period were completed with significant variances.

There are three elements to be controlled in a construction project: progress against time; cost against budget and quality against specification (Austen, 1995). Quality in construction typically involves ensuring compliance with minimum standards of material and workmanship in order to insure the performance of the facility according to the design (Hendrickson, 2008). This is in line with the eight dimensions of quality namely; durability, aesthetics, conformance, serviceability, perception, reliability, performance and features (Garvin, 1984).

Concrete is one of the major construction materials in building construction industry. To get quality concrete products, proper care and control has to be taken during selection of constituent materials and production processes. Professionals and firms involved in the construction industry should give special emphasis to quality control to ensure minimal re-work.

Re-work has a very high impact on project performance which results in projects over shooting their planned budget and planned duration, and degradation of project quality. It effects organisational performance leading to loss of profit/reduced profit, de-motivation of workers, and loss of future work/business (Chidiebere., 2018). (Davis, 1989) reported that rework can cause additional cost to construction of up to 12.4% of the total project cost. similarly, (Love & Edwards, 2004) affirmed that rework is a main contributor to time wastage and schedule overruns which ultimately impact on cost, resources and quality. Rework would naturally increase total project costs by 12.6% and the indirect cost of rework is as high as six times the cost of rectifying failures (Love P. E., 2002). According to (Cooper, 1993), rework emerges as overtime, additional resources such as labour, plant, workers, and reductions in project scope and quality and schedule slippage.

Studies have revealed that the consequence of poor-quality work such as rework are; denying clients value for their monies; dissatisfied customers; unsafe structures; contract disputes; battered reputation; resource wastage; loss of business; loss of profit/revenue; reduce market share; and increased time and cost of construction; extra charges, and increased professional fees (Simpeh, 2012).

While reliable building codes are widely used in design, builders in developing countries often fail to meet acceptable standards. Structural defects are frequently identified too late, often after catastrophic collapse (Raul H. F., 2014). In Kenya, building construction is one trade where any individual can join without a modicum of either academic and/or professional qualifications. The result has been the emergence of quack contractors (Mutiso, 1997). Today, the safety of buildings is compromised by the entry into the market of building materials which do not meet set standards. It has become evident that some developers avoid engaging competent professionals during the construction stage. This has been the case in many recent residential developments in major towns, particularly in Nairobi and a major contributory factor to recent collapses (Mutiso, 1997). It was noted that between 2006 and 2014, 17 building collapsed causing 802 deaths and 291 injuries (Raul, 2014). The Ministry of Nairobi Metropolitan in their study on the building safety and security in the built environment attributed building failure to, among others, poor quality of material and poor-quality concrete (Ministry of Nairobi Metropolitan, 2013).

The local authority personnel charged with the supervisory or inspection responsibility, have miserably failed to ensure that the various stages of construction comply with approved standards of design and safety (Mutiso, 1997). Raul (2014), in his study of strategies to reduce the risks of buildings collapsing in developing countries, noted that widespread fraud and the current quality control practices are not effective in ensuring structural reliability of new and existing buildings in Nairobi. Thousands of dangerously weak buildings will be built and millions of people will be exposed to unnecessarily high risks unless better quality control processes and regulations are implemented. Their efforts will be most effective if attention is given to the promotion and enforcement of prudent quality control protocols.

The effects of building structural failures cannot be overstated. The consequences are usually in the form of economic and social implications. These includes loss of human lives, injuries, economic waste in terms of loss of property, investments, jobs, incomes, loss of trust, dignity and exasperation of crises among the stake holders and environmental disaster. It should be noted that in the event of such causality, the reputation of the industry to deliver quality products becomes questionable, with the committed consequence of the Government resorting to the employment of the foreign professionals.

Quantitatively, the losses the Kenyan Government incurs due to poor quality construction is estimated to be 10% of the annual earnings (BORAQS, 2015) (Situma, 2013). Even with minor defects, re-construction may be required and facility operations impaired. Increased costs and delays are the result. In the worst case, failures may cause personal injuries or fatalities.

(Josephson, 2002) estimated that the cost of non-conformance amounted to 7.1% of total construction work hours. It is believed that the direct effects of redoing and rectifying poor quality work on project management businesses according to (Palaneeswaran, 2006) are; additional time for remedying failures and extension of supervision time among others.

2.5 Concrete strength modelling theory

The theories used in this research are the concrete strength prediction models. These include; the British standards (BS 8110) model, German model, Abrams' law, Bolomey's law and the ACI model. These theories are studies of the factors that influence the rate of development of strength in concrete.

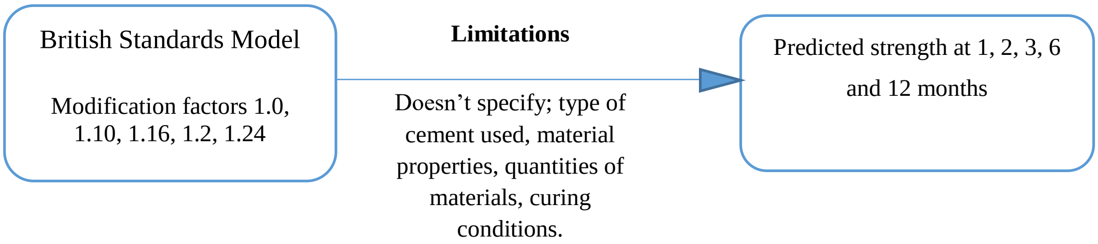
2.5.1 British standards (BS 8110) model

This theory was developed by the British Standards Institution (BSI). It intimates that compressive strength in concrete increases with age and gives modification factors for permissible strength as 1.0, 1.10, 1.16, 1.2 and 1.24 for 1, 2, 3,6 and 12 months as minimum age of member when full design load is applied. For high strength concrete, the British code allowed to add 0, 4.2, 5.5, 7.7 and 10.2 MPa over the permissible strength at 28 days for 1, 2, 3, 6 and 12 months, respectively (BSI, 1985). Table 2.6 shows the predicted compressive strength according to (BSI, 1985) for normal concrete cylinder.

Table 2.10: Predicted strength for normal concrete cylinder (BSI, 1985)

Grade	Characteristic strength Fcu	Cube strength at an age of				
		7 days	2months	3months	6months	1 year
	N/MM^2	N/MM^2	N/MM^2	N/MM^2	N/MM^2	N/MM^2
20	20	13.5	22	23	24	25
25	25	16.5	27.5	29	30	31
30	30	20	33	35	36	37
40	40	28	44	45.5	47.5	50
50	50	36	54	55.5	57.5	60

The British standards (BS) strength prediction does not specify the criteria used to come up with the modification factors; i.e. type of cement used, constituent material properties, quantities of materials used and curing conditions.



2.5.2 German model

In Germany, the relation between 28-day strength (fc28) and the 7-day strength (fc7), is taken to lie between,

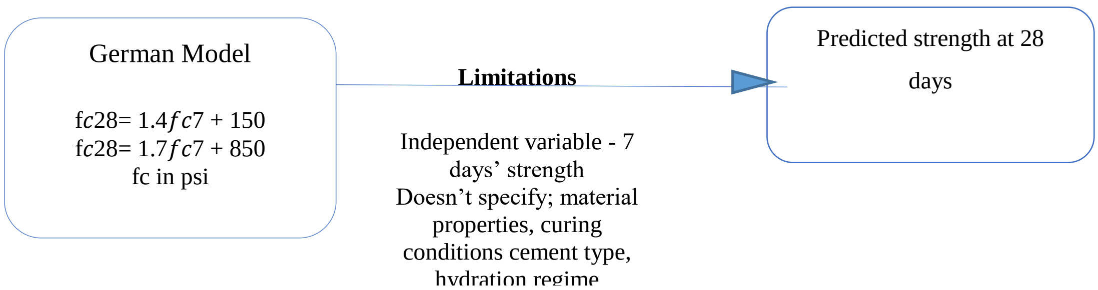
$fc28 = 1.4fc7 + 150$ ………………*equation -1* *(Shetty, 2006)* and

$fc28 = 1.7fc7 + 850$ ………*equation -2* *(Shetty, 2006)*

fc is being expressed in psi

where, fc7 and fc28 - strengths at 7 and 28 days, respectively.

This model does not take into account the constituent material properties, curing conditions and the cement type and hydration regime. The model also requires use of observed 7 days' compressive strength as a constant employed to predict concrete strength at 28 days which is not a good representation and therefore casts doubt on the model.



2.5.3 Abrams' Law

This model was developed by D. A. Abrams. It states that, "for a full compaction at a given age and normal temperature, the strength of concrete is inversely related to the water-cement ratio" (Abrams, 1919). The generally accepted rule is that an increase in the water-cement ratio decreases the concrete strength whereas a decrease in the water-cement ratio increases strength (A. Kapelko, 2013). This relationship can be expressed as in equation 3, in which A and B are constants whose values depend on the quality of the cement used, the age of the concrete, curing conditions etc, and w/c is the water-cement ratio.

$$fc = A/(B^\wedge w/c) \dots\dots\dots\dots\dots \textit{equation -3}$$

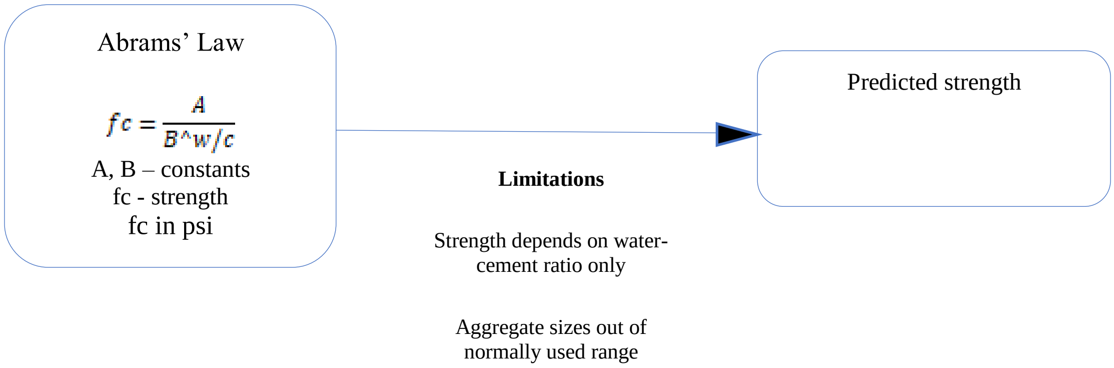
According to (Abrams, 1927) for 7 days, A and B take the values of 63.45 and 14 respectively resulting to equation 4.

$$fc7 = \frac{A}{B^\wedge w/c} = \frac{63.45}{14^\wedge w/c} \dots\dots\dots\dots\dots\dots\dots \textit{equation -4}$$

Further, the values given for A and B based on 28-day tests of 1:4 mix (cement/aggregate ratio), pebble aggregate graded 0-31.75mm, fineness modulus 5.75 are 96.3 and 8.2 respectively (Abrams, 1919) giving us equation 5.

$$fc28 = \frac{A}{B^\wedge w/c} = \frac{96.3}{8.2^\wedge w/c} \dots\dots\dots\dots\dots\dots\dots\dots\dots \textit{equation -5}$$

In Abrams' equation the strength of concrete at a given age and cured in water at a prescribed temperature is assumed to depend primarily on two factors only, the water-cement ratio and the degree of compaction (Abrams, 1919). Furthermore, the model uses aggregate sizes which are out of normally used range. This model is incomplete because different coefficients of proportionality values are needed whenever any factor affecting the strength of concrete changes. The coefficients of proportionality parameters depend on cement type and strength, aggregate gradations and proportions, admixtures, curing conditions, testing conditions and age of concrete (Moutassen, 2015). The model is also limited to predicting for 7- and 28-days age only.



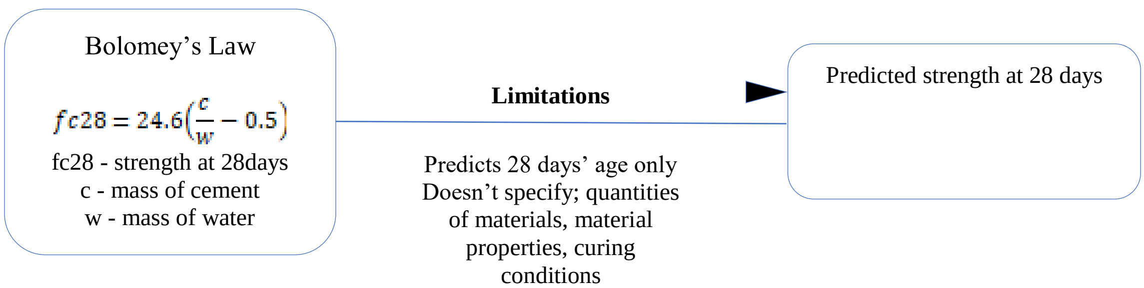
2.5.4 Bolomey's Law

Bolomey's law relates the cement-water ratio to the compressive strength of concrete containing normal weight aggregate. It gives the following relationship between concrete strength and concrete constituents for predicting the 28-day concrete strength;

$$fc28 = 24.6\left(\frac{c}{w} - 0.5\right) \ldots\ldots\ldots\ldots\ldots\ldots \textit{equation 6}$$

where *fc28*- strength at 28days, c- mass of cement, w- mass of water

Bolomey's prediction model is assumed to depend primarily on cement-water ratio. It doesn't take into account other factors like quantities of constituent materials, material physical and chemical properties and curing conditions. The model is also limited to predicting strength at 28 days age only.



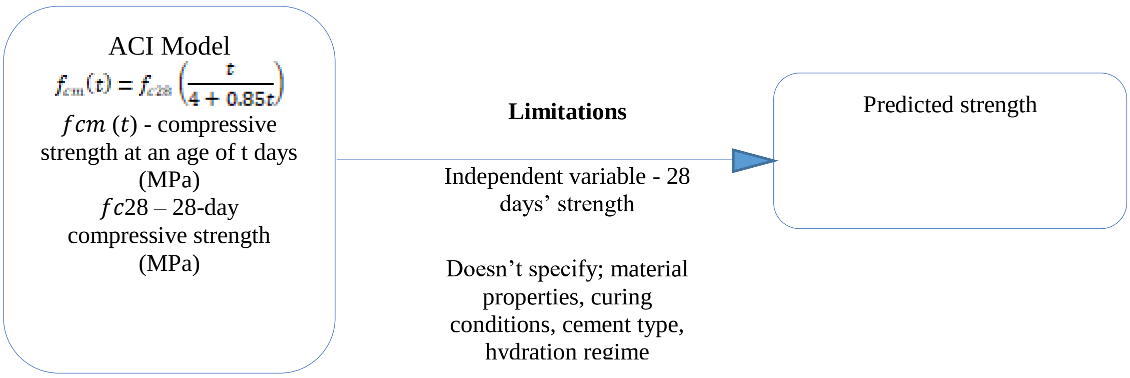
2.5.5 ACI Model

The ACI committee 209, in its research on prediction of creep, shrinkage and temperature effects in concrete structures and also on analysis of the prediction models, came up with Equation 2-7 for prediction of compressive strength of the standard concrete cylinder made with ordinary Portland cement which is moist-cured and tested in a standard condition. This equation can be used to predict the concrete strength over its lifetime (ACI Committee 209, 1997).

$$f_{cm}(t) = f_{c28}\left(\frac{t}{4+0.85t}\right) \ldots\ldots\ldots\ldots\ldots \textit{equation 7}$$

Where $f_{cm}(t)$ is the mean compressive strength at an age of *t* days (MPa)

f_{c28} is the mean 28-day compressive strength (MPa)



The ACI model does not take into account the constituent material properties and hydration regime. The model also requires use of observed 28 days' compressive strength as a constant employed to predict concrete strength throughout the lifetime of concrete which may be erroneous. This theory also limits the prediction to concrete produced using ordinary Portland cement.

As applied in this study, these theories hold the expectation that the concrete compressive strength (dependent variable) would be influenced by the following independent variables; water-cement ratio, cement-water ratio and generation of a formulae based on observed results.

This is not only erroneous but grossly understated and misleading. Other parameters including physical and chemical properties of the constituents of concrete and their influence on concrete strength cannot be ignored. Therefore, efforts should be concentrated on models that take into account the influence of different constituents' parameters on the concrete strength in order to have more reliable and accurate results for the prediction of concrete strength (Zain, 2008).

2.6 concrete performance modelling

Concrete performance modelling is a complex process due to the presence of different factors that contribute to the strength development with age. A number of modelling techniques have been used by researchers including artificial intelligence approaches and simulation models, empirical or computational modelling and statistical techniques.

An artificial neuron network (ANN) is a computational model based on the structure and functions of neural networks. A neural network consists basically of a number of simple processing units called neurons which are multilayered. This model requires preexisting data to predict to enable the concrete strength modelling which unfortunately may not be present.

Logistic Regression is defined as a classification algorithm that uses probability to determine the success or failure of an event. It is based on sigmoid function where output is probability and input can be the variables. It is used mainly in classification of a target variable (output) which can only take discrete values for a given set of inputs. Most versatile where dependent variable is dichotomous This would not be appropriate for Concrete modelling.

Polynomial regression is a regression analysis which shows the relationship between independent variable x and a dependent variable y and the dependent variable is represented as a nth degree polynomial in x. Polynomial regression model cannot be extrapolated hence making it difficult to accurately model the concrete strength gain.

Simple Linear Regression model estimates the relationship between one independent variable and one dependent variable using a straight line. This limitation in variables makes it inappropriate where more than one variables are involved.

Multi Linear Regression model is able to determine the relative influence of two or more predictor variables to the independent variable. This makes it offer much higher prediction accuracies than the simple linear regression model.

The consideration of different independent variables to examine compressive strength in Multi Linear Regression model makes it possible to identify any anomalies in the variants that determine the concrete strength. In Multiple Regression framework you not only estimate the dependence of the dependent variable on the input variables, i.e. the main effects but also the influence exerted on dependent variable by the interaction among these input variables. This offers MLR as the preferred method for concrete strength modelling.

2.6.1 Multiple Linear Regression Model (MLRM)

This is a statistical model used in research for data description and inference. Inferential statistics are used to answer questions about the data, to test hypotheses (formulating the alternative or null hypotheses), to generate a measure of effect, typically a ratio of rates or risks, to describe associations (correlations) or to model relationships (regression) within the data and in many other functions (Alexopoulos, 2010).

The choice of a statistical model is guided by the shape of the relationship between the dependent and independent (explanatory) variables. Modeling attempts to predict the outcome (dependent variable) based on values of a set of predictor variables (independent variables). These methods allow assessment of the impact of multiple variables (covariates and factors) in the same model. Regression analysis is often employed to model this relationship. There are various types of regression analysis and the model depends on the type of the distribution of the dependent variable (Rosner, 1995) (Draper & Smith, 1998);

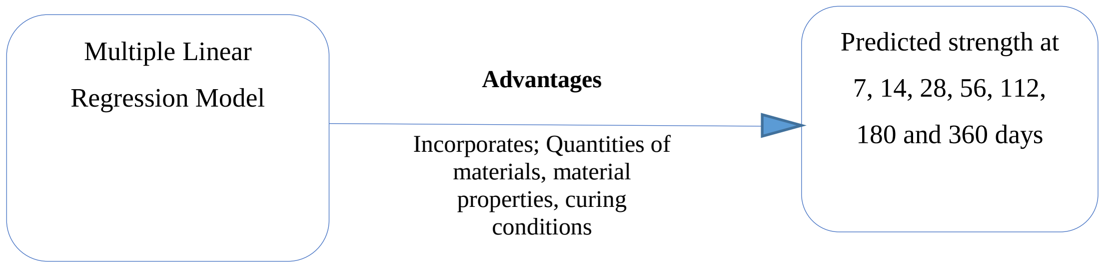
Multiple linear Regression model uses two or more independent variables to predict concrete compressive strength. The equation is of the form,

$$f = b_0 + b_1X_1 + b_2X_2 + b_3X_3 \ldots\ldots\ldots + b_nX_n$$

Where f is the dependent variable;

b_0, b_1, b_3 ......, b_n are coefficients;

X_1, X_2, X_3 ....., X_n are variables which can be replaced by the independent variables.



There are multiple benefits of using regression analysis;

1. It indicates the significant relationships between dependent variable and independent variables.
2. It indicates the strength of impact of multiple independent variables on a dependent variable.
3. It has the ability to indicate outliers or anomalies.

Broadly speaking, the multilinear prediction model is valuable for concrete practice and research purposes. In construction, the prediction models can be useful in estimating the strength of concrete at different ages. It may help to spot relatively high risks of failure in strength of concrete and allow preventive interventions. The research posits that multilinear prediction model could make better decisions based on approximate estimations of concrete strength. A summary of the different models in use and the respective shortcomings is shown in figure 2-4.

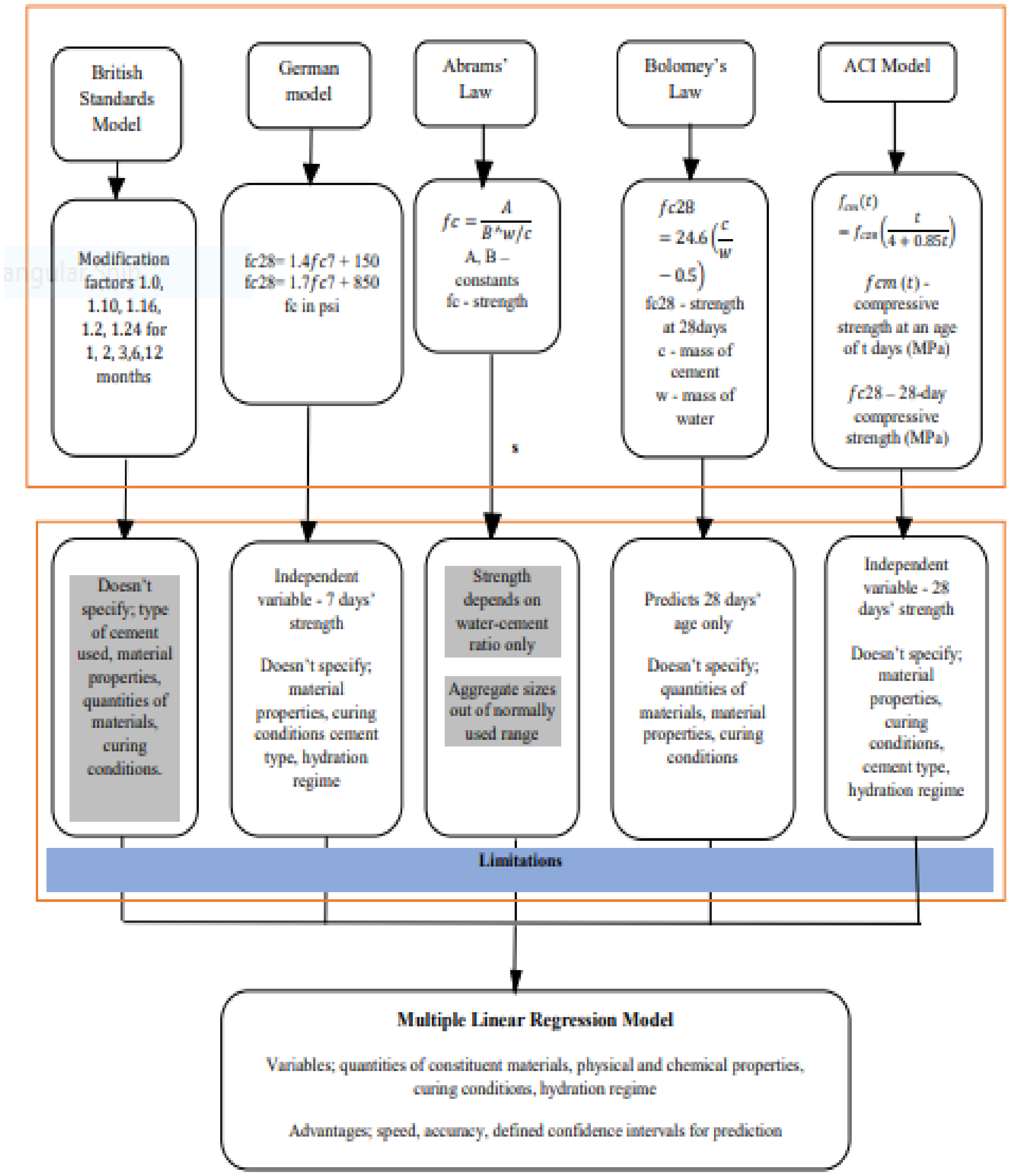


Figure 2.4: Theoretical framework

2.7 Conceptual framework

In order to achieve the new Performance model, the study has been conceptualized as shown in Figure 2.5. This can be expressed in the form fc= {weight proportions of aggregates, silicate, alumina, silt & clay}.

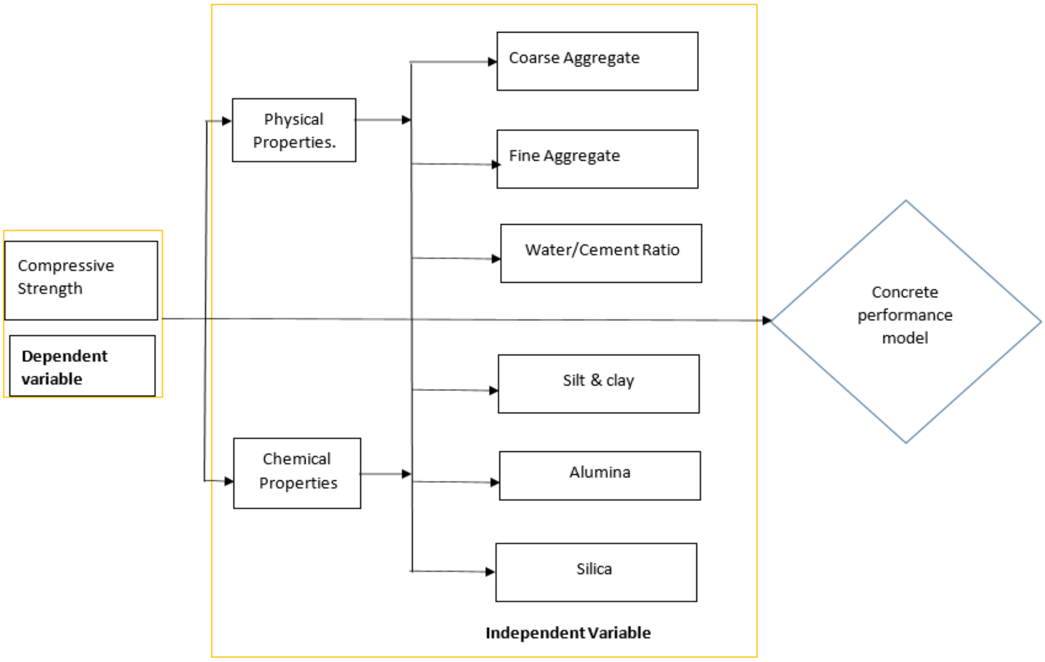


Figure 2.5: Summary of conceptual framework

In this research a relationship between the concrete strength and the constituent aggregate properties was established. The dependent variable was concrete compressive strength while the independent variables was classified under two categories; chemical and physical properties. The chemical properties that influence concrete strength are silica and aluminium oxide concentrations while the physical properties were identified as the weight proportions of fine and coarse aggregates,silt and clay content and the water & cement.

2.8 Summary of Past Studies on Concrete

Numerous studies have been done to establish the properties of concrete from which various limitations have been identified. These have helped the research to identify gaps, which this research attempts to address.

Table 2.11: Past studies and associated Research gaps

Article	Findings	Research gap
Victoria A. Okumu, 2016 The Effect of the Properties of Constituent Materials on the Quality of Concrete in Kenya "11"	➢ High silt & clay content reduces the compressive strength of concrete ➢ River sand contributes to higher compressive strengths in concrete than quarry dust when slump is fixed	➢ Research to be done on all other fine aggregates used in Kenya (Nairobi Metropolitan)
Hannah Nyambura Ngugi, 2014 The Effects of Sand Quality on Compressive Strength of Concrete: A case study of Nairobi County and its Environs. "12"	➢ Building sands used in Nairobi county and its environs contained silt and clay content that exceed allowable limits. ➢ Presence of impurities in sand significantly contribute to reduction in compressive strength of concrete which may lead to collapse of buildings if not addressed in the concrete design mix.	➢ The research attributed failure to achieve compressive strength to presence of impurities in the aggregates hence the need to research on other properties that influence strength in concrete.
David Otieno Koteng, 2013 Concrete use for Sustainable Development"13".	➢ Use of stone dust from stone crushing quarries has not been widely used as fine aggregates.	➢ Research to determine the suitability of quarry dust to be used as fine aggregates.
Joseph Kuta & Daudi M Nyaanga, 2014 Effect of Quality of Engineering Materials on Construction and Quality of Buildings "14"	➢ The cause of failure of structures are attributed to low quality materials and lack of quality assurance mechanism.	➢ Research on physical and chemical properties to determine suitability of different fine aggregates before use.
Ministry of Nairobi Metropolitan, 2013 Safety and Security of the Built Environment. "15"	➢ Material and poor-quality concrete contribute to buildings failures	➢ Need for sufficient research to ascertain the quality of different fine aggregates used in Nairobi Metropolitan.
Raul H, 2014 Strategies to reduce the risk of Buildings Collapse in Developing Countries.	➢ 75% of the buildings surveyed in Nairobi county had concrete that failed to meet the standards specified by the structural engineers	➢ Need for quality assurance in construction.
Concrete prediction models (BS, German, Abram, Bolomeys & ACI)	➢ Don't specify Material properties ➢ Prediction limited to 28days ➢ Strength based on W/C ratio only	➢ Need for a prediction model that incorporates material properties and prediction beyond 28 days
M.F.M Zain, Suhad M Abdi, M Jamil, Che-Ani A.I , 2008 Mathematics regression model for the prediction of concrete strength	➢ Mix constituents have an influence on concrete compressive strength	➢ Need for concrete prediction model that includes all variables affecting concrete strength

Conclusion

In Kenya various fine aggregates have been used in construction works. Key among these includes quarry dust, manufactured sand, sand from Naivasha and Natural river sands from different sources. Literature reviewed on past studies established insufficient data in the quality attributes of different fine aggregates used in concrete, the effect on the concrete performance. Further, the existing concrete strength prediction models are limited in days and material composition and therefore a more inclusive and long term modelling for predicting the concrete strength necessary.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

This chapter captures the methodology employed in achieving the set out objectives in the study. It discusses the philosophical assumptions underpinning the research strategy. It describes in detail the research design, sampling techniques, testing instrumentation and methods, data collection procedures, validation of the test results, processing and analysis techniques used in the study and formulation of concrete strength prediction model.

This research followed a quantitative approach with data collected based on the research objectives and hypothesis, tested and obtained results for use in the concrete performance and prediction model.

3.2 Philosophical Underpinning

Birks (2014) defines philosophy as "a view of the world encompassing the questions and mechanisms for finding answers that inform that view" (p.18). Philosophy helps to identify knowledge gaps upon which to base research and the method with which the gaps are filled (Mills & Birks, 2014). The philosophical underpinnings fall under a cohesive triad of basic beliefs about the ontology and epistemology which guide methodological choices (McManum, Mulhall, Mohamed, & Amr, 2017). Epistemology is the philosophy of how we come to acquire knowledge and the beliefs on the way to generate, understand and use knowledge that are deemed to be acceptable and valid (Wahyuni, 2012). Ontology refers to the individual's existing assumptions about reality and how they view the world. Together, ontology and epistemology describe what the researcher knows and how they gain knowledge (Norman & Yvonna, 2011) (Kerry, 2013).

The research approach taken for the first part of this study was the ontological objectivist approach whereby the phenomenon under investigation was taken as tangible and measurable. Quantitative research design was adopted due to the belief that all phenomena can be reduced to empirical indicators which represent the truth (Sales, Lohfeld, & Brazil, 2002). The researcher observed the acceptance and rejection of different fine aggregates used in Nairobi Metropolitan which triggered the study. Also observed was the use of these different fine aggregates in the same batching ratios without consideration of their different properties. It is believed that the Properties of the fine aggregates influence strength development of resultant concrete and hence the need to gather adequate data to justify the same. These quantifiable observations are more analytical in nature and lend themselves to statistical analysis (Remenyi, Brian, Arthur, & Ethne, 1998).

The study also adopted an epistemological approach which took the realist and positivist stance. Realism is the belief that reality exists independent of the human mind. It emphasizes the subject matter of the physical world, particularly science and mathematics (LeoNora & Gelbrich, 2019). In this study, the researcher believed that to understand the effects of different fine aggregates on concrete strength, all observable data (physical, chemical and mineralogical properties of the fine aggregates) had to be scrutinized. This was achieved through observation and experimentation.

The positivist paradigm asserts that real events can be observed empirically and explained with logical analysis. The criterion for evaluating the validity of a scientific theory is whether our knowledge claims are consistent with information we are able to obtain using our senses (Kaboub, 2008). To generate a research strategy to collect these data, the research used existing theory to develop a hypothesis. This hypothesis was tested and confirmed, in whole or part, or refuted, leading to the further development of theory which may then be tested by further research (Saunders, Lewis, & Thornhill, 2009). It is frequently advocated that the positivist uses a highly structured methodology in order to facilitate replication (Gill & Johnson, 2002). Furthermore, the emphasis is based on quantifiable observation that lend themselves to statistical analysis (Saunders, Lewis, & Thornhill, 2009).

3.3 Research Design

This research attempts to explore quality and performance model of concrete based on quality attributes of different fine aggregates. The main basis of the study is emerging use of different fine aggregates in Nairobi Metropolitan. The research paradigm followed is quantitative in nature using an experimental approach. Figure 3-1 demonstrates the design employed to achieve the intended aim of the study.

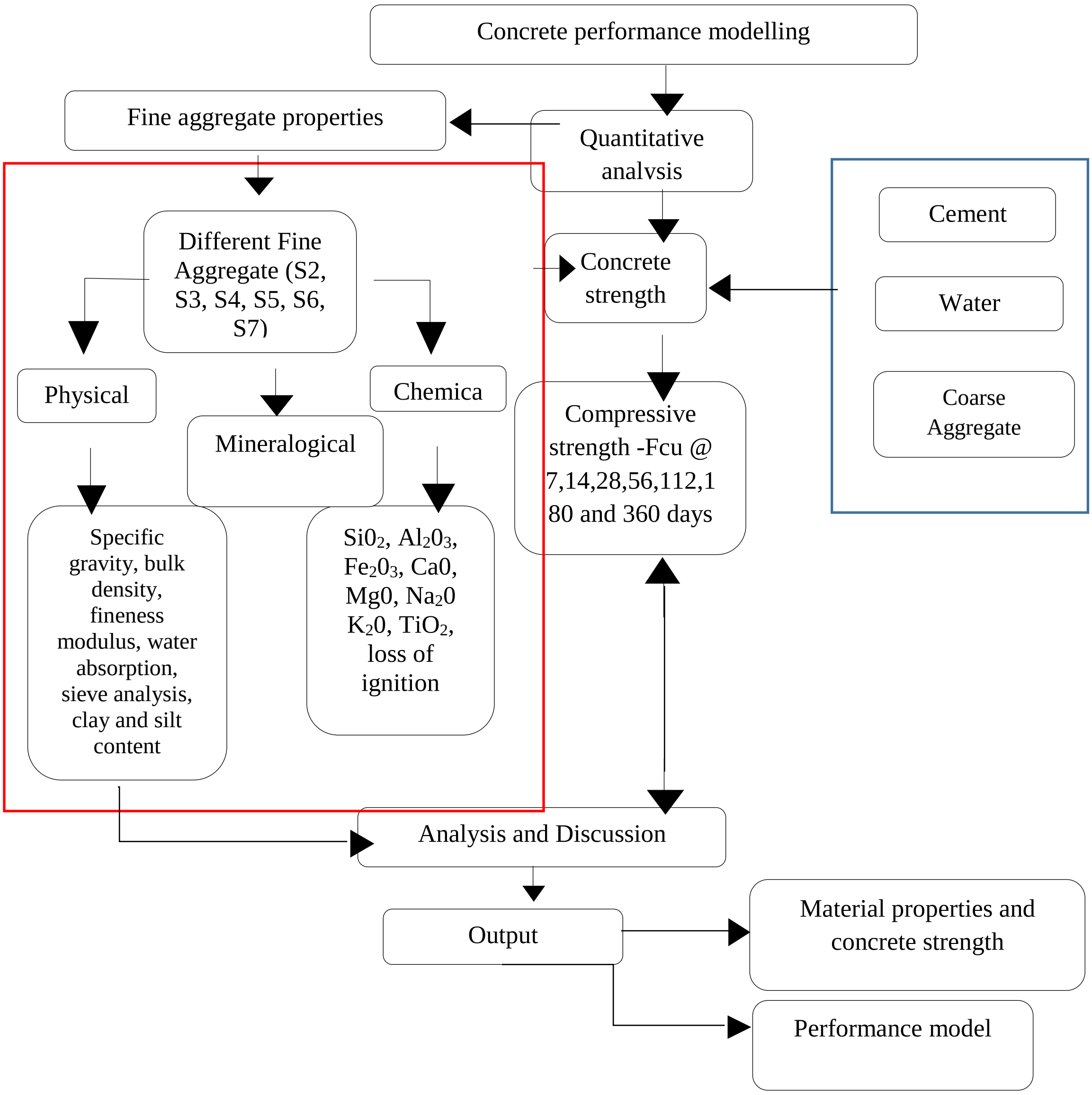


Figure 3.1: Research design flow chart

3.4 Research Methods

This section captures the method used in carrying out the research. It captures the material sourcing, sampling and use, sampling methods, material preparation, testing and equipment, Concrete mix design batching, curing, testing and concrete strength prediction modelling.

3.4.1 Material Sourcing and Sampling

Although the research is domiciled in Nairobi metropolitan, the materials were sourced from different locations. This was informed by the most commonly used sands within Nairobi Metropolitan. The sampling locations was based on the preferred harvesting zones. The geological locations of the sampling stations and their respective coordinates are shown in Figure 4.1.

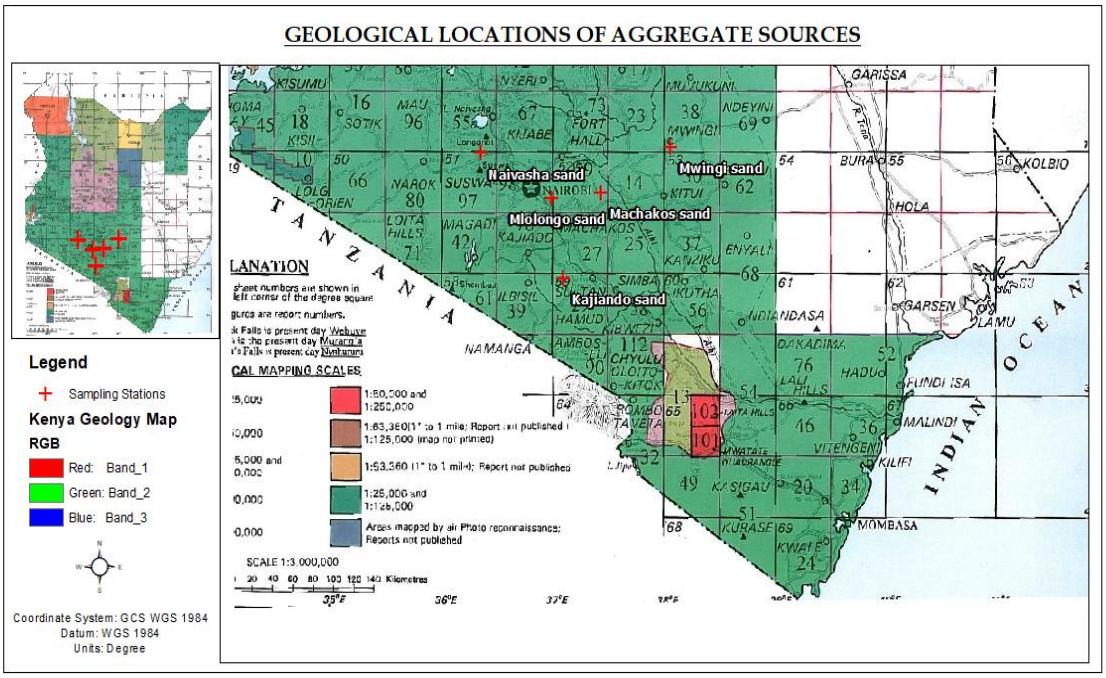


Figure 3.2: Geological and sampling locations of aggregate sources showing most popular sources of fine aggregates supplied in Nairobi Metropolitan.

The specific extraction points for the sand were natural river sands from Mwingi (00^0 58’ 4.36” S, 38^0 03’ 35.66” E), Machakos (01^0 20’ 29.4 ”S, 37^0 26’ 15.2” E) and

Kajiado (02^0 02’ 28.9” S, 37^0 06’ 43.7” E), quarry dust and rock sand from Mlolongo (01^0 23’ 11.1” S, 36^0 50’ 31.5” E) and Naivasha from Naivasha quarry (01^0 00’ 47.6” S, 36^0 21’ 19” E). Table 3.1 shows a summarized location where samples were obtained. This was informed and guided by the most popular extraction points.

Table 3.1: Sampling stations and their coordinates

Sample	Station location	Latitude	Longitude
S2	Mwingi	00^0 58’ 4.36” S	38^0 03’ 35.66” E
S3	Kajiado	02^0 02’ 28.9” S	37^0 06’ 43.7” E
S4	Mlolongo	01^0 23’ 11.1” S	36^0 50’ 31.5” E
S5	Machakos	01^0 20’ 29.4” S	37^0 26’ 15.2” E
S6	Naivasha	01^0 00’ 47.6” S	36^0 21’ 19” E
S7	Mlolongo	01^0 23’ 11.1” S	36^0 50’ 31.5” E

3.4.2 Relationship between Physical, Chemical and Mineralogical properties of Fine-aggregate (Objective 1)

In order to achieve the intended objective, different materials were subjected to testing and the results obtained compared with the existing British standards. Due to their different form in characteristic owing to their geological origins, the parameters served as a baseline for conducting performance of concrete made from the different fine aggregate materials besides establishing their suitability at the very preliminary stage.

3.4.2.1 Materials, testing and Instrumentation

The materials used in the research comprised of cement, coarse aggregates, fine aggregates and clean. Other than the fine materials which required testing for chemical & physical properties and Mineralogical composition, the rest were considered standard due to their controlled source and manufacturing procedures.

The sampling of each fine aggregate material was done in accordance with the British standards for each test parameter while crystalline formation was done using X –ray diffraction method and validated with Atomic absorption spectrometry.

3.4.2.2 Cement

The cement was normal setting Portland Cement class 42.5, designated as CEM I (EAS-KS, 2001).

3.4.2.3 Coarse Aggregate

The coarse aggregate used in the experiment was sourced from Mlolongo quarry, which produces crushed aggregate. It was necessary to use coarse aggregate from one source for all the specimens to ensure no variations brought in the experiment. The aggregate was purchased in separate batches with maximum aggregate size of 10mm and 20mm in the ratio 1:2 in line with the requirements of the concrete mix design using the Department of Environment/ British method (D.O.E). The aggregate was checked for particle shape, size and cleanliness.

3.4.2.4 Fine Aggregate

The fine aggregate was sourced from six locations that popularly supply the Nairobi Metropolitan area. The exact coordinates of the quarries from which these fine aggregates were collected was captured through Global Positioning System (GPS). This was done so as to describe the general geological and environmental phenomena occurring in the area, and the effect on the fine aggregate being sourced. The following are the fine aggregates and the designations that were provided during the experiment; S2 - Mwingi river sand, S3 – Kajiado sand, S4 – Rock sand, S5 – Machakos river sand, S6 – Naivasha sand and S7- Quarry dust.

3.4.2.5 Storage of Material-cement

The cement bags were stacked neatly (maximum of 10 bags) and stored on a raised platform within the laboratory. The bags were protected from puncture and great care taken to prevent any contact with moisture. The piles of cement were clear off the walls and adequate space was provided between individual piles to allow for easy access (about 900mm). Tarpaulins (water proof paper) were placed on top of the cement.

3.4.2.6 Storage of material -Coarse Aggregate

The ballast was stored in the open as the effect of weather elements are insignificant on its properties. However, care was taken to ensure the different maximum aggregate size heaps were not mixed to ensure consistency in the experiment, procedure and results achieved. Figure 3.1 shows the storage of the coarse aggregates used in the study.

Figure 3.3: Storage of coarse aggregates

3.4.2.7 Storage of Fine Aggregate

The different fine aggregates were stored in heaps in the yard separated by blocks to avoid mixing with each other as shown in Figure 3.2. The required testing samples were drawn in accordance to BS EN 932-1:1997 and put in bags to be taken to the laboratory for testing.

Figure 3.4: Storage of fine aggregates

3.4.2.8 Sampling for Fine aggregate material testing

The sampling of the fine aggregates from the piles was done by taking approximately equal amounts from different points over the complete stock pile. This was done in accordance to BS EN 932-1:1997 (BSI, 1997).

3.4.2.9 Material Testing

Cement was not subjected to tests in this research as it is produced under controlled industry conditions. Coarse aggregates were considered to be standard since they were common for all samples. They were only tested for aggregate crushing value to assess the strength. The variable in this study was fine aggregates which required to undergo testing.

3.4.2.10 Testing of Fine Aggregate

The procedures followed in administering these tests are outlined in the appendices. The tests were classified into physical, chemical and mineralogical property tests. The properties of these fine aggregates were not compared to standard sand. This is because standard sand does not define the chemical and mineralogical properties which depend on geological formation. Instead, the study ran a comparative analysis of the samples. For the physical properties, the results were compared to the British standards for sand as used in concrete manufacture to check conformance.

3.4.2.11 Physical Properties Tests

The physical characteristics of fine aggregates influence the properties of both freshly mixed and hardened concrete. In this study, the following physical properties have been considered; Grading, fineness modulus, silt& clay content, bulk density, specific gravity, water absorption, particle shape and texture. Aggregate grading affects relative aggregate proportions, cement and water requirements, workability, pumpability, economy, porosity, shrinkage and durability of concrete. The physical properties were established in accordance with the standards. The physical properties tested are shown in the Table 3.2.

Table 3.2: Physical properties test parameters, methods and specifications

Physical parameter	Tested method acceptable limits	Accepted limits
Bulk density	BS 812-2:1995 BS EN 1097-3:1998	NP
Particle density and water absorption	BS 812-2:1995	Table H1-water absorbtion against oven dried density
	BS 813-2:1995 BS 813-2:1995	Max 2.3%
Particle size distribution (grading)	BS 822	Grading curves
	BS EN 1260: 2002	Table 2- General grading requirements Table 11-max value of fines content Table B1 and B2- coarseness and fineness
Specific gravity	BS 812-2:1995	Min 2.6
Clay and silt content	BS 882	Max 4%
NP- No		

NP- Not provided

Bulk Density -The bulk density of the specimens was determined in accordance with the regulations set up in **BS EN1097– 3:1998**. The standard defines (loose) bulk density as the quotient obtained when the mass of dry aggregate filling a specified container without compaction is divided by the capacity of that container.

Particle Density and Water Absorption -These properties were determined following the procedure set out in **BS812– 2:1995**. Since the test involved fine aggregate, whose nominal size is less than 5mm, the pycnometer (gas jar) method was used.

Particle Size Distribution –The aggregate samples were graded in accordance with procedures set out in **BS812– 1:1992.** Variations in grading can seriously affect the uniformity of concrete (PCA, 2011). Very fine sands are often uneconomical; very coarse sands can produce harsh, unworkable mixtures. In general, aggregates that do not have a large deficiency or excess of any size and give a smooth grading curve produces the most satisfactory results (Camp, 2018). To give a visual representation of the grading, the results were plotted on a graph, whose ordinate indicate the percentage passing and the abscissa indicates the sieve sizes on the logarithmic scale. This was used to determine the suitability of the fine aggregates for concrete manufacture. Figure 3.4 shows the testing for particle size distribution in the laboratory.

Figure 3.5: Testing of fine aggregates

Fineness modulus -The fineness modulus of the specimens was determined in accordance with the regulations set up in **BS EN 933-8.** This was done by adding the cumulative percentages of the mass retained on each sieve divided by 100. This was used to determine the grading zone of the different samples that influence the water-cement ratio and workability.

Specific Gravity -This specific gravity of the samples was tested in accordance with British standard **BS 812-102:1995 C128**.

Clay Particles and Friable Materials- These properties were determined following the procedure set out in British Standard (BSI, 1992).

3.4.2.12 Chemical and mineral Properties Tests

The chemical properties were obtained using Atomic Absorption spectrometry (AAS) and validated using X-Ray Fluoresce (XRF) method. The mineralogical properties were determined using the X-Ray diffraction (XRD) method and counter checked with the geological formation of the catchment areas. The chemical properties tested in this study were; silicon dioxide, aluminium oxide, iron (III) oxide, calcium oxide, magnesium oxide, sodium oxide, potassium oxide, titanium dioxide and loss of ignition. The procedure followed to determine these properties is laid out in the British Standard **BS EN1744 – 1:2009**. The precise equipment used for the chemical analysis was the Bruker S1-Titan X-ray fluorescence machine (XRF) while the mineralogical composition was tested using the Bruker D2 phaser X-ray diffraction machine (XRD). The chemical properties tested are shown in the Table 3.3.

Table 3.3: Chemical properties test parameters, methods and specifications

Chemical parameter	Tested Method	Accepted limits
Silicon Dioxide	**BS EN 1744-1**	NP
Aluminium Oxide	BS EN 1744-2	NP
Iron III Oxide	BS EN 1744-3	NP
Calcium Oxide	BS EN 1744-4	NP
Magnesium oxide	BS EN 1744-5	NP
Sodium oxide	BS EN 1744-6	NP
Potassium oxide	BS EN 1744-7	NP
Titanium dioxide	BS EN 1744-8	NP
Loss of ignation	BS EN 1744-9	NP

NP- not provided

3.4.2.13 Comparative analysis of fine aggregate material and Mineralogical Properties

The Physical and chemical properties of the materials obtained for the six different types of aggregates were compared against the British standard parameters for sand. Variations were used in informing their influence on the quality of concrete. The Mineralogical composition of the materials obtained in the laboratory were checked against the established properties from the Ministry of Mining and Geological to validate the chemical composition of the different fine aggregates.

3.4.2.14 Data reliability and validity

Reliability refers to the consistency, stability or dependability of data. It is the state that exists when data is sufficiently complete and error free to be convincing for its purpose and context (Morgan & Waring, 2004). Similar results obtained from successive repeated experiments measures reliability (Fisher, Foreit, Laing, Stoeckel, & Townsend, 2002). The data is expected to meet the test of evidence in terms of sufficiency, competence and relevance as per the British standards for concrete manufacture and testing (Comptroller General, 2011).

The chemical property tests for the fine aggregates were done using Atomic Absorption Spectrometry and validated using X-ray fluorescence tests. Three tests run were done on all the physical properties from each material sample. The mineral properties were tested using X-ray diffraction method and counter-checked with data from the geological maps from the Ministry of mining.

3.4.3 Concrete strength and prediction models comparative analysis (Objective 2)

Concrete was made from different fine aggregate materials and cured for a total of 360 days. The strength of concrete at different ages namely 7, 14, 28, 56, 112, 180 and 360 days were tabulated and a strength development curve generated. This was further compared with the existing models after British standards, German, Bolomys and ACI to establish the behavior and therefore the acceptability of the concrete obtained from the different materials.

3.4.3.1 Concrete Mix design

The fine aggregate physical properties were used in the determination of the various proportions in the mix design. The Department of Environment (D.O.E.)/British method was used to produce grade C30/37 concrete for the different fine aggregates as per the British standards. The key parameters considered were grade designation, type of cement, maximum nominal size of aggregate, maximum water-cement ratio, minimum cement content, slump and type of aggregate.

3.4.3.2 Concrete batching, mixing and Placement

Weight batching was used to proportion the concrete mixes; a concrete mix design is the ratios adopted for the production of concrete are as generally accepted. Batching by weight is more accurate than batching by volume since weight batching avoids the problem created by bulking of damp sand (Mamlouk & Zaniewski, 1999). Concrete block cubes of dimension 150mm depth, 150mm length and 150mm width were prepared from the fine aggregate specimens and tested at specific intervals to determine their strength development characteristics. A total of 27 cubes were done for each material. The blocks were cast on metallic concrete cubes.

The concrete was mixed manually using shovels taking care to be fast enough to ensure the time difference between the first and last cubes to be cast that would not affect the strength development. The mixing was carried out following the guidelines prescribed in the standards.

The concrete volume for each sample was;

Concrete volume; $0.15 \times 0.15 \times 0.15 = 0.081 + 10\%\ wastage = 0.0891\ m^3$

Figure 3.6: Concrete mixing and slump testing

The concrete was poured into the moulds by hand using a shovel. Care was taken to avoid dropping the concrete through a height of more than 0.5m or throwing across a distance sufficiently large to cause segregation. Concrete was filled in the cubes as shown in Figure 3.7 in three layers with each layer receiving 25 blows from a 1kg rod dropping a height of 600mm. Compaction of the concrete was done with the use of a poker vibrator. Each mould was stored carefully to avoid mixing the cubes and allow for marking after they hardened. The cubes were marked indicating the sand type (S_n), concrete grade $(C30/37)$, slump and the date and time of casting. The markings were made by indenting the surface of the cubes as shown in Figure 3.8.

Figure 3.7: Concrete placement and marking

3.4.3.3 Curing of Concrete

Plastic drums were used to cure the concrete cubes due to their relatively high capacity, durability and availability. The drums have dimensions of 880mm height and 570mm diameter. One drum was used to hold only one set of cubes prepared from one type of fine aggregate, to prevent any accidental mixing and provide redundancy should the marking on the cubes become indiscernible. Six drums were used for this experiment. The concrete made from the samples were moist cured for 28 days and thereafter left in laboratory air for the remaining duration up to 360 days.

Sample	S2	S3	S4	S5	S6	S7
C30/37						

Figure 3.8: Drums for curing of concrete cubes

3.4.3.4Concrete Testing

The concrete cubes were tested for compressive strength using the universal testing machine (UTM). To achieve reliability, three cubes for each sample were crushed on the 7^{th}, 14^{th} and $28^{th\ 56th}$, 112^{th}, 180^{th} and 360^{th} days the mean of the values of strength from the three cubes taken as the compressive strength for that particular batch. The compressive strength of the concrete cubes was tested in accordance to (BSI, 2009).

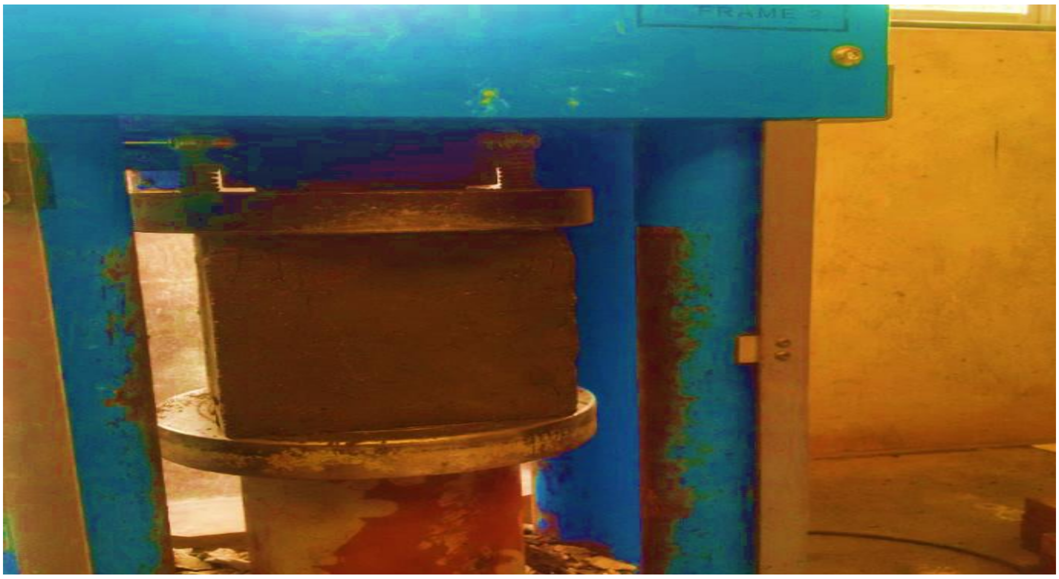


Figure 3.9: Compressive strength testing in the laboratory

3.4.3.5 Concrete strength comparative analysis.

The results of the cube strengths obtained were analyzed for strength development over the period and compared with the exiting prediction models to assess the degree of suitability of the concrete made from the different materials. The models used for comparison w*ere Bs8110, German, Bolomy and ACI.*

3.4.3.6 Concrete strength reliability and Validity

Reliability was achieved by the crushing of three cubes for each sand-type, and characteristic strength combination and the mean value for the three cubes taken as the actual result. The acceptability of the results were based on the crushed cubes being within 10% of each other (BSI, 1983). The compressive strength results were counter-checked by a second run of concrete casting and testing of the same samples.

3.4.4 Concrete Performance modelling and Validation (Objective 3)

The strength development curves for concrete with each type of fine aggregate was then drawn. The validity of the compressive strength tests was checked using the already available values for the compressive strength measured at different intervals from relevant sources.

Statistical modeling was used in the formation of the strength prediction model. Multiple linear regression analysis was conducted on the data sets using Advanced Excel software. This method was preferred because the formulating datasets had more than one explanatory variable with one dependent variable whose values were continuous and approximately normal. This method also has the ability to show anomalies and outliers in the statistical analysis.

The dependent variable was concrete strength at different ages. The independent (explanatory) variables included quantities of the fine aggregates, coarse aggregates, water and cement used in concrete production, concentrations of silica and alumina, silt & clay content and water-cement ratio. Regression coefficients were obtained and checked against the minimum allowable confidence intervals to ascertain validity of the model.

3.4.4.1 Data Analysis

Data analysis refers to the examination and summarization of data with the aim of extracting useful information and coming up with conclusions. It entails the 'cleaning', sorting and coding of raw data collected and processing it for purposes of interpretation using Microsoft Excel.

The Concrete strength data obtained over a period of 360 days was tabulated for analysis using multiple linear regression model. For each fine aggregate material, a set of 3 results at each testing age were tabularized. To complete the data set, physical and chemical properties were added in the matrix to achieve more holistic and inclusive results. The strength of concrete considered were at 7, 14, 28, 56, 112, 180 and 360 days. The Physical and chemical parameters were the mass of Fine and Course aggregate, water content, cement weight, Percentage of Silicon dioxide and Aluminum oxide in the Fine aggregate material, Silt & clay and Water cement ratio. The Strength of concrete at the respective age of concrete was used as the dependent variable and all the other parameters as independent variable. Descriptive and inferential statistical methods were used to analyze the data collected to observe any patterns and correlations that may exist. The coefficients obtained for each dependent variable gave the size of the effect on the dependent variable. The sign on the coefficient depicts the direction of effect of the variable on the dependent variable. The Coefficient of determination (r^2) showed the fraction of the dependent variable accounted for by the independent variable. A coefficient of determination of more than 75% was considered significant. A small value of F-significance implied model significance. The data has been presented with the aid of tools such as pie charts, graphs, tables and statistical equation models.

3.4.4.2 Data Reliability and Validity

Reliability in the multiple-linear regression model was achieved by using strength results obtained from the first run of concrete to formulate the model for the different ages of concrete up to 360 days. The validation of the finally developed model was carried out using a different set of strength test results obtained from a second run of concrete casting running for 180 days and not included in the formulation of the model.005C\\\\\\ Figure 3.8: Drums for curing of concrete cubes.

CHAPTER FOUR

RESULTS AND DISCUSSION

This section captures the presentation of the results, discussion on the science and interpretation of their relevance. It covers the objectives of the study supported by the data obtained from the methods used to achieve the intended purpose. The geographical locations of the sample sources of the fine aggregates, research gap and methods have been revisited. The results and analysis of tests done on mineralogical, physical and chemical properties of fine aggregate samples, results and analysis of the compressive strength of the resulting concrete from each aggregate sample and the strength prediction model over 360 days has been covered

4.1 Study and sampling Area

The geological locations of the sampling stations and their respective coordinates are shown in Figure 4.1. These are the most popular sources of fine aggregates supplied in Nairobi Metropolitan.

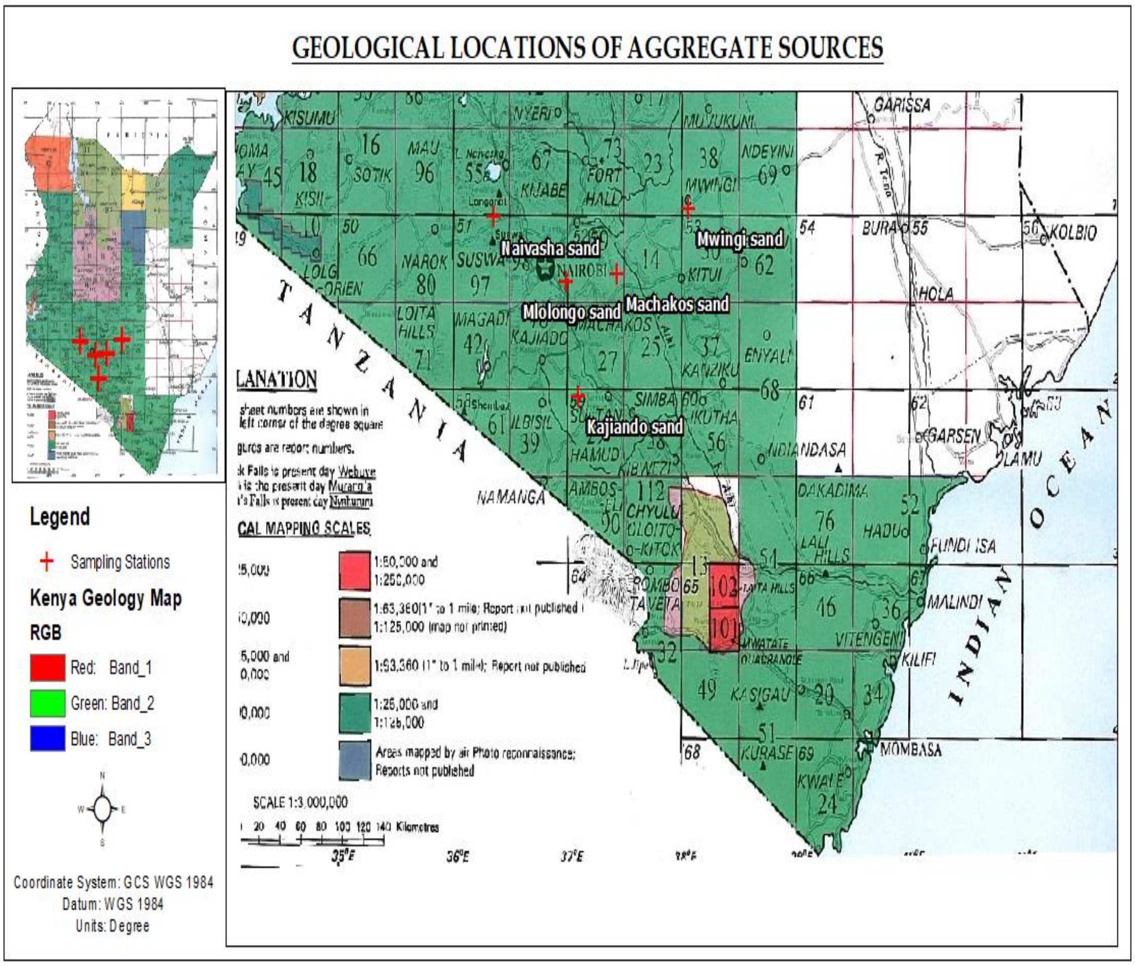


Figure 4.1: Geological locations of aggregate sources

4.2 Establishing the Relationship between Mineralogical, Physical and Chemical Properties of Fine Aggregates (Objective1).

The fine aggregates were subjected to mineralogical physical and chemical properties tests to check whether they were within the recommended limits for concrete production and therefore suitable for concrete production.

4.2.1 Crystalline formation of aggregates- Mwingi River sand.

The assessment and understanding of the crystalline nature of the fine aggregate materials was established by reviewing the geological formation of the catchment area of each source of aggregate. This sand was sampled from a local river at Mwingi, location coordinates 00^0 58' 4.36" S, 38^0 03' 35.66" E. The geographical presentation of the catchment area is as shown in Figure 4.2.

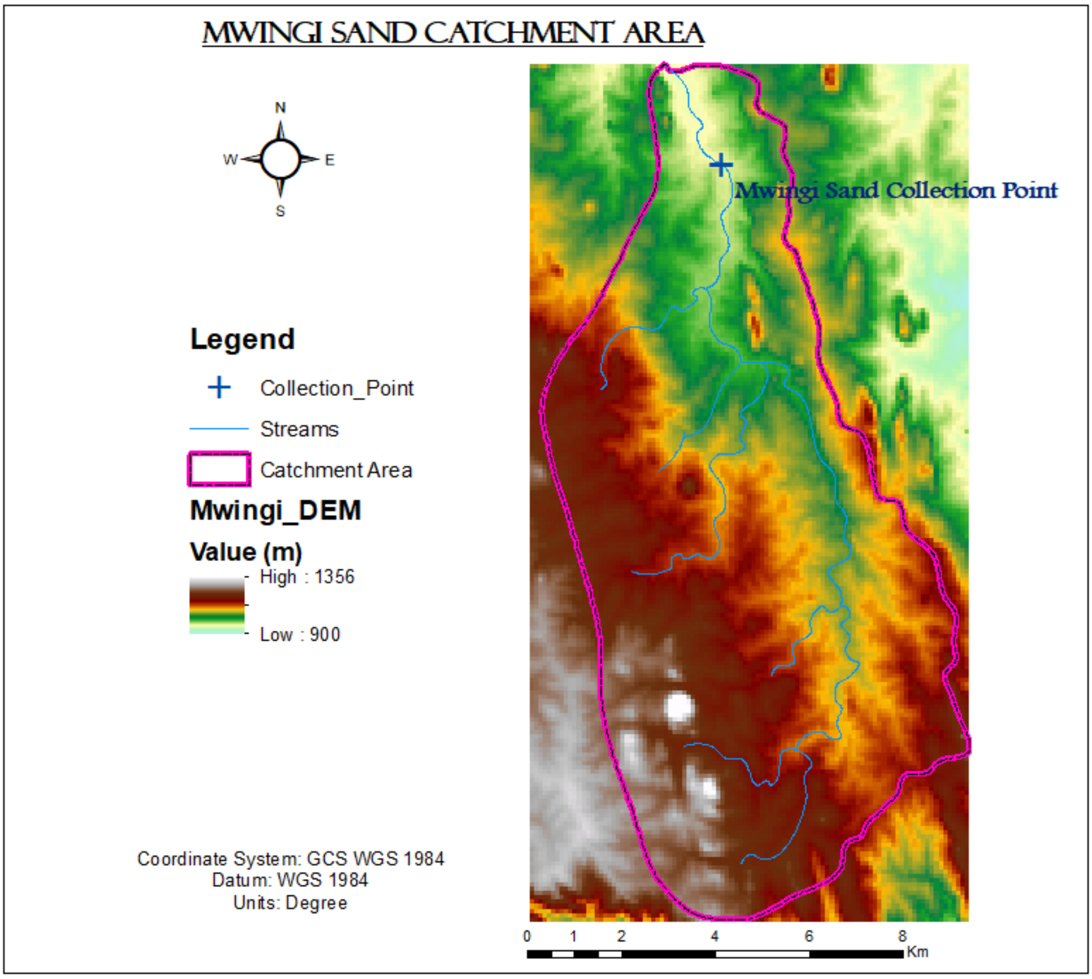


Figure 4.2: Mwingi river sand (S2) catchment area

The XRD laboratory test results for Mwingi river sand are shown in Figures 4.3 and 4.4.

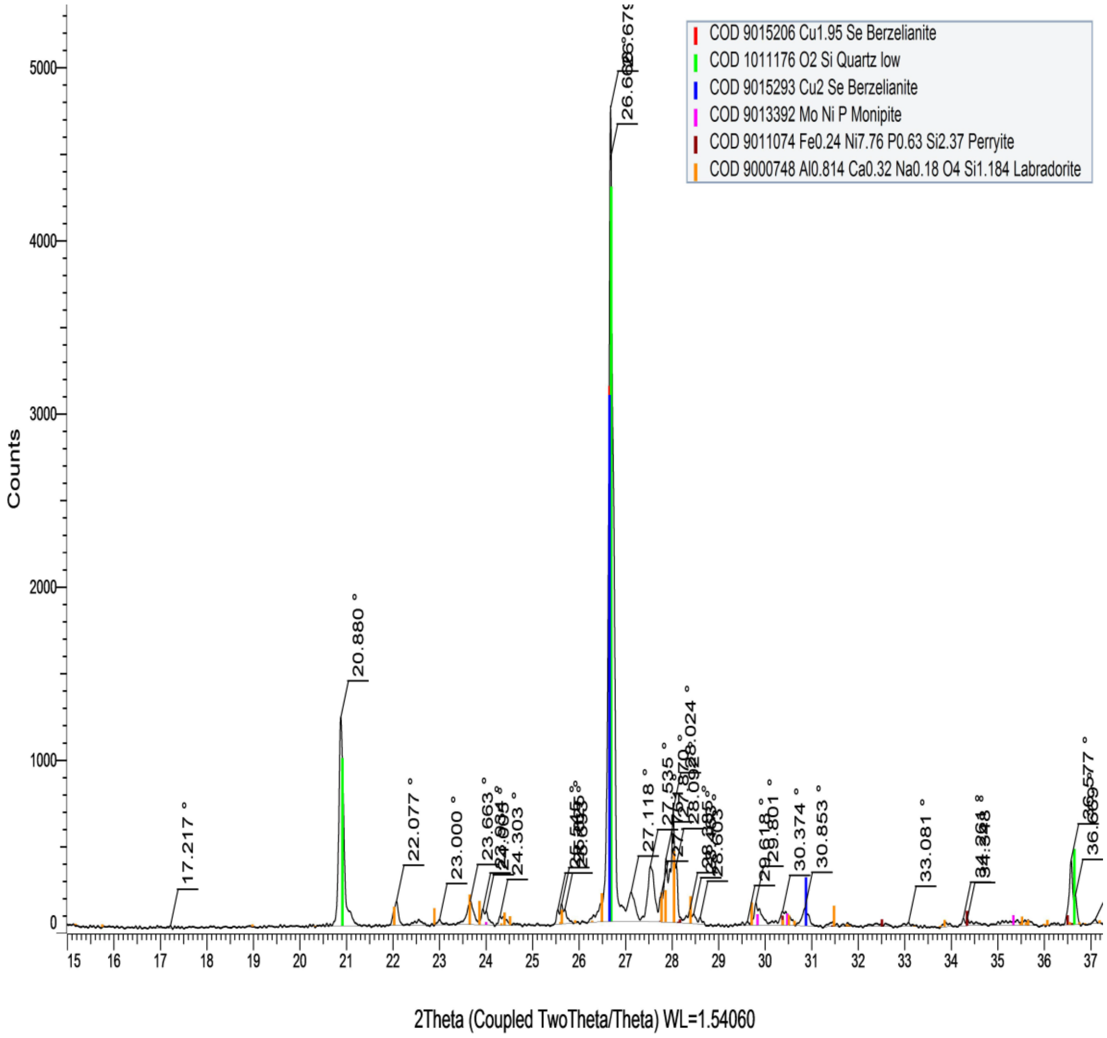


Figure 4.3: X-ray patterns (nm) of S2 (Mwingi river sand)

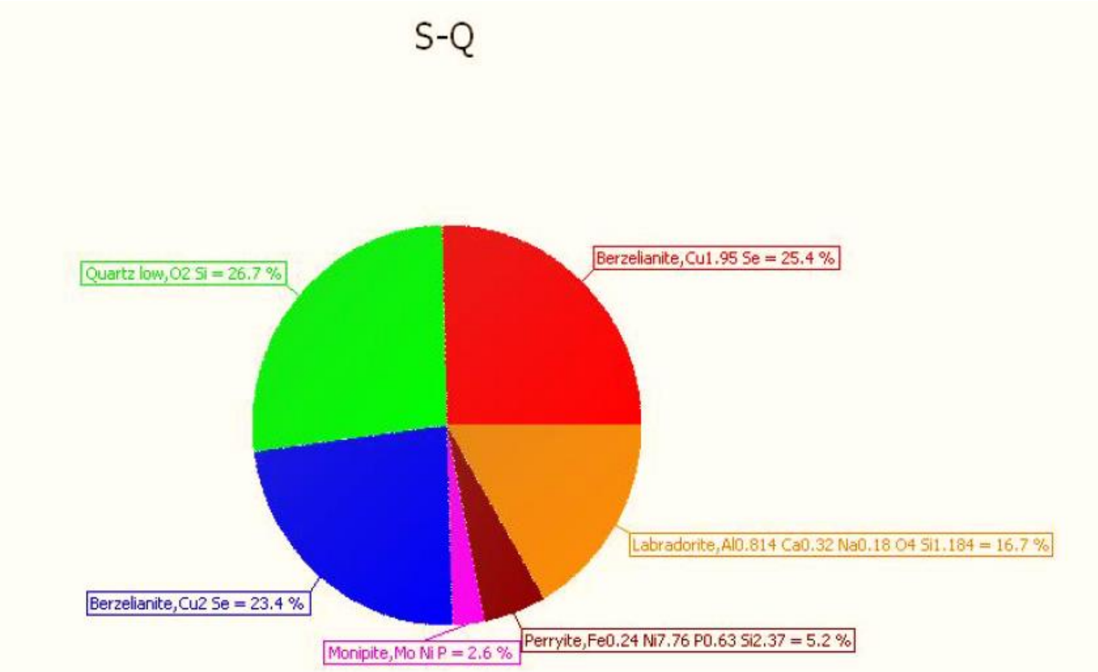


Figure 4.4: Mineral constituents of S2 (Mwingi river sand)

Figure 4.2 shows the extent, material travel distance and altitude of the catchment area. The Sample drop height is 436m with an estimate longest travel distance of 30 kilometers. The attrition effects on the material generates smooth and round shaped aggregates suitable for concrete. Figure 4.3 and Fig 4.4 shows the laboratory test of the samples and gives a crystalline structure of sand. The results obtained shows a fine aggregate material with dominant quartz low and berzalianite minerals and traces of monipite, labradorite and perryite. Quarts and berzalinites have tough and malleable properties ideal for concrete.

From the geological survey of the area as obtained from the geological map of Mwingi area, report No 38-degree sheet 45 S.W quarter, indicates a highly metamorphosed series of sedimentary origin. The rocks mainly constitute quartz and iron oxides minerals (Crowther, 1957). Our laboratory findings are validated by the existing research data on the mineralogical properties of sand from the area.

It was deduced from the analysis that the minerals of the tested sample besides being similar to the mineral composition of the rocks at the catchment area, they have properties which are good for concrete production.

4.2.2 Crystalline formation of aggregates - Kajiado river sand

This sand was sampled from a local river at Kajiado, location coordinates 02^0 02' 28.9" S, 37^0 06' 43.7" E. The geographical presentation of the catchment area is as shown in Figure 4.5.

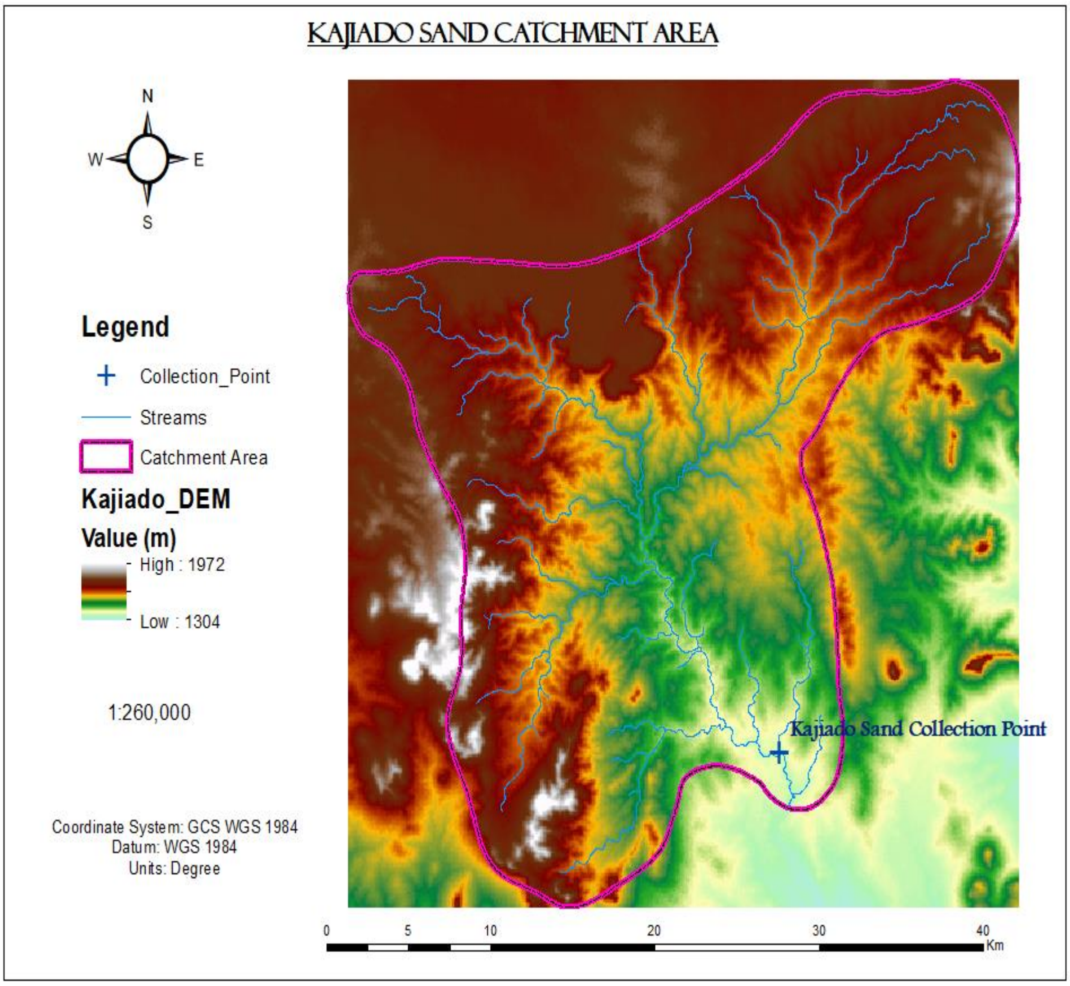


Figure 4.5: Kajiado river sand (S3) catchment area

The XRD laboratory test results for Kajiado river sand are shown in Figures 4.6 and 4.7.

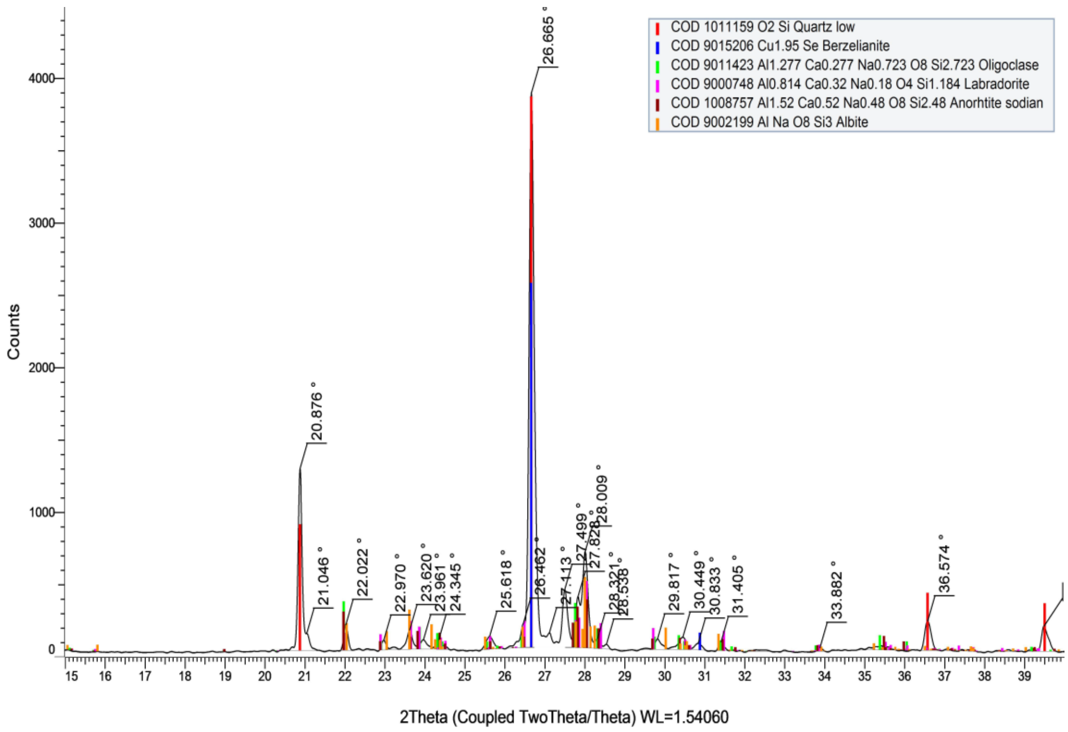


Figure 4.6: X-ray patterns (nm) of S3 (Kajiado river sand)

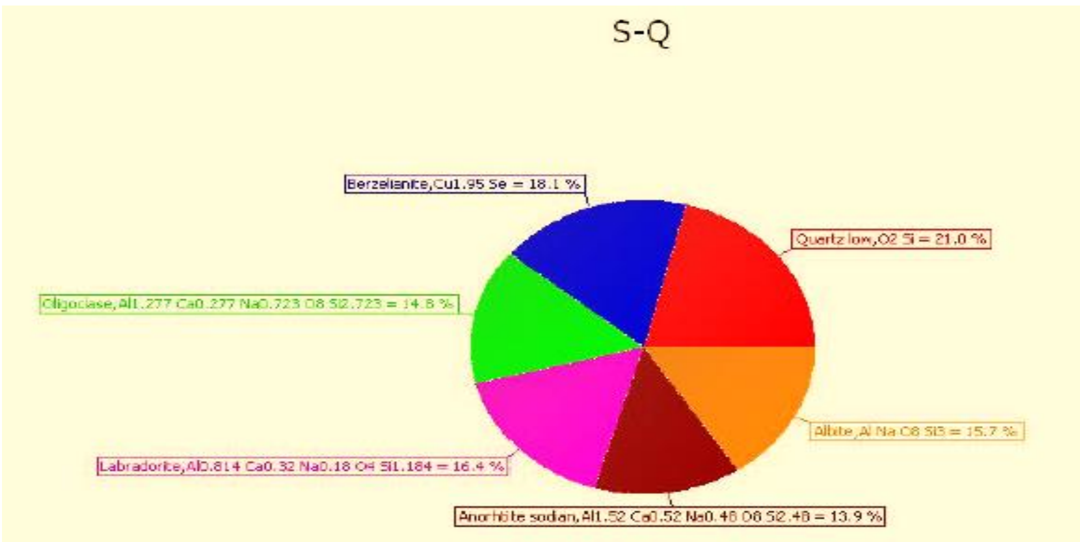


Figure 4.7: Mineral constituents of S3 (Kajiado river sand)

Figure 4.5 shows material drop height as approximately 650 m with an estimate longest travel distance of 100 kilometers. The attrition effects on the material generates smooth and round shaped aggregates suitable for concrete. Figure 4.6 and Figure 4.7 shows the laboratory test of Kajiado river sand and gives a crystalline structure of quartz low, berzalianite, labradorite, albite, oligoclase and anorhtite sodian in almost equal distribution. This indicates a balanced basaltic aggregate with strong and hard properties appropriate for concrete

The geological survey of the area as obtained from the geological map of Kajiado area, report No 70 degree sheet 51 S.E quarter, indicates the presence of volcanic rocks mainly consisting of basalts, alkali trachytes and pyroclastics. These rocks are mainly composed of labradorite, orligoclase and quartz (Matherson, 1964). Our laboratory findings are validated by the existing research data on the mineralogical properties of sand from the area

It was deduced from the analysis that the minerals of the tested sample besides being similar to the mineral composition of the rocks at the catchment area, they have properties which are good for concrete production.

4.2.3 Crystalline formation of aggregates -Rock sand

This sand was sampled from a quarry at Mlolongo area, location coordinates 01^0 23’ 11.1” S, 36^0 50’ 31.5” E. The geographical presentation of the catchment area is as shown in Figure 4.8.

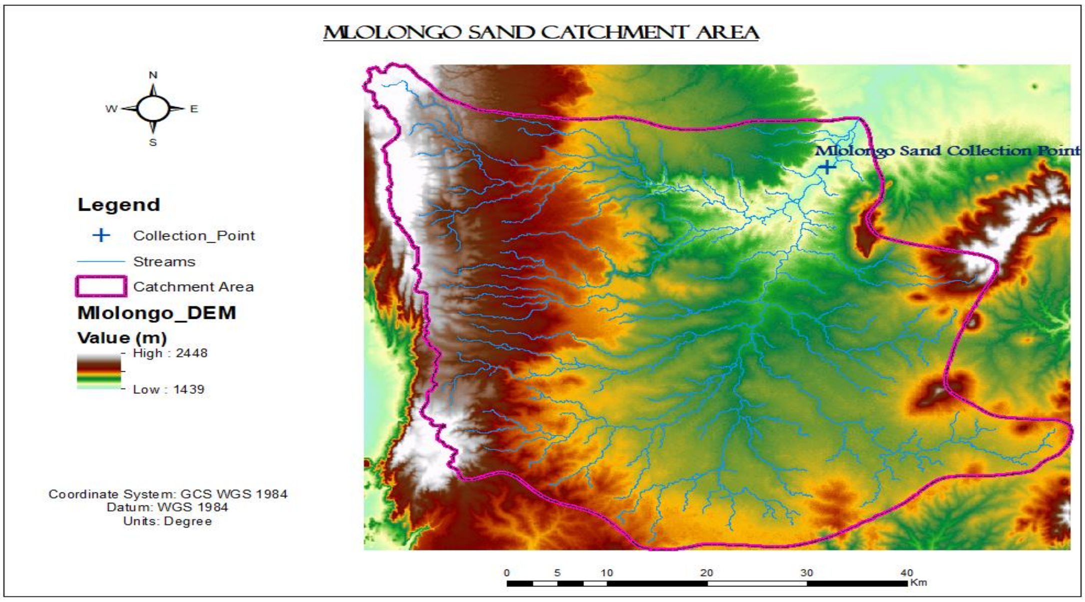


Figure 4.8: Rock sand (S4) catchment area

The XRD laboratory test results for rock sand are shown in Figures 4.9 and 4.10.

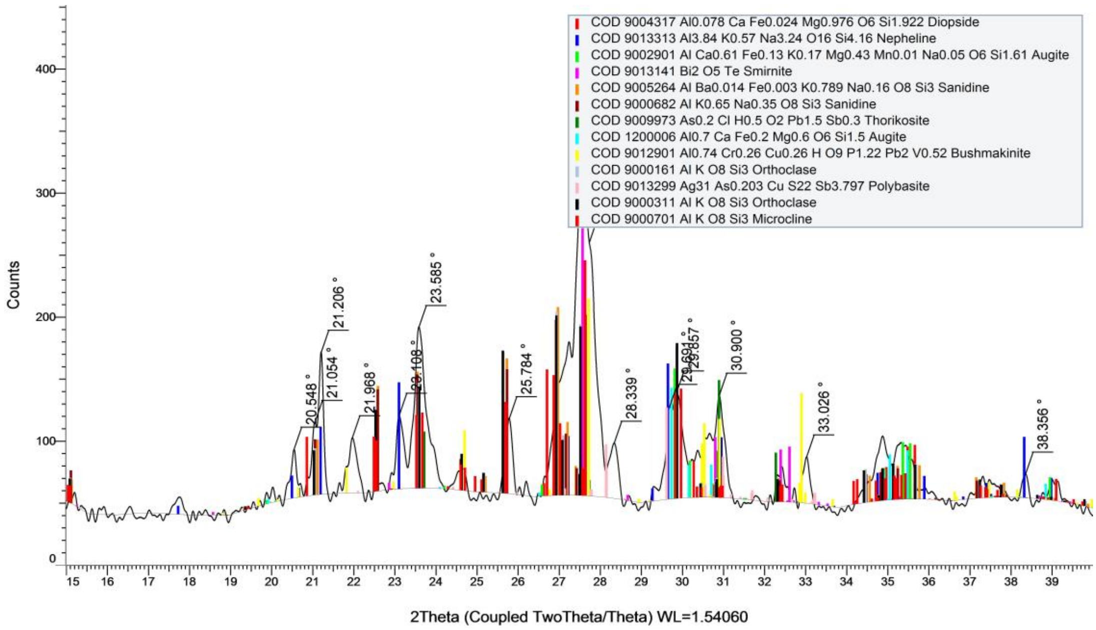


Figure 4.9: X-ray patterns (nm) of S4 (rock sand)

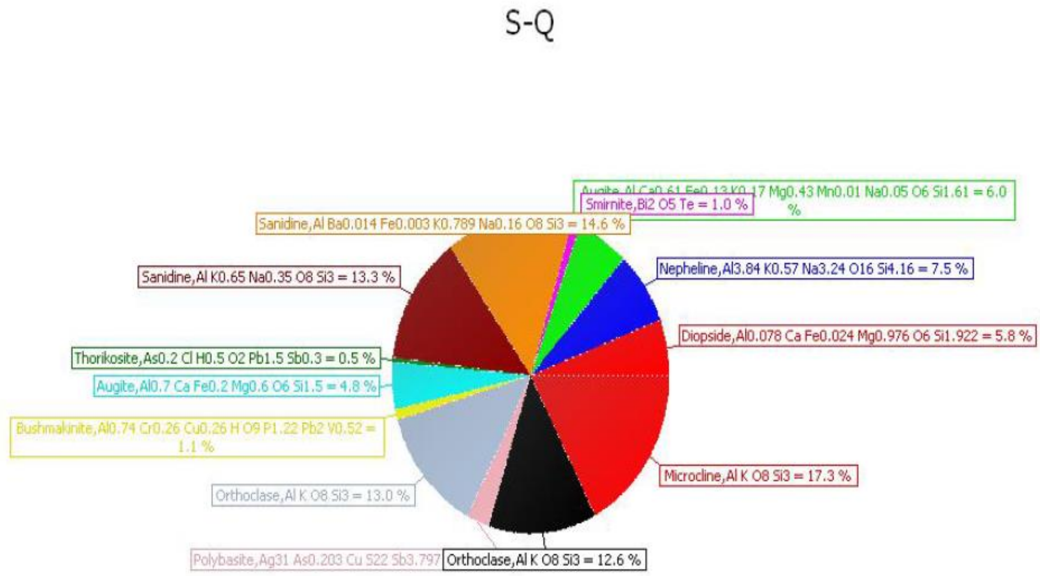


Figure 4.10: Mineral constituents of S4 (rock sand)

Figure 4.8 shows the sampling for the rock sand material. This is mined from the ground and therefore the effect of the travel and fall distance is not experienced by the aggregates. Lack of abrasion effect makes the aggregates irregular in shape and therefore enhanced bonding with concrete.

The laboratory test of the samples of rock indicate presence of orthoclase and sanidine as the predominant minerals and traces of microcline, diopside, nepheline, smirnite, augite, thoricosine and bushmakinite. This igneous formation makes the aggregates hard and strong for concrete formation.

The geological survey of the area as obtained from the geological map of the Nairobi area, report No 98-degree sheet 51 N.E quarter, indicates the presence of lavas, welded tufts and other pyroclastics overlying a foundation of poorly exposed, folded and metamorphosed Precambrian rocks of the Mozambique Belt. All the volcanic rocks have undergone extensive faulting on more than one occasion during the formation of the Rift Valley. The rocks are constituted mainly of sanidine, anorthoclase, nepheline and feldspar (Saggerson, 1991). This validates our laboratory findings on the mineralogical properties of sand from the area

It was deduced from the findings that the fine aggregate material though with irregular shape could result to a strongly bonded concrete. The presence of silicates could also contribute to a prolonged setting time but an increase in strength.

4.2.4 Crystalline formation of aggregates- Machakos river sand

This sand was sampled from a local river at Machakos, location coordinates 01^0 20' 29.4" S, 37^0 26' 15.2" E. The geographical presentation of the catchment area is as shown in Figure 4.11.

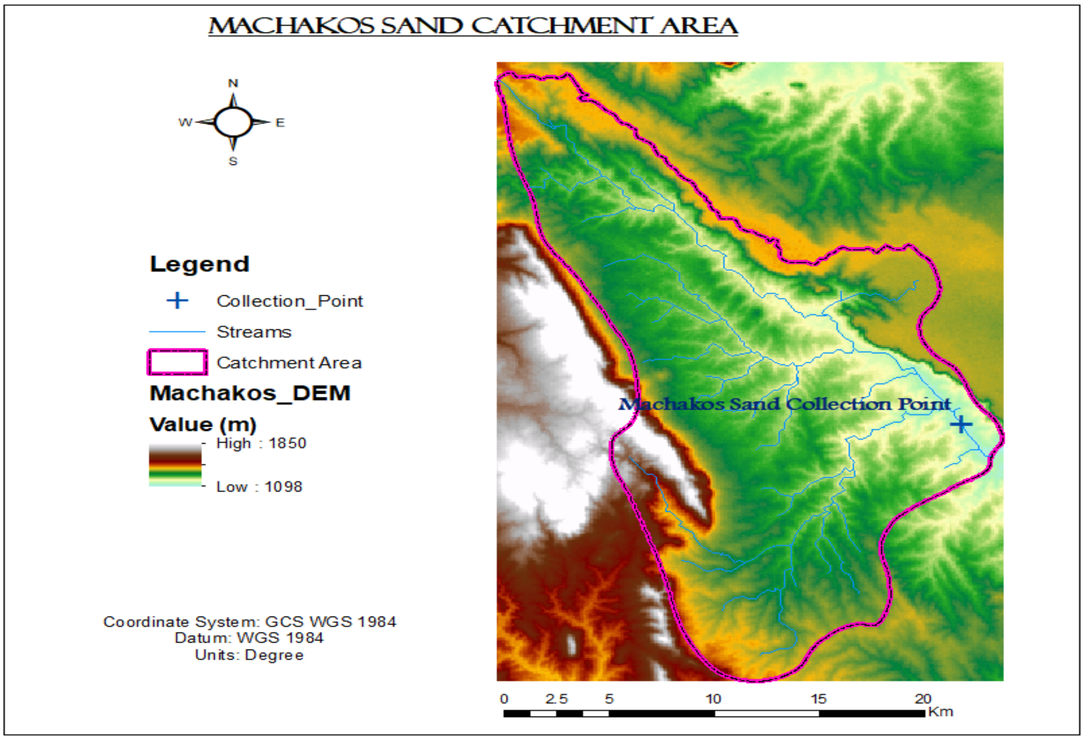


Figure 4.11: Machakos river sand (S5) catchment area

The XRD laboratory test results for Machakos river sand are shown in Figures 4.12 and 4.13.

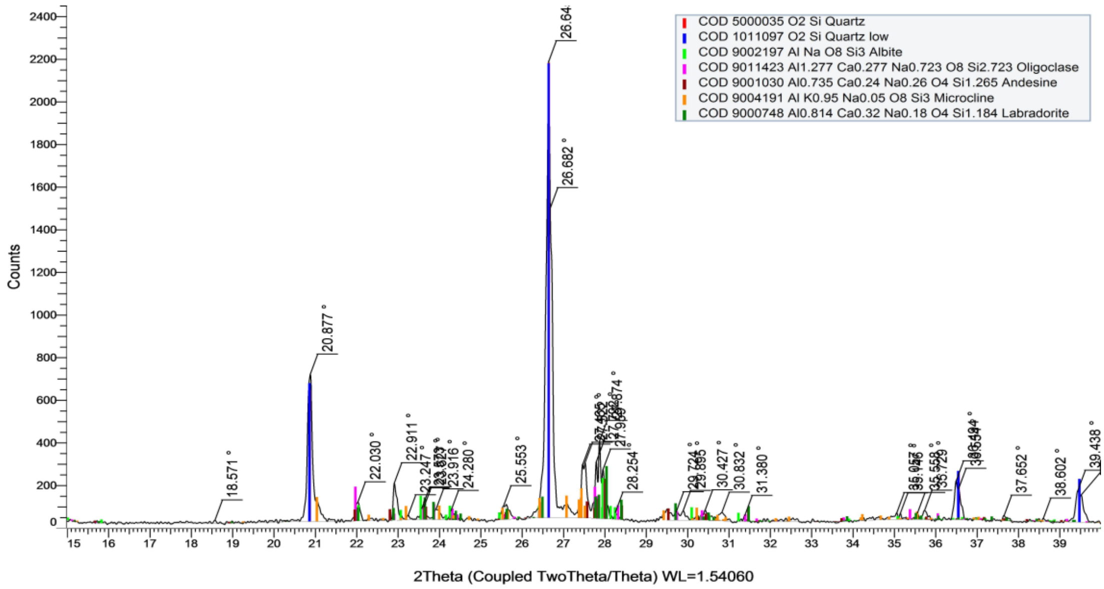


Figure 4.12: X-ray patterns (nm) of S5 (Machakos river sand)

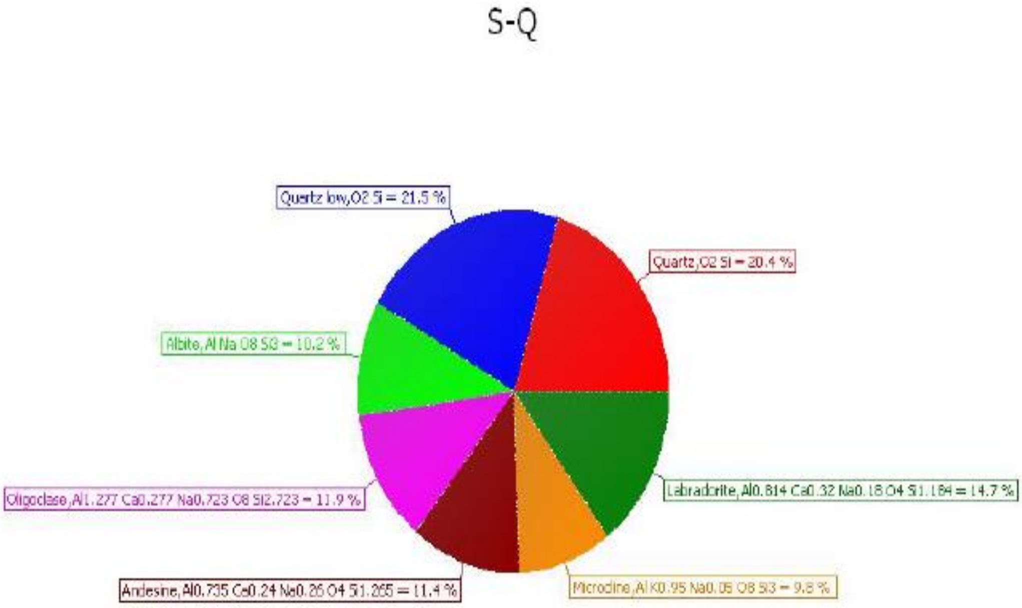


Figure 4.13: Mineral constituents of S5 (Machakos river sand)

Figure 4.1 shows material drop height as approximately 800 m with an estimate longest travel distance of 80 kilometers. The attrition effects on the material generates smooth and round shaped aggregates suitable for concrete. Figure 4.12 and Figure 4.13 shows the laboratory test of Machakos river sand and gives a crystalline structure dominated quartz low, quartz and other minerals from labradorite, microcline, albite, oligoclase and andesine.

The geological survey of the area as obtained from the geological map North Machakos Thika area, report No 59-degree sheet 52 N.W quarter, indicates the presence of metamorphic series of pelitic, psammitic and calcareous rocks formed during the Volcanic era. These rocks are mainly composed of pure quartzites and calcium-silicate minerals (Saggerson, 1991). Our findings from the laboratory validated by this documented evidence.

The analysis of the sand from Machakos river depicts a well-rounded and smooth aggregates from the years of attrition during the travel. The presence of quarzitic material makes the Sand adequately tough and strong making it excellent for concrete production.

4.2.5 Crystalline formation of aggregates- Naivasha sand

This sand was sampled from a quarry at Naivasha area, location coordinates 01^0 00’ 47.6” S, 36^0 21’ 19” E. The geographical presentation of the catchment area is as shown in Figure 4.14.

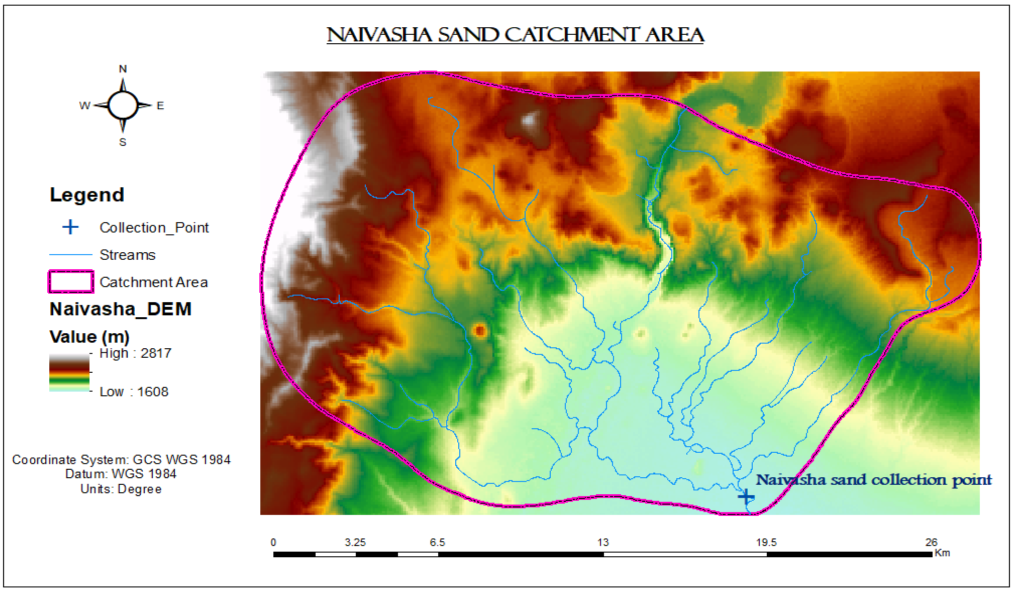


Figure 4.14: Naivasha sand (S6) catchment area

The XRD laboratory test results for Naivasha are shown in Figures 4.15 and 4.16..

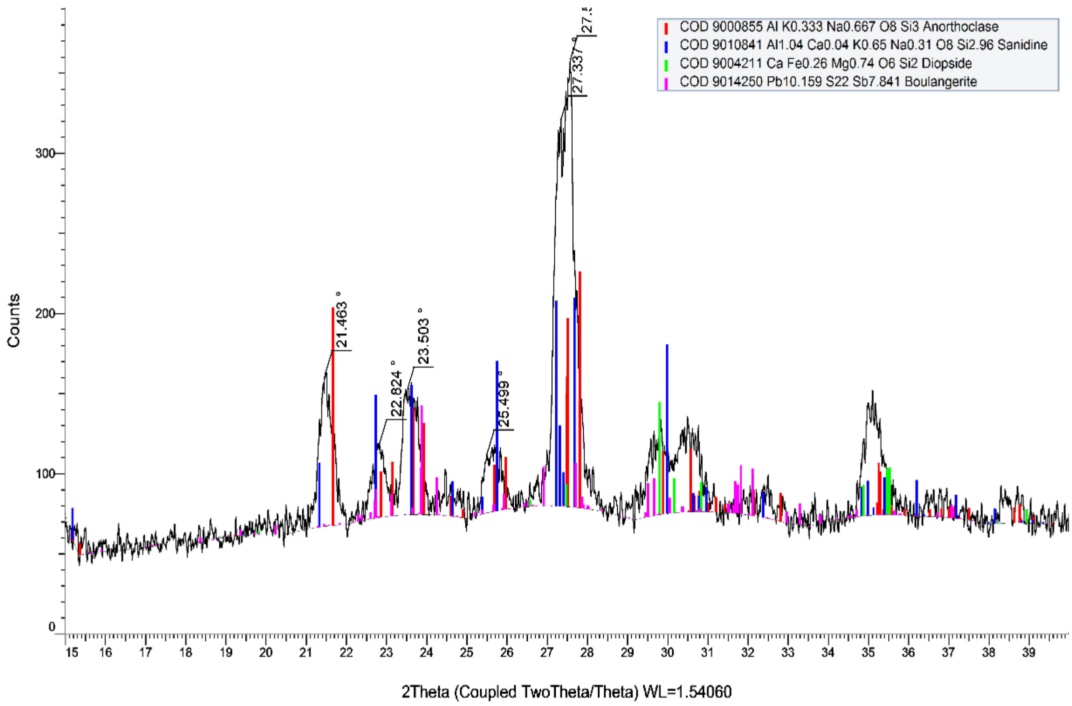


Figure 4.15: X-ray patterns (nm) of S6 (Naivasha river sand)

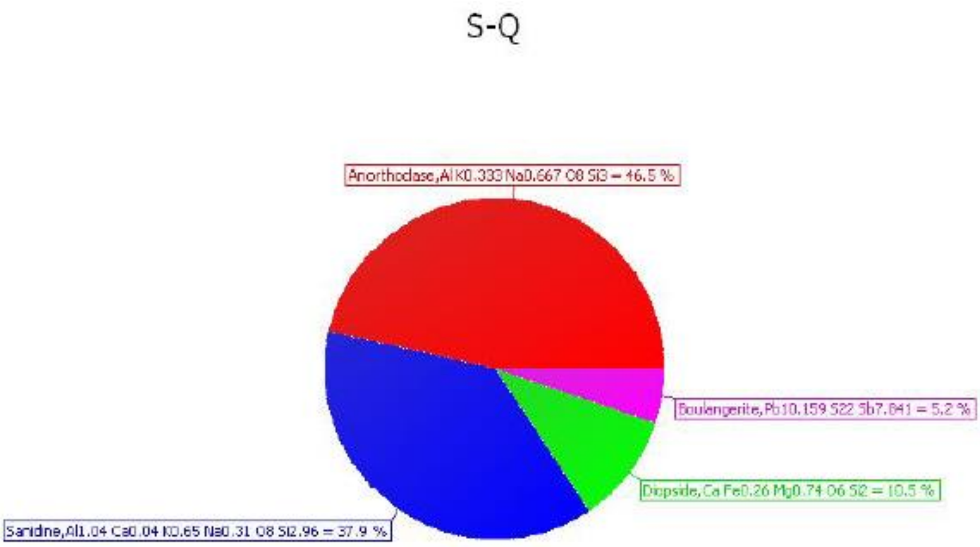


Figure 4.16: Mineral constituents of S6 (Naivasha sand)

Figure 4.14 shows the extent of the sand mining from Naivasha pushed down a fall of about 1000m either by runoff or the rivers. The sand is mined on the lowland valleys in fairly smooth and fine in state attributed to the attrition from the fall and the effect of volcano in the region.

Figure 4.15 and 4.16 shows the laboratory test of the samples of rock and indicate presence of sanidine as the predominant mineral and traces of anorthoclase, diopside and boulangerite.

The geological survey of the area as obtained from the geological map of Naivasha area, report No 97-degree sheet 51 N.W quarter, indicates the presence of lavas, pyroclastics and lacustrine deposits formed during the Volcanic era. The rocks are mainly composed of sanidine and boulangerite. This validates our laboratory findings and the mineralogical composition of the aggregates.

It was construed from the analysis that this sand has high fines and consequently low fineness modulus. The concrete produced from this material may be of low strength.

However the presence of Aluminium silicates could enhance the strength making it a good material for concrete production.

4.2.6 Crystalline formation of Aggregates-Quarry Dust

This fine aggregate was sampled from a quarry at Mlolongo area, location coordinates, 01^0 23' 11.1" S, 36^0 50' 31.5" E. The geographical presentation of the catchment area is as shown in Figure 4.17.

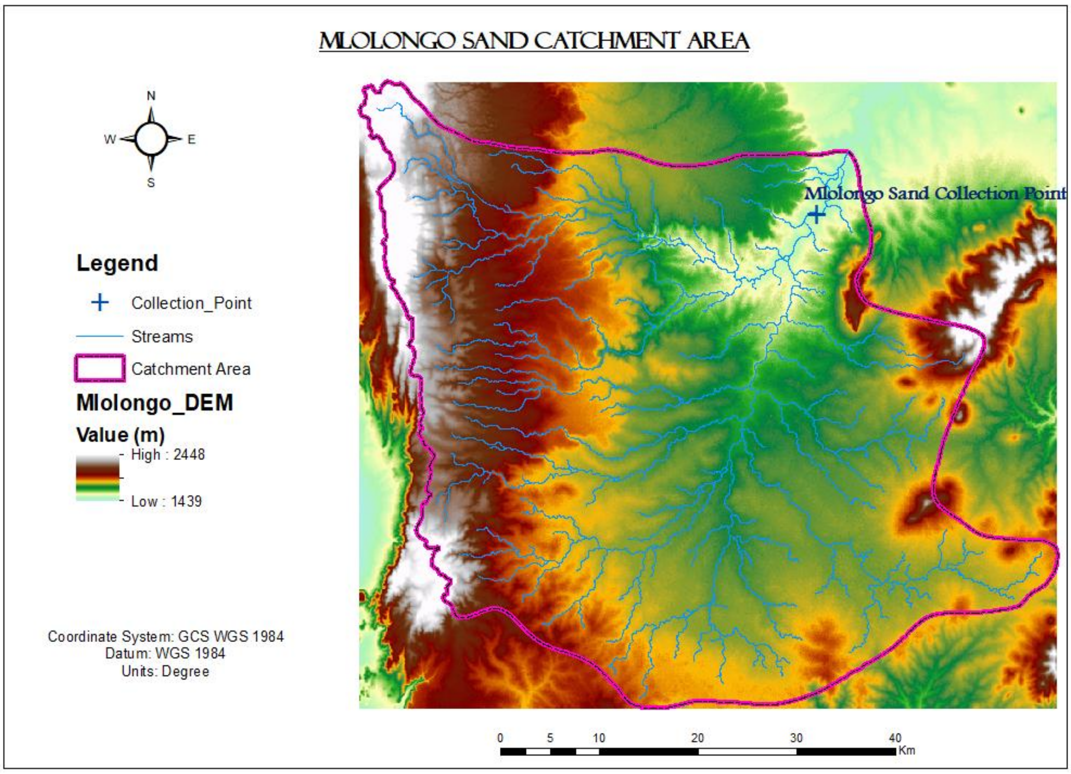


Figure 4.17: Quarry dust (S7) catchment area

The XRD laboratory test results for quarry dust are shown in Figures 4.18 and 4.19.

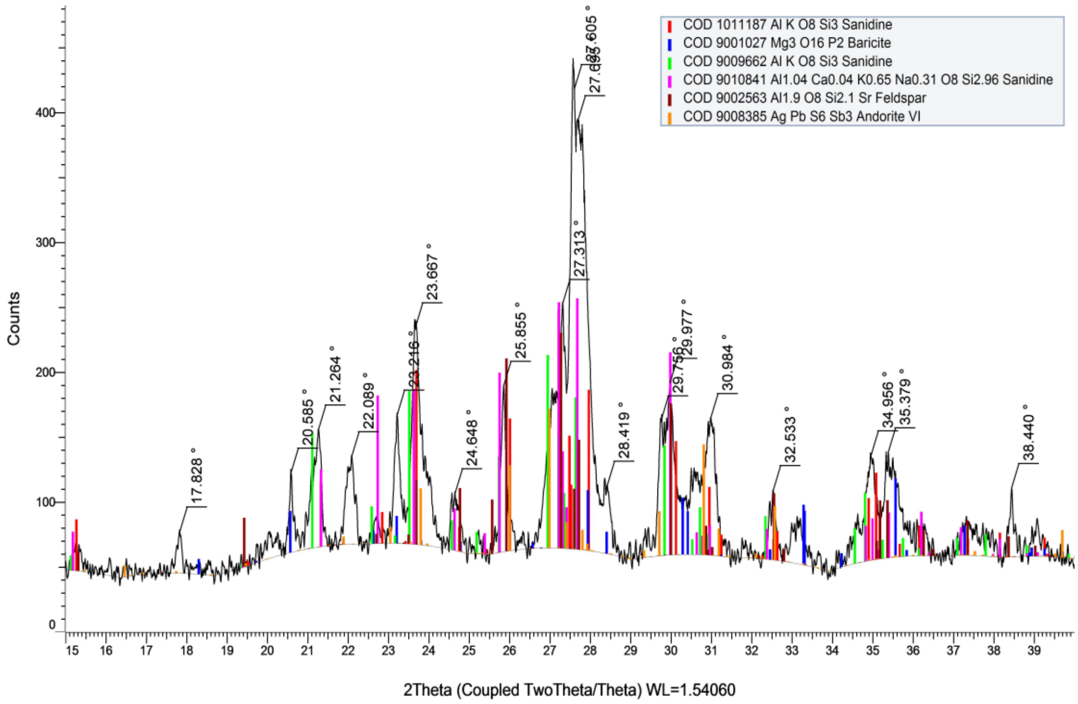


Figure 4.18: X-ray patterns (nm) of S7 (quarry dust)

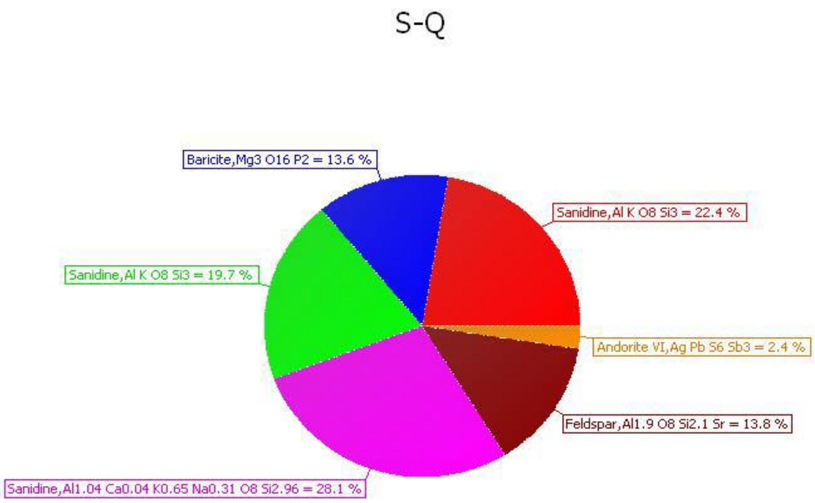


Figure 4.19: Mineral constituents of S7 (quarry dust)

Figure 4.17 shows the source of quarry dust. The extent of the catchment does not influence the quality since the dust is mined from the ground. This is a byproduct of course aggregate production without washing to reduce the silt content. The material is irregular with high silt content

Figure 4.18 and 4.19 shows the laboratory test of the samples of rock indicating Sanidine as the predominant mineral and traces of andorite (VI), feldspar and baricite.

The geological survey of the area as obtained from the geological map of the Nairobi area, report No 98-degree sheet 51 N.E quarter, indicates the presence of lavas, welded tufts and other pyroclastics overlying a foundation of poorly-exposed, folded and metamorphosed Precambrian rocks of the Mozambique Belt. All the volcanic rocks have undergone extensive faulting on more than one occasion during the formation of the Rift Valley. The rocks are constituted mainly of sanidine, anorthoclase, nepheline and feldspar (Saggerson, 1991). The laboratory analysis tested sample is validated by similar mineral composition of the rocks at the catchment area

It was deduced from the findings that the fine aggregate material though with irregular shape could result to a strongly bonded concrete but poor in strength because of high silt content. The presence of silicates from sanidine could also contribute to a prolonged setting time but an increase in strength.

4.2.7 Mineralogical Composition summary

The geological formation of all the samples from the respective catchment areas conform to the laboratory XRD results shown in Table 4.1. This table is a summary of the mineralogical composition of the different fine aggregates as obtained from the laboratory.

Table 4.1: Percentage mineral composition of all fine aggregates

Mineral	Formular	S2	S3	S4	S5	S6	S7
Labradorite	A10.814 CaO.32NaO.18 O4Sil.184	16.7	16.4		14.7		
Berzaliatrite	Cul.95 Se	25.4	18.1				
Berzaliatrite	Cu2 Se	23.4					
Perryite	FeO.24 Ni7.76P0.63 si2.37	5.2					
Monipite	Mo NiP	2.6					
Quartz low	O2 Si	26.7	21		21.5		
Quartz	O2 Si				20.4		
Albite	Al Na O8 Si3		15.7		10.2		
Orligoclase	All.277 CaO.52 NaO.48 O8 Si2.48		14.8		11.9		
Anorchtite Sodian	All.52 Ca0.52 Na0.48 O8 Si2.48		13.9				
Polybasite	Ag3l As0.203 Cu S22 Sb3.797			2.6			
Sanidine	Al Ba0.014 Fe0.003 K0.789 Na0.16 O8 S3			14.6			
Sanidine	Al K0.65 Na0.35 O8 Si3			13.3			
Sanidine	Al1.04 Ca0.04 K0.65 Na0.31 O8 Si2.96					39.7	28.1
Sanidine	Al K O8 Si3						42.1
Augite	Al Ca0.61 Fe).13 K0.17 Mg0.43 Mn0.01 Na0.05 O6 Sil.61			6			
Orthoclase	Al K.O8 Si3			25.6			
Microcline	Al K.O8 Si3			17.3			
Microcline	Al KO.95 NaO.05 O8 Si3				9.8		
Diopade	Al0.078 Ca Fe0.024 Mg0.976 O6 Sil.922			5.8			
Diopade	Ca Fe0.026 Mg0.74 O6 Si2					10.5	
Augite	Al0.7 Ca Fe0.2 Mg0.6 O6 Sil.5			4.8			
Bushmakinite	A10.74 Cr0.26 H O9 P1.22 Pb2 V0.52			1.1			
Nepheline	A13.84 K0.57 Na3.24 O16 Si4.16			7.5			
Thonkosite	As0.2 ClH0.5 O2 Pb1.5 Sb0.3			0.5			
Smimite	Bi2 O5 Te			1			
Andesine	A10.735 CaO.24 NaO.26 O4 Sil.265				11.4		
Boulangerite	Pb10.159 S22 Sb7.841					5.2	
Anorthoclase	Al K0.33 Na0.667 O8 Si3					46.5	
Andorite VI	Ag Pb S6 Sb3						2.4
Feldspar	All.9 O8 Si2.1 Sr						13.8
Baricite	Mg3 O16 p2						13.6
		100	99.9	100.1	99.9	102	100

From table 4.1, it is observed that the aggregates mineral composition varies depending on the geology of the source area. This confirms variability in material types and the need to establish the respective properties to ensure that the right quality is achieved at all times. All the materials exhibited mineralogical composition that could influence varying strength in concrete.

4.2.8 Physical Properties of fine aggregates

This section captures the results and discussions on the physical properties of the different fine aggregate materials and their acceptability for concrete production.

4.2.8.1 Sieve analysis – Mwingi Sand (S2)

The sieve analysis test results of Mwingi river sand are shown in Table 4-2 and Figure 4-20.

Table 4.2: Sieve analysis of S2 (Mwingi river sand)

Sieve Size (mm)	Wt. Ret (g)	Cum. Ret (g)	% cum. Ret	% Passing	Lower Limit (%)	Upper Limit (%)
10.00	4.5	4.5	0.5	99.5	100	100
5.00	20.5	25	2.5	97.5	89	100
2.36	51.7	76.7	7.7	92.3	60	100
1.18	178.8	255.5	25.6	74.4	30	100
0.60	335.8	591.3	59.2	40.8	15	100
0.30	145.5	736.8	73.8	26.2	5	70
0.15	237.5	974.3	97.6	2.4	0	15
Pan	24	998.3				
	998.3					

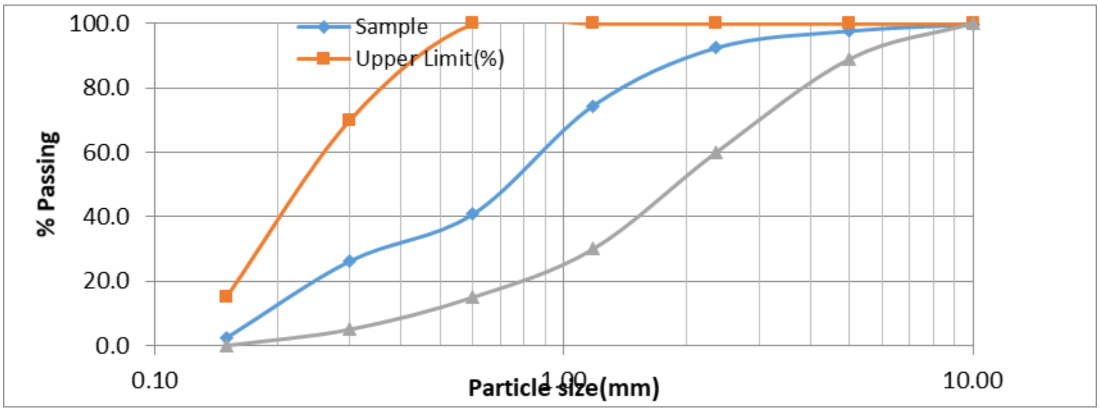


Figure 4.20: Grading of S2 (Mwingi river sand)

From Table 4.2, the mass retained in sieve size 10mm and 5mm were observed to be 2.5% of the total mass giving a cumulative mass of 25g coarse aggregate. The mass retained in sieve sizes 2.36, 1.18, 0.6, 0.3 and 0.15 were observed to be 95.1% giving a cumulative mass of 949.3g fine aggregate. 24g of material passed through the 0.15mm sieve to the pan. 1.7g of fine aggregate was lost during the experiment. This did not exceed the acceptable limit for loss (0.3% of the original mass) and therefore results acceptable for use.

Figure 4.20, shows the grading curve for Mwingi Sand. The results indicate that the particle sizes fell within the overall grading limits and additional grading limits for medium and coarse. The aggregate had a rich type of gradation (Malewar, 2017). This indicates that the coarse and fine aggregate were in appropriate proportions to produce satisfactory concrete

4.2.8.2 Sieve analysis -Kajiado river sand (S3)

The sieve analysis test results of Kajiado river sand are shown in Table 4.3 and Figure 4.21.

Table 4.3: Sieve analysis of S3 (Kajiado river sand)

Sieve Size (mm)	Wt. Ret (g)	Cum. Ret (g)	% cum. Ret	% Passing	Lower Limit (%)	Upper Limit (%)
10.00	6.2	6.2	0.6	99.4	100	100
5.00	12.3	18.5	1.9	98.2	89	100
2.36	24.3	42.8	4.3	95.7	60	100
1.18	71	113.8	11.4	88.6	30	100
0.60	196	309.8	31.0	69.0	15	100
0.30	172	481.8	48.2	51.8	5	70
0.15	470.2	952	95.2	4.8	0	15
Pan	48	1000				
	1000					

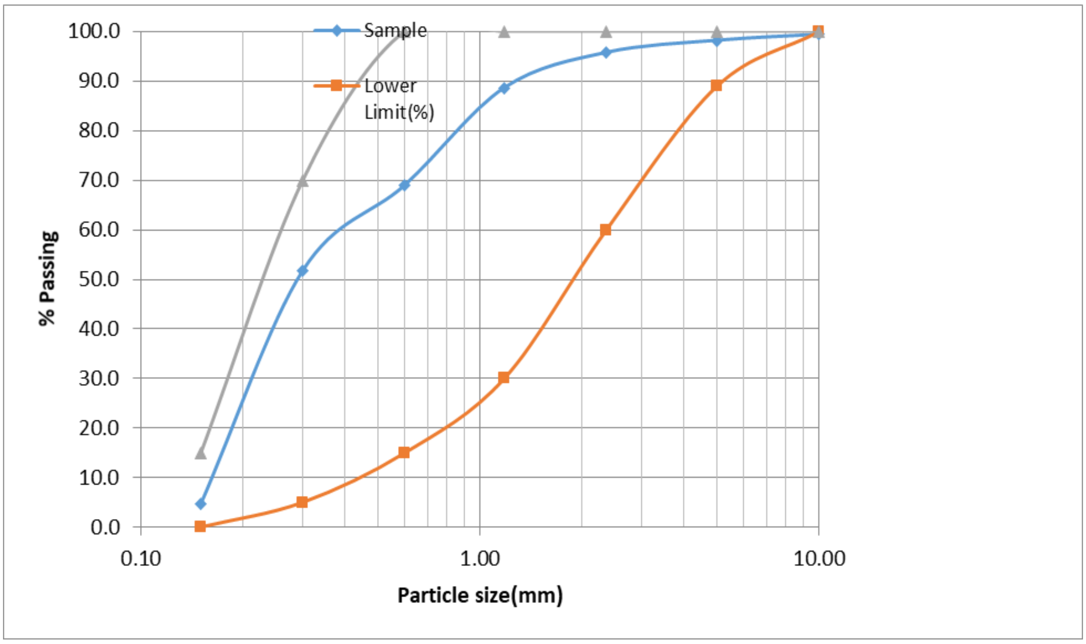


Figure 4.21: Grading of S3 (Kajiado river sand)

From Table 4.3, the mass retained in sieve size 10mm and 5mm was observed to be 1.9% of the total giving a cumulative mass of 18.5g coarse aggregate. The mass retained in sieve sizes 2.36, 1.18, 0.6, 0.3, and 0.15 were observed to be 94.7% giving a cumulative mass of 933.5g fine aggregate. 34g of fine aggregate passed through the 0.15mm sieve to the pan. Sieve size 0.15mm retained the highest percentage of particles indicating that the sample had a large quantity of fines particles. There were no losses during the experiment and therefore results obtained within acceptable limit for loss (0.3% of the original mass).

Figure 4.21 shows the particle sizes fell within the overall grading requirements and additional grading limits for fine and medium. This indicates that the coarse and fine aggregate were in suitable proportions and therefore rich type of gradation (Malewar, 2017) hence would produce concrete that is satisfactory.

4.2.8.3 Sieve analysis - Rock sand (S4)

The sieve analysis test results of Kajiado river sand are shown in Table 4.4 and Figure 4.22.

Table 4.4: Sieve analysis of S4 (rock sand)

Sieve Size (mm)	Wt. Ret (g)	Cum. Ret (g)	% cum. Ret	% Passing	Lower Limit (%)	Upper Limit (%)
10.00	0	0	0.0	100.0	100	100
5.00	2	2	0.2	99.8	89	100
2.36	267.8	269.8	27.0	73.0	60	100
1.18	284	553.8	55.5	44.5	30	100
0.60	3207.735.8	761.5	76.3	23.7	15	100
0.30	75.7	837.2	83.9	16.1	5	70
0.15	100.7	937.9	94.0	6.0	0	15
Pan	60	997.9				
	997.9					

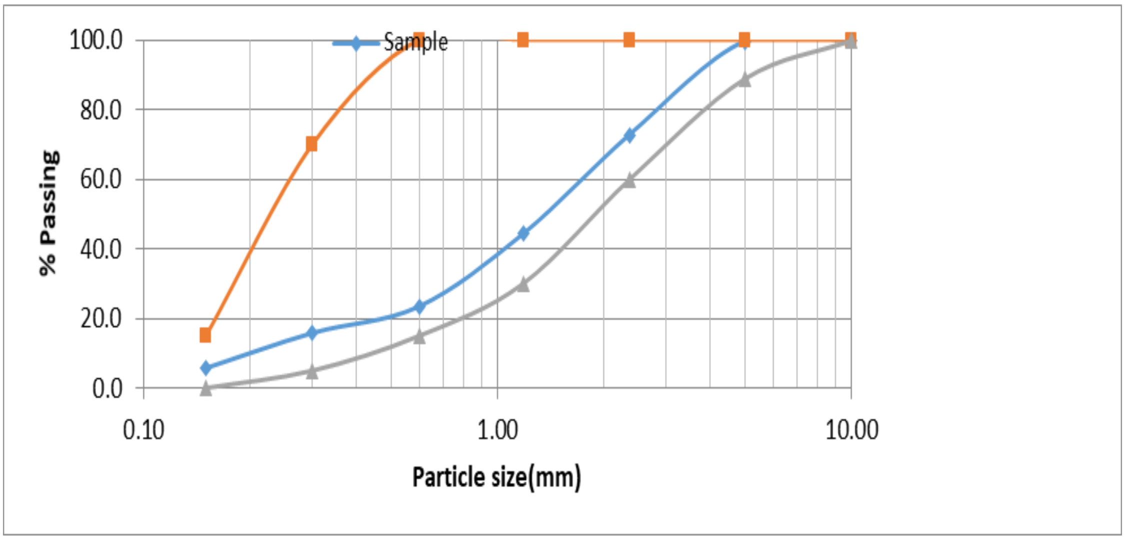


Figure 4.22: Grading of S4 (rock sand)

In Table 4.4, the mass retained in sieve size 10mm and 5mm were observed to be 0.2% of the total mass giving a cumulative mass of 2.0g of coarse aggregate. The mass retained in sieve sizes 2.36, 1.18, 0.6, 0.3, and 0.15 were observed to be 93.8% giving a cumulative mass of 935.9g of fine aggregate. 60g of fine aggregate passed through the 0.15mm sieve to the pan. In addition, 2.1g of fine aggregate was lost during the experiment. This did not exceed the acceptable limit for loss (0.3% of the original mass) and therefore results acceptable for use.

Figure 4.22, shows the masses retained in all the sieves were within the maximum specified in (BSI, 2012).The highest percentage of particles was retained in 1.18mm sieve which means that the aggregate has a high quantity of fines. The aggregate shows a distribution closer to gap gradation because of the little aggregate in the medium size range. (Malewar, 2017). The particle sizes fell within the overall grading limits and additional grading limits for medium and coarse. This indicates that the coarse and fine aggregate are appropriate for satisfactory concrete production.

4.2.8.4 Sieve analysis -Machakos river sand (S5)

The sieve analysis test results of Machakos river sand are shown in Table 4.5 and Figure 4.23.

Table 4.5: Sieve analysis of S5 (Machakos river sand)

Sieve Size (mm)	Wt. Ret (g)	Cum. Ret (g)	% cum. Ret	% Passing	Lower Limit (%)	Upper Limit (%)
10.00	12.7	12.7	1.3	98.7	100	100
5.00	23.3	36	3.6	96.4	89	100
2.36	47.2	83.2	8.3	91.7	60	100
1.18	115.8	199	19.9	80.1	30	100
0.60	328.7	527.7	52.8	47.2	15	100
0.30	210.2	737.9	73.8	26.2	5	70
0.15	234.7	972.6	97.3	2.7	0	15
Pan	27.3	999.9				
	999.9					

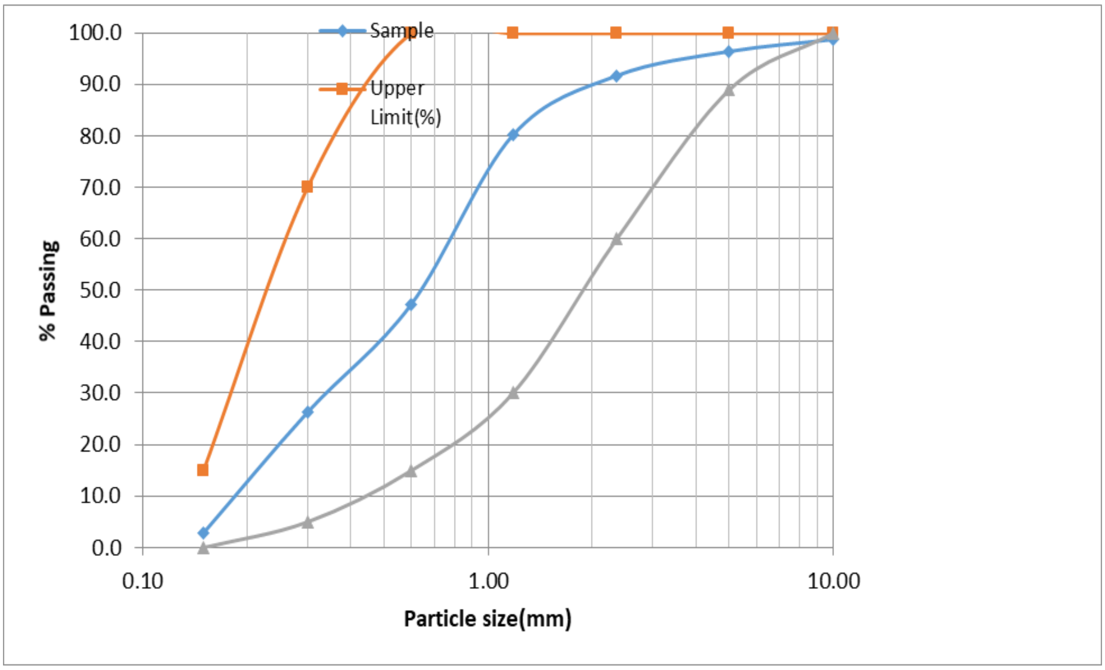


Figure 4.23: Grading of S5 (Machakos river sand)

From Table 4.5, the mass retained in sieve size 10mm and 5mm were observed to be 3.6% of the total mass giving a cumulative mass of 36g coarse aggregate. The mass retained in sieve size 2.36, 1.18, 0.6, 0.3, and 0.15 were observed to be 93.7% giving a cumulative mass of 936.6g fine aggregate. In addition, 27.3g of fine aggregate passed through the 0.15mm sieve to the pan. 0.1g of fine aggregate was lost during the experiment. This did not exceed the acceptable limit for loss (0.3% of the original mass) and therefore results acceptable for use.

Figure 4.23 shows the aggregate had a rich type of gradation (Malewar, 2017). The particle sizes fell within the overall grading limits and additional limits for fine, medium and coarse. This indicates that the coarse and fine aggregate were in suitable proportions sufficient to produce satisfactory concrete.

4.2.8.5 Sieve analysis -Naivasha sand (S6)

The sieve analysis test results of Naivasha sand are shown in Table 4.6 and Figure 4.24.

Table 4.6: Sieve analysis of S6 (Naivasha sand)

Sieve Size (mm)	Wt. **Ret (g)**	**Cum. Ret (g)**	**% cum. Ret**	**% Passing**	**Lower Limit (%)**	**Upper Limit (%)**
10.00	5.8	5.8	0.6	99.4	100	100
5.00	24.8	30.6	3.1	96.9	89	100
2.36	46.3	76.9	7.7	92.3	60	100
1.18	104.8	181.7	18.2	81.8	30	100
0.60	198.3	380	38.1	61.9	15	100
0.30	136.8	516.8	51.8	48.2	5	70
0.15	268.7	785.5	78.7	21.3	0	15
Pan	212.7	998.3				
	998.3					

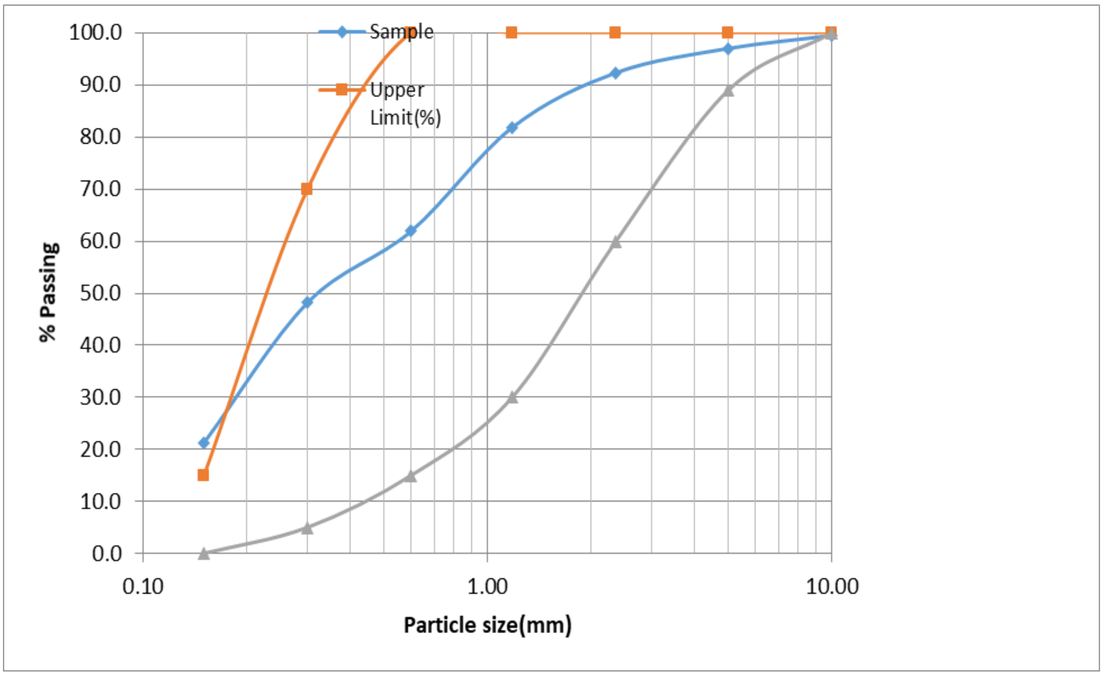


Figure 4.24: Grading of S6 (Naivasha sand)

From Table 4.6, the mass retained in sieve size 10mm and 5mm were observed to be 3.1% of the total mass giving a cumulative mass of 30.6g of coarse aggregate. The mass retained in sieve size 2.36, 1.18, 0.6, 0.3 and 0.15 were observed to be 71% giving a cumulative mass of 754.9g of fine aggregate. 212.7g of fine aggregate passed through the 0.15mm sieve to the pan. 1.8g of fine aggregate was lost during the experiment. This did not exceed the acceptable limit for loss (0.3% of the original mass) and therefore results acceptable for use.

The aggregate particles fell within the overall grading limits and additional limits for fine and medium. There was high proportion of particles of smaller size giving a rich type of gradation (Malewar, 2017). This is suitable for concrete production.

4.2.8.6 Sieve analysis -Quarry dust (S7)

The sieve analysis test results of quarry dust are shown in table 4.7 and figure 4.25.

Table 4.7: Sieve analysis of S7 (quarry dust)

Sieve Size (mm)	Wt. Ret (g)	Cum. Ret (g)	% cum. Ret	% Passing	Lower Limit (%)	Upper Limit (%)
10.00	1.7	1.7	0.2	99.8	100	100
5.00	148.2	149.9	15.0	85.0	89	100
2.36	239.8	389.7	39.1	60.9	60	100
1.18	204.3	594	59.6	40.4	30	100
0.60	169	763	76.5	23.5	15	100
0.30	66.8	829.8	83.2	16.8	5	70
0.15	96.3	926.1	92.9	7.1	0	15
Pan	71.2	997.3				
	997.3					

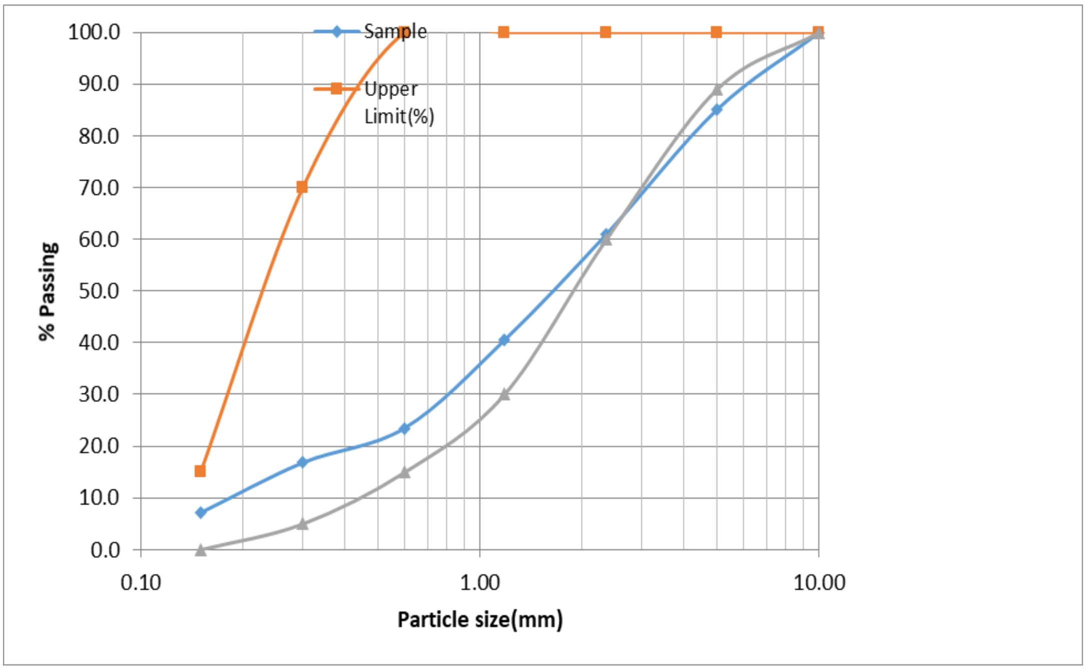


Figure 4.25: grading of s7 (quarry dust)

Table 4.7 shows the mass retained in sieve size 10mm and 5mm to be 15.0% of the total mass giving a cumulative mass of 149.9g of coarse aggregate. The mass retained in sieve size 2.36, 1.18, 0.6, 0.3 and 0.15 were observed to be 77.7% giving a cumulative mass of 776.2g of fine aggregate. 77.9g of fine aggregate passed through the 0.15mm sieve to the pan. 2.7g of fine aggregate was lost during the experiment. This did not exceed the acceptable limit for loss. (0.3% of the original mass) and therefore results acceptable for use.

Figure 4.25 shows the particle sizes falling within the overall grading limits and additional limits for coarse. There is more course than fine aggregates in the material making medium/course. The aggregate had an open type of gradation (Malewar, 2017). This indicates that the coarse, medium and fine particle proportions were adequate to produce satisfactory concrete.

4.2.8.7 Sieve analysis -All samples combined

The sieve analysis test results of all samples are shown in table 4.8 and figure 4.26. This is a representation of the gradation using the overall grading envelop.

Table 4.8: Sieve analysis of all sample aggregates

Sieve Size (mm)	S2% Passing	S3% Passing	S4% Passing	S5% Passing	S6% Passing	S7% Passing	Lower Limit (%)	Upper Limit (%)
10.00	99.5	99.4	97.7	98.7	99.6	99.8	100	100
5.00	97.5	98.1	99.5	96.4	97.3	84.9	89	100
2.36	92.3	95.7	72.7	91.7	92.8	60.9	60	100
1.18	74.4	88.5	44.3	80.1	82.4	40.4	30	100
0.60	40.8	68.6	23.4	47.2	62.4	23.8	15	100
0.30	26.5	51.1	15.9	26.2	48.7	16.9	5	70
0.15	24	3.4	5.8	2.7	21.6	7.1	0	15
Pan	24	48	60	27.3	212.7	71.2		

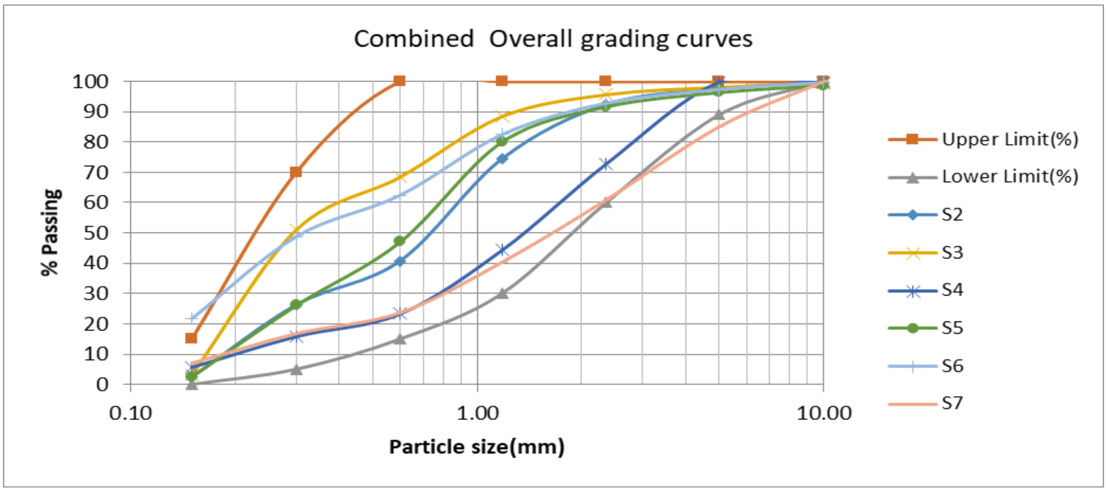


Figure 4.26: Combined overall grading of all sample aggregates

From Figure 4.26, in accordance to the limits in (BS, 1975); All the samples richly fall within the overall grading envelop. S6, has exceeded the upper limit of the fine material passing sieve 0.15mm by 10%. In addition, S7 has more course sand retained in sieve 5mm, exceeding the lower bound requirement by 4%. Despite the variations, the overall envelop depicts fine aggregate materials suitable for concrete.

Combined coarse grading curves

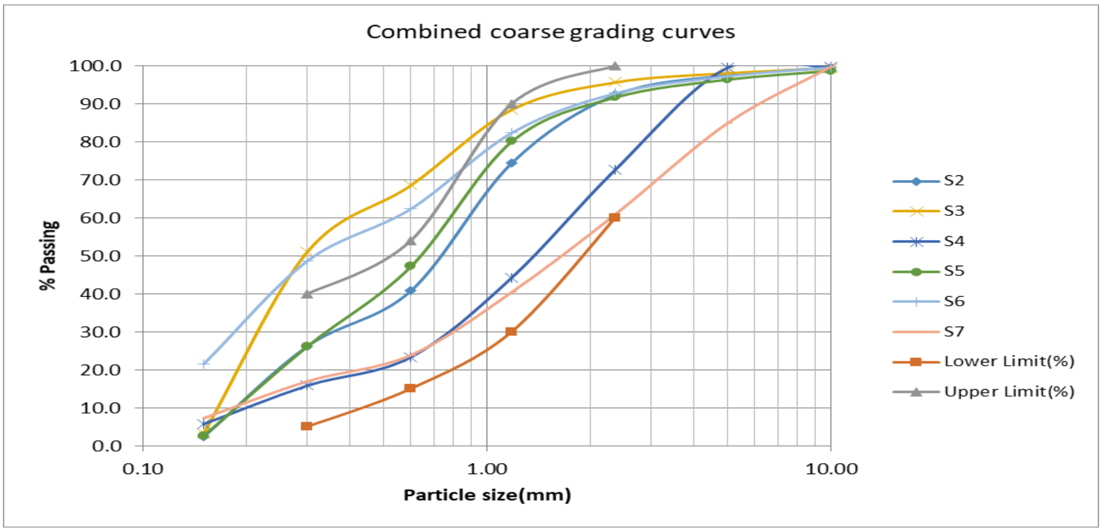


Figure 4.27: Combined coarse grading of all sample aggregates

From Figure 4.27 sand in accordance to the limits in (BS, 1975); the samples S3 and S6 fell above the upper limit showing the particles making the finer. Samples S2, S4, S5 and S7 fell within the limits showing the particles are coarse. The finer sand produces more cohesive and stronger concrete. In this respect while all the aggregates qualify for concrete production, S3 and S6 could give stronger concrete.

Combined medium grading curves

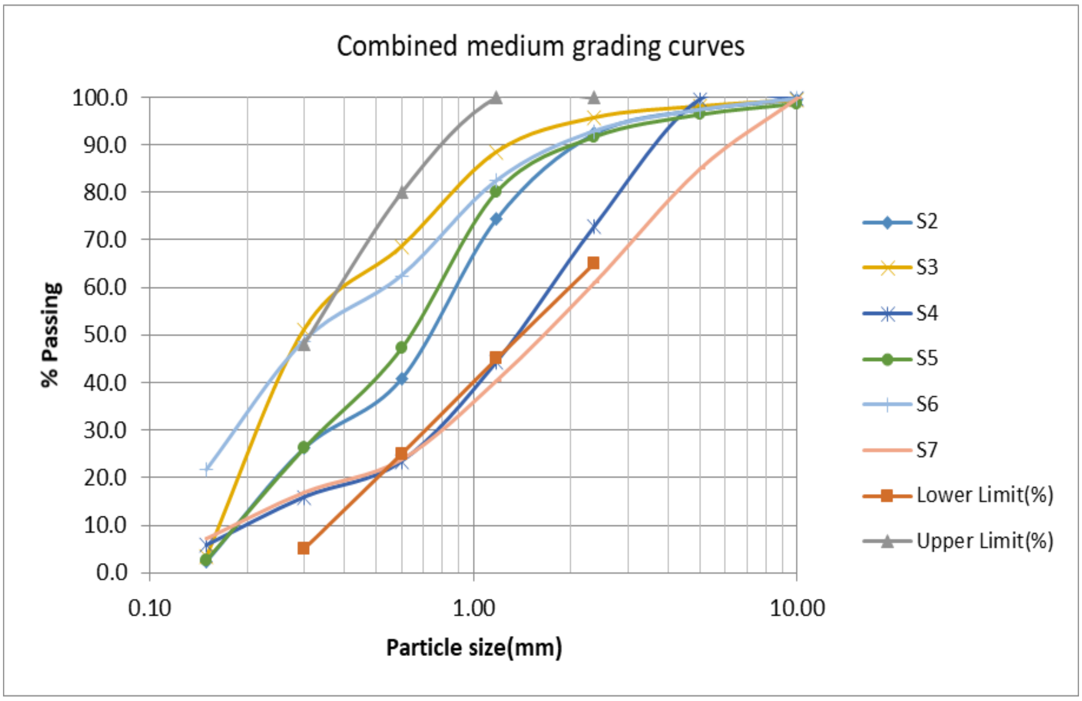


Figure 4.28: Combined medium grading of all sample aggregates

From Figure 4.28 and in accordance to the limits in (BS, 1975); Samples S3 and S6 fell slightly above the upper limit of the medium gradation curve showing that they are finer. Samples S2 and S5 fell within the range showing that the particles have medium gradation. Sample S4 and S7 fell below the lower limit indicating that the aggregate particles are coarser.

Combined fine grading curves

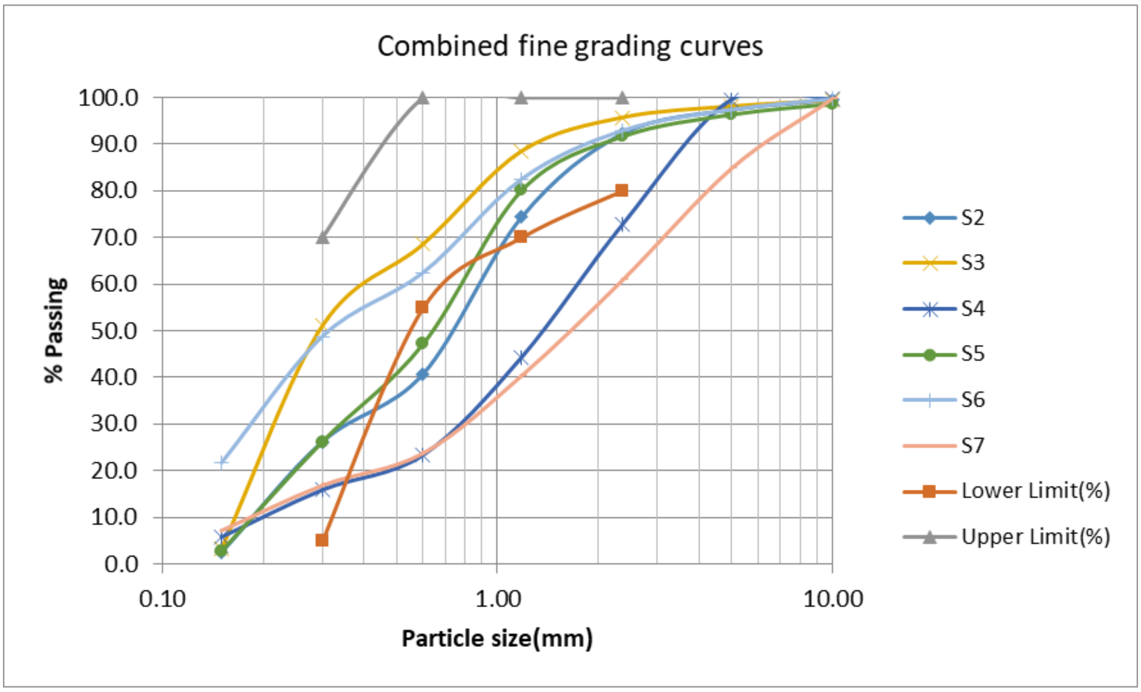


Figure 4.29: Combined fine grading of all sample aggregates

From Figure 4.29, in accordance to the limits in (BS, 1975); Samples S2, S4, S5 and S7 fell below the lower limit indicating that the aggregate particles have a coarser gradation. Samples S3 and S6 fell within the limits showing that the aggregate particles have fine gradation. Using the fine grading envelop, the material S3 and S6 were firmly confirmed as fine, S4 and S7, course and S2 and S5 medium/course.

4.2.8.8 Fineness Modulus

The fineness modulus is a measure of the fineness of aggregates and is useful in determining the proportions of fine and coarse aggregates to be used in concrete mixtures. A higher fineness modulus implies a coarser aggregate hence requires more water to produce workable concrete (Neville, 2011). Coarser aggregates lower the surface or bond area for the same volume contributing to a decrease in compressive strength (Somayaji, 2001).

The fineness modulus was computed for all the samples to determine their suitability for concrete production. Fineness modulus of fine aggregate is useful in determining the proportions of fine and coarse aggregates to be used in concrete mixtures. The standard limits of fineness modulus are 2.3-3.1. The fineness modulus of the samples is as shown in Table 4.9.

Table 4.9: Fineness modulus of samples

Sample	Fineness Modulus
S-2	2.66
S-3	1.92
S-4	3.37
S-5	2.54
S-6	1.94
S-7	3.66

A higher fineness modulus implies presence of excessively coarse materials which will produce harsh concrete mixes that is difficult to place, consolidate and finish. A lower fineness modulus implies a presence of excessively fine materials which will result in a higher water demand (Seegebrecht, 2018). From Table 4.9, it was observed that S2 and S5 fell within the expected range of between 2.3 -3.1 and therefore would produce satisfactory concrete. S4 and S7 fell above the range which indicates coarser particles. Concrete produced from expected to be of lower strength. S3 and S6 fell below the range indicating finer aggregates which can be attributed to degradation of fine aggregate due to friction and abrasion. S3 and S6 expected to produce concrete with higher strength than S4 and S7.

4.2.8.9 Silt and Clay Content

Silt and clay content influence the strength development in concrete and should be maintained within the recommended limits of 4% maximum (BSI, 1992). (Okumu, 2016). The silt and clay content of the samples is shown in Table 4.10.

Table 4.10: Silt and clay content of samples

Sample	Silt and clay%
S-2	4.85
S-3	4.16
S-4	2.06
S-5	6.66
S-6	9.37
S-7	11.9

From Table 4.10, the silt and clay content in the aggregate samples was observed to vary between 2.06-11.9%. Most of the samples exceed the maximum limit of clay content according to the British standard that sets a maximum limit of 4% (BSI, 1992). Sample S7 recorded the highest level of silt and clay content, which can be attributed to the manufacturing process of the sand. S6 also recorded a high level of silt which can be explained by the weathering and volcanic action in the catchment area. The presence of impurities (clay and silt) in sand significantly contribute to reduction in compressive strength of concrete. Due to their high silt content, S5, S6 and S7 expected to produce low strength concrete despite other parameters being with acceptable limits.

4.2.8.10 Bulk Density

The bulk density of aggregate refers to the weight of aggregate divided by its volume. The volume includes that occupied by the aggregates as well as the voids between aggregate particles. The void content between the particles affect the paste requirements in the mix design. The bulk density of the samples is shown in Table 4.11.

Table 4.11: Bulk density of the samples

Sample	Bulk density kg/m^3
S-2	1497
S-3	1469
S-4	1407
S-5	1613
S-6	1327
S-7	1684

From Table 4.11, bulk density of the aggregate samples ranges from 1327-1684kg/m^3. The standard limits for this is not provided by the BS EN1097- 3:1998. Samples S5 and S7 recorded the highest bulk densities and this can be attributed to the proportions of the different elements' constituents. Bulk density is influenced by the shape and size of the aggregate particles and is enhanced by the presence of smaller particles that can be added to the voids of larger particles. The shape of the aggregate particles affects the closeness of the particles (Afsar, 2012). Very low densities imply more voids hence a greater cement paste requirement. All the samples were within the expected bulk density range and therefore acceptable for concrete production.

4.2.8.11 Specific Gravity

The specific gravity of aggregates refers to the ratio of its mass to the mass of an equal volume of water and is used in computations for mixture proportioning (Camp, 2018). Specific gravity below the acceptable minimum limit of 2.6 implies the presence of deleterious materials which are lighter than good aggregates (Arumugam, 2014).Variations in the specific gravity influence the volumetric composition of concrete mixture and likely result in discrepancies in yield of concrete batches (Karthik, 2011). The specific gravity of the samples is shown in Table 4.12.

Table 4.12: Specific gravity of the samples

Sample	Specific gravity	Apparent Specific gravity
S-2	2.12	2.57
S-3	2.06	2.5
S-4	2.24	2.6
S-5	2.31	2.63
S-6	1.73	2.36
S-7	2.27	2.59

The specific gravity of all the aggregates samples ranged between 1.73- 2.31. These fell below the minimum accepted limit of specific gravity required in a concrete mix according to the BS 812-102:1995 standards which set a min of 2.6. This shows presence of contaminants lighter than the aggregates. Contamination can occur at the catchment area of the various aggregates during formation. The lowest was S6 (Sand from Naivasha) whose value could be explained by the past volcanic activity and presence of deleterious particles.

4.2.8.12 Aggregate Shape and Texture

Aggregate shape and texture greatly influence fresh concrete properties like workability and bond between the particles and are especially considered when in need of high compressive strength. Rough, angular and elongated particles have greater water requirements to achieve workability. Angular aggregates produce bulk material with higher stability than rounded aggregates. However, the angular aggregates are more difficult to work into place than the rounded aggregates because of their shape. For the purpose of procuring Portland cement concrete, round and smooth aggregate particles are desirable to improve workability of fresh concrete (Mamlouk & Zaniewski, 1999).

All the samples were subjected to a texture and shape examination. The particle shape and surface texture of the samples are shown in Table 4.13.

Table 4.13: Particle shape and surface texture of samples

Sample	Sieve Analysis	Surface texture	Particle shape
S-2	C&M	Rough	R
S-3	F	Smooth	R
S-4	C	Coarse	A
S-5	C&M	Rough	R
S-6	F&M	Smooth	R
S-7	C	Coarse	Fl & E

C- Coarse, M- Medium, F- fine, R- Round, A-Angular, Fl- Flacky, E- Elongated

From Table 4.13, samples S2 and S5 were observed to be rough and round while samples S3 and S6 were observed to be smooth and round. This can be attributed to the attrition and abrasion actions during their transportation and deposition of the aggregates in their respective catchment areas. Samples S4 was observed to be coarse and angular while S7 was coarse, flaky and elongated. This can be attributed the manufacturing process of the aggregates. Rough surface texture contributes to concrete strength due to the enhanced bond between the aggregates and cement paste. Smooth texture reduces the bond between cement paste and particles.

4.2.8.13 Water Absorption

The water absorption of the samples is shown in Table 4.14.

Table 4.14: Water absorption of the samples

Sample	Water Absorption
S-2	8.3
S-3	8.62
S-4	6.31
S-5	5.16
S-6	15.3
S-7	5.37

From Table 4.14, the water absorption of all the aggregate samples was observed to range between 5.16-15.3%. These exceed the 2.3% maximum accepted limit of water absorption according to BS 813-2:1995 standards. This can be attributed to the petrological character of the parent rocks at the catchment area that resulted in formation of the aggregates and the weather period during sampling. A high water absorption indicates a large amount of porous material in the samples (Hu, 2005). Aggregates with a high water absorption will require more water to produce workable concrete (Afsar, 2012). Although the desirable absorption is 2.3%, care should be taken to consider the water content of the aggregate before use.

4.2.8.14 Physical properties summary

The summary of the physical properties of all the samples are summarized as shown in Table 4.15.

Table 4.15: Physical properties of fine aggregate samples

Sno.	Test parameter	Units	S-2	S-3	S-4	S-5	S-6	S-7	Permissible limits
1	Specific gravity		2.12	2.06	2.24	2.31	1.73	2.27	Min 2.6
2	Apparent Specific gravity		2.57	2.5	2.6	2.63	2.36	2.59	NP
3	Bulk density	Kg/M3	1497	1469	1407	1613	1327	1684	NP
4	Water absorption		8.3	8.62	6.31	5.16	15.3	5.37	Max 2.3%
5	Fineness module		2.66	1.92	3.37	2.54	1.94	3.66	2.3-3.1
6	Silt and clay content	%	4.85	4.16	2.06	6.66	9.37	11.9	Max 4%
7	Sieve analysis		C&M	F	C	C&M	F&M	C	NP
8	Surface texture		Rough	Smooth	Coarse	Rough	Smooth	coarse	NP
9	Particle shape		R	R	A	R	R	FL&E	NP

C-Coarse; M-Medium; F –fine; R- Round; A- Angular; FL – Flocky; E- Elongated; NP- Not Provided

From the Table 4.15, a comparative analysis of the different physical properties indicates materials of generally low specific gravity and high silt content but S4 which could be attributed to the washing of silt from the aggregate before use. S3 (Kajiando) has the lowest fineness modulus followed by S6 (Naivasha) and therefore expected to have sand of high strength. S7 (Mlolongo) has the highest Fineness modulus and therefore expected to have concrete with low strength. The results obtain indicates that materials properties are variable and dependent on the geological formation of the source. The resultant concrete can also not exhibit similar properties in a given age due to the variability.

4.2.9 Chemical properties of Fine Aggregates

The chemical properties of aggregates have a great influence on strength development in concrete. The main chemical constituents of importance are silicon (IV) oxide, aluminum (III) oxide and calcium oxide which influence the setting time, early strength and final concrete strength. Silica concentrations of between 70-90% prolong the setting time but increase the final concrete mix strength while alumina concentrations of between 8-12% reduce the setting time but increases the concrete strength. Calcium oxide concentrations of between 2-5% prolong the setting time of concrete but gives an early strength. (Penn State University, 2000).

Table 4.16: Chemical properties of fine aggregates (XRF)

S/No.	Parameter (%)	S-2	S-3	S-4	S-5	S-6	S-7
1	SIO_z	76.00	78.00	67.00	80.00	69.00	65.00
2	AI_zO_3	11.00	9.00	17.00	10.00	14.00	19.00
3	Fe_zO_3	1.40	1.20	4.00	1.00	5.50	4.00
4	CaO	1.60	1.50	1.40	2.50	1.30	1.40
5	MgO	0.80	1.00	0.05	0.02	0.04	0.08
6	Na_zO	2.00	1.40	1.50	1.80	3.00	4.00
7	K_zO	1.00	1.00	3.00	1.00	1.80	1.60
8	TIO_z	0.30	0.17	1.40	0.12	0.30	0.60
9	LOI	0.72	1.04	3.50	1.70	2.00	3.80

From the Table 4.16 above it is observed that;

The silicon (IV) oxide concentration in aggregate samples varied between 65-80%. The highest concentrations were recorded in samples S2, S3 and S5. This can be attributed to the quartz mineral predominant in the samples which is made of high concentrations of silica. Samples S4, S6 and S7 recorded lower concentrations of silica. This is because the predominant mineral found in the aggregates were sanidine and orthoclase which had lower concentrations of silica. Silica concentrations of between 70-90% prolong the setting time but increase the final concrete mix strength. It is expected that S4 and S6 to have a lower concrete strength in the early age but eventually gather strength to maturity.

The alumina concentration varied between 9-19% in all the aggregate samples. The highest concentrations were recorded in samples S4, S6 and S7 due to the predominant sanidine mineral in the samples which has alumina. S2 recorded lower concentrations because only one trace mineral, labradorite, contained in the sample has aluminium (III) oxide. S3 contained small traces of labradorite, orligoclase, albite and anorthite sodian which cumulatively contributed low concentrations of aluminium (III) oxide. S5 also contained small traces of microcline, albite, orligoclase and andesine which cumulatively contributed low concentrations of aluminium (III) oxide. Alumina concentrations of between 8-12% reduce the setting time but increase the concrete strength. S4, S6 and S7 have a high Alumina and expected to have early strength while S2, S3 and S5 will have lower early strength but gradually increase as the concrete age increases.

The calcium oxide concentration for all aggregate samples varied between 1.3- 2.5%. The highest concentration was recorded in sample S5 and this can be attributed to the presence of labradorite, andesine and oligoclase minerals constituted in the aggregates which contain calcium oxide. Samples S2, S3, S4, S6 and S7 recorded lower concentrations because of the mineral composition of the aggregates. S2 contained traces of labradorite; S3 contained traces of labradorite, anorthite sodian and orligoclase; S4 contained traces of augite and diopside; S6 contained sanidine and diopside and S7 contained sanidine which has low concentrations of calcium oxide. Calcium oxide concentrations of between 2-5% prolong the setting time of concrete but give an early strength. Apart from S5 which has a high value of 2.5%, the rest fall below which indicate a reduction in the early strength.

The iron (III) oxide concentration varied from 1-5.5% in the aggregate samples. The highest concentrations were recorded in samples S4, S6 and S7. This is due to the presence of boulangerite which is a grey metallic mineral in S6, baricite and augite minerals which contain iron in S7 and S4 respectively. Samples S2, S3 and S5 recorded lower concentrations due to the mineral compositions of the aggregates that contained very small traces of minerals containing iron. The iron concentration in aggregates has no significant effect on concrete strength but gives the gray color to the concrete.

The magnesium oxide concentration in all the samples varied from 0.02-1%. The highest concentrations were recorded in samples S2 and S3. The mineral composition of these samples does not indicate any presence of magnesium therefore the traces found can be attributed to external factors like contamination during transportation of the sediments by the rivers. The presence of 0.5-1% magnesium oxide helps in minimizing crack development by exhibiting long term expansion to compensate for shrinkage of concrete mass as it cools (Du, 2005).

The concentration of sodium oxide in all the aggregate samples varied between 1.4-4%. Sample S2, S6 and S7 recorded the highest concentrations. This can be attributed to the presence of high concentrations of berzalianite, anorthoclase and feldspar minerals in the respective samples which contain sodium oxide. Samples S3, S4 and S5 recorded lower concentrations. This is due to low concentrations of sodium oxide in the minerals constituted in the samples. Sodium oxide has no significant effect on concrete strength (Penn State University, 2000).

4.2.10 Fine Aggregates quality in concrete.

The fine aggregates used in this research were tested for conformance to the British standards of good quality material. Conformance refers to the extent to which the facility is consistent with the standards. Table 4.17 shows the conformance of the materials to the physical properties standards and recommended chemical properties ranges given for aggregates used in concrete production concrete production.

Table 4.17: Conformance with pre-defined standards

		Conformance-pre-defined standards					
Sno.	Test Parameter	S-2	S-3	S-4	S-5	S-6	S-7
1	Specific gravity	X	X	X	X	X	X
2	Water Absorption	X	X	X	X	X	X
3	Fineness module	V	X	X	V	X	X
4	Silt and clay content	X	X	V	X	X	X
5	Sio_2	V	V	X	V	X	X
6	AI_2O_3	V	V	X	V	X	X
7	CaO	X	X	X	V	X	X

From table 4.17, it was observed that samples S2 and S5 conformed to the recommended standards for properties of fine aggregate required for concrete production by 43% while sample S3 and S4 conformed by 28%. Samples S6 and S7 had 0% conformance. From this analysis, S6, S7 should be modified to enhance their properties for use in concrete production.

4.3 Concrete compressive strength and prediction models comparative analysis (Objective 2)

The concrete from the fine aggregate samples underwent compressive strength tests for a period of one year to determine their strength development and suitability for concrete production. A model was developed to predict concrete strength gain over 360 days for the samples which was then validated using the compressive strength test results.

Aggregates are not truly inert and their physical, thermal, and sometimes also chemical properties influence the performance of concrete (Neville, 2011). Compressive strength of concrete depends on chemical and mechanical properties of the ingredients used and the concrete mix proportions. The main physical properties influencing strength are specific gravity, water absorption, fineness modulus and silt & clay content while the main chemical properties are silica, alumina and calcium oxide.

The design mix was prepared using the target strength of concrete grade C30/37N/mm^2 at 28 days. The target 7-day, 14-day and 28-day target strength for the cubes were 24.05N/mm^2, 33.3N/mm^2 and 37N/mm^2 respectively. Table 4.18 and 4.19 shows the casting dates for the two runs for the cubes made from the samples.

Table 4.18: B Run 1 crushing periods

			RUN 1			
Dates	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**
0	6/12/2017	7/12/2017	9/1/2018	8/12/2017	12/1/2018	16/01/18
7	13/12/17	14/12/17	16/01/18	15/12/17	19/01/18	23/01/18
14	20/12/17	21/12/17	23/01/18	22/12/17	26/10/18	30/01/18
28	3/1/2018	4/1/2018	6/2/2018	5/1/2018	9/2/2018	13/02/18
56	31/01/18	1/2/2018	6/3/2018	2/2/2018	9/3/2018	13/03/18
112	28/03/18	29/03/2018	1/5/2018	30/03/18	4/5/2018	8/5/2018
180	4/6/2018	5/6/2018	8/7/2018	6/6/2018	11/7/2018	15/07/18
360	21/11/2018	22/11/18	25/12/18	23/11/18	28/12/18	1/1/2019

Table 4.19: Run 2 crushing periods

	RUN 2					
Dates	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**
0	14/04/2018	15/04/18	21/04/18	22/04/18	24/04/18	4/5/2018
7	21/04/18	22/04/18	28/04/18	29/04/18	1/5/2018	11/5/2018
14	28/04/18	29/04/18	5/5/2018	6/5/2018	8/5/2018	18/05/18
28	12/5/2018	13/05/18	19/05/18	20/05/18	22/05/18	1/6/2018
56	9/6/2018	10/6/2018	16/06/18	17/06/18	19/06/18	29/07/18
112	4/8/2018	5/8/2018	11/8/2018	12/8/2018	14/08/18	24/08/18
180	11/10/2018	12/102018	18/1018	19/10/18	21/10/18	31/1018

In concrete reaction, the main cement chemical properties responsible for the early and ultimate compressive strength development is CaO, SiO_2, Al_2O_3 and Fe_2O_3 required to form silicates and aluminates of calcium such as the tri-calcium silicate ($3CaO{\cdot}SiO_2$) and di-calcium silicate ($2CaO{\cdot}SiO_2$) which are responsible for the initial setting and early strength gain of the cements in concrete and the ultimate compressive strength development respectively. Iron oxide reacts with calcium and aluminium to form the tricalcium aluminoferrite ($4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$) which imparts hardness and strength to the cement and consequently to the concrete (Mamlouk & Zaniewski, 1999); (Okumu, 2016).

Concrete strength improvement is rapid at early ages but continues more slowly thereafter for an indefinite period. When moist curing is stopped, concrete strength development continues for a short period until concrete internal relative humidity drops to about 80% (PCA, 2011) (Camp, 2018). In this research, the concrete made from the samples was moist-cured for 28 days and thereafter left in laboratory air for up to 360 days. The compressive strength of the samples was determined on day 7, 14, 28, 56, 112, 180 and 360.

4.3.1 S2- Mwingi river sand

The compressive strength development results for concrete cubes made from Mwingi river sand are shown in Table 4-20 and Figure 4-30.

Table 4.20: Compressive Strength of Mwingi river sand

Days	S2
7	24.76
14	32.15
28	41.90
56	53.73
112	47.46
180	40.30
360	48.05

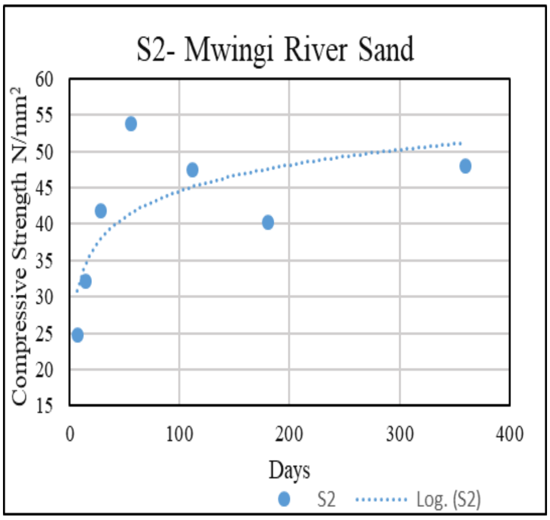


Figure 4.30: strength development for Mwingi river sand

Table 4.20 and Figure 4.30 shows the compressive strength of concrete made from Mwingi river sand. It was observed that the strength increased with age. The concrete achieved the characteristic target strength at 28 days and continued to increase gradually up to 360 days. The rate of strength gain from 28 days to 360 days was 14.68%.

The high strength can be attributed to the high fineness modulus and sand's silica and alumina concentrations of 76% and 11% respectively which fell within the range recommended for concrete strength development. This is despite of the sand not conforming to all the physical property specifications for sand used in construction as per the British Standards. This implies that other properties and factors such as chemical properties of the fine aggregates could have a significant contribution to the strength development. The sand also had rough surface texture which contributed to concrete strength from the enhanced bond between the aggregates and cement paste. This indicates that Mwingi sand is of good quality and surpassed the 28-day target strength of 30/37 concrete and thus suitable for construction.

4.3.2 S3- Kajiado River sand

The compressive strength development results for concrete cubes made from Kajiado river sand are shown in Table 4.21 and Figure 4.31.

Table 4.21: Compressive Strength of Kajiado river sand

Days	S3
7	25.49
14	31.19
28	34.75
56	46.85
112	43.74
180	41.84
360	49.71

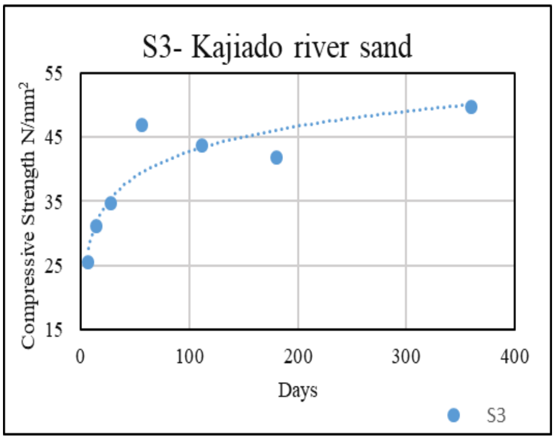


Figure 4.31: Compressive strength development for Kajiado river sand

From the compressive strength results of concrete made from Kajiado river sand, it was observed that the strength development was progressive. At 28 days, the resultant concrete yielded a strength lower than the characteristic strength but within the acceptable deviation limits. The strength slowly progressed to 46 N/mm^2 at 56 days surpassing the target 28-day strength. This was followed a gradual gain up to 360 days. The growth in compressive strength from 28 days to one year was 33.73%.

This sand had low fineness modulus and slightly higher silt content than the recommended maximum of 4%. Although the sand strength development in the first 28 days was lower, it eventually increased and surpassed that for Mwingi sand. This could be attributed to the sand's silica and alumina concentrations of 78% and 9% respectively responsible for strength development. Kajiado river sand and its resultant concrete is of acceptable quality for use in the construction industry.

4.3.3 S4- Rock sand

The compressive strength development results for concrete cubes made from rock sand obtained from Mlolongo are shown in Table 4.22 and Figure 4.32.

Table 4.22: Compressive Strength of rock sand

Days	S4
7	20.89
14	25.12
28	28.68
56	34.47
112	40.46
180	34.40
360	41.88

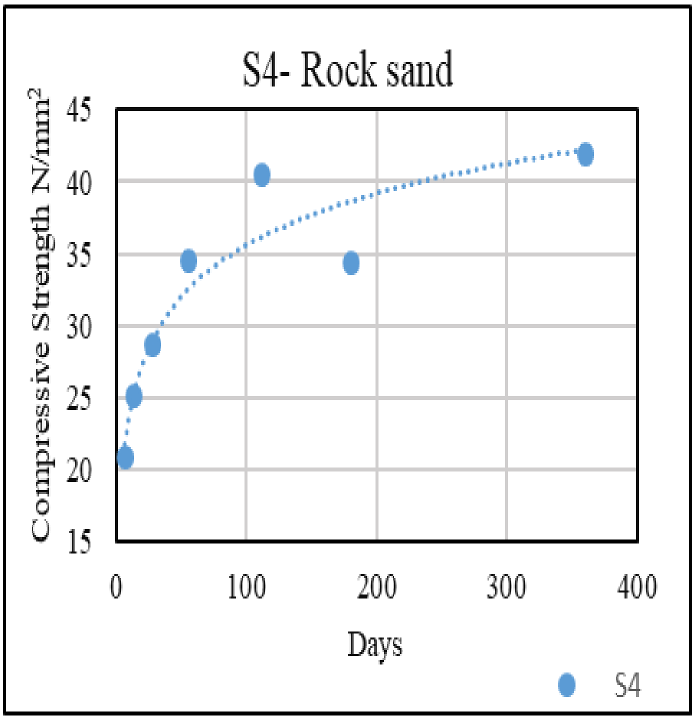


Figure 4.32: Compressive strength development for rock sand

From the compressive strength results of concrete made from rock sand, it was observed that the strength development was progressive with age. At 28 days, the resultant concrete failed to attain the characteristic strength by a deviation exceeding the acceptable range. A continued increase in strength up to 56 days caused the concrete to achieve the target strength within the acceptable deviation limits. At 112 days, the concrete surpassed the 28-day target strength followed then gradually increased up to 360 days. The growth in compressive strength from 28 days to one year was 46.02%. This was the highest increase in strength among the samples that were tested. High fineness modulus was expected to produce acceptable strength of concrete at 28 days but this was not the case. This means there are other parameters influencing the 46.2% strength development. The increase in concrete strength could be attributed to the high concentration of the Aluminium Oxide.

The failure to achieve the target 28-day strength required can be attributed low concentration of silica (67%) in the aggregate samples that fell outside the recommended limit for concrete strength development. This may produce a more durable concrete due to low Alkali silica reaction. The rock sand also failed to conform to the physical property requirements for sand fit for use in concrete production (Table 4.15). Further, Loading should be done only two months after the concrete has gained sufficient strength. The sand may also be modified to improve the physical properties for concrete manufacture should early concrete strength gain be required.

4.3.4 S5- Machakos river sand

The compressive strength development results for concrete cubes made from Machakos river sand are shown in Table 4.23 and Figure 4.33.

Table 4.23: Compressive Strength of Machakos river sand

Days	S5
7	21.79
14	27.62
28	33.66
56	40.78
112	42.35
180	45.04
360	41.75

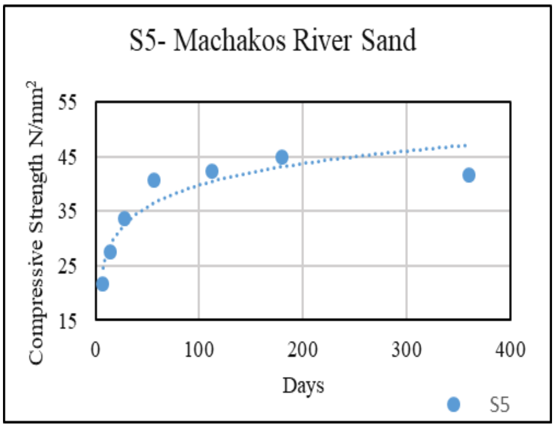


Figure 4.33: Compressive strength development for Machakos river sand

From the compressive strength test results of the concrete cubes made from Machakos river sand, it was observed that the strength development with curing age was progressive. The concrete cubes failed to meet the characteristic target strength at 7, 14 and 28 days. However, at 56 days it obtained the characteristic target strength. The compressive strength increased up to 45.04 N/mm^2 at 180 days then decreased to 41.75N/mm^2 at 360 days due to reaction of the cement with the high silt content in the fine aggregate. The growth in compressive strength from 28 days to one year was 24.09%.

The failure to achieve the target 28-days strength, despite the sample having silica and alumina concentrations within the recommended limits (Table 4.16) could be as a result of the high silt and clay concentration in the sand. A high silt and clay concentration reduces the bond between the aggregates and the cement paste. To improve the strength and quality of the concrete, Machakos river sand should be washed to reduce the silt and clay content.

4.3.5 S6- Naivasha sand

The compressive strength results for concrete cubes made from Naivasha sand are shown in Table 4.24 and Figure 4.34.

Table 4.24: Compressive strength of Naivasha sand

Days	S6
7	20.89
14	24.75
28	28.19
56	33.23
112	33.20
180	37.98
360	37.91

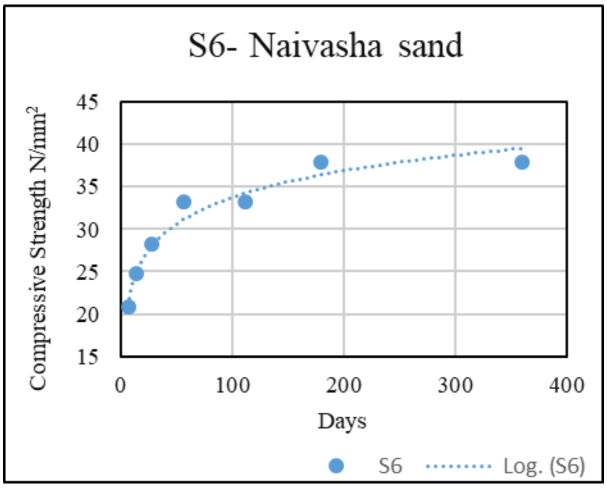


Figure 4.34: Compressive strength development for Naivasha sand

From the compressive strength results of concrete made from Naivasha sand, it was observed that the strength increased with age. At 28 days, the resultant concrete failed to attain the characteristic strength by a deviation exceeding the acceptable range. The strength gain was gradual after 28 days but still failed to achieve the target 28-day strength at 56 and 112 days. The concrete attained the target strength at 180 days and stabilizes to 360 days. The growth in compressive strength from 28 days to one year was 33.43%.

The low strength can be due to low silica concentrations in the sand ideal for high strength development. Further, sand from Naivasha has very high silt content that affects strength development of the concrete. The Strength development is slow but eventually attained after 6 months. Loading for structures made from this sand should therefore be done only after 180 days. Otherwise, sand improvements should be made mandatory for early concrete strength requirements.

4.3.6 S7- Quarry dust

The compressive strength development results for concrete cubes made from quarry dust obtained from Mlolongo area are shown in Table 4.25 and Figure 4.35.

Table 4.25: Compressive Strength of quarry dust

Days	S7
7	23.03
14	26.06
28	25.91
56	36.64
112	31.48
180	41.58
360	39.61

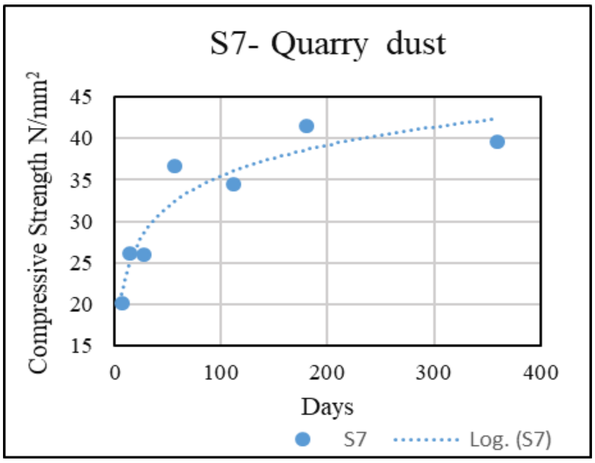


Figure 4.35: Compressive strength development for quarry dust

From the compressive strength results of concrete made from quarry dust, it was observed that the strength development was progressive with age. At 28 days, the resultant concrete failed to attain the characteristic strength by a deviation exceeding the acceptable range. A continued increase in strength up to 56 days resulted in the concrete achieving the target strength within the acceptable deviation limits. The strength gradually reduced up to 112 days then increased up to 180 days surpassing the target strength. The strength then gradually reduced until 360 days. The growth in compressive strength from 28 days to one year was 43.20%.

The quarry dust did not conform to the physical properties (table 4.15) requirements with high silt and clay content not suitable for concrete production. Further, the low silica concentrations in the sand which fell out of the recommended limits for high strength development. This indicates that the quality of the quarry dust was not satisfactory for use in construction. However, should this material be used, loading should be done only after 2 months when the concrete has gained sufficient strength. The sand should be modified to improve the physical properties for concrete manufacture e.g. washing to reduce the silt and clay content.

4.3.7 Comparative analysis of the strength development for all samples

The compressive strength development of concrete cubes made from all the fine aggregate samples are summarized in Table 4.26 and Figure 4.36.

Table 4.26: Compressive strength of all fine aggregate samples

Days	S2	S3	S4	S5	S6	S7	Target Strength N/MM^2
7	24.76	25.49	20.89	21.79	20.89	20.03	24.05
14	32.15	31.19	25.12	27.62	24.75	26.06	33.30
28	41.90	34.75	28.68	33.66	28.19	25.91	37
56	53.73	46.86	34.47	40.78	33.23	36.64	
112	47.46	43.74	40.46	42.35	33.20	34.48	
180	40.30	41.84	34.40	45.04	37.98	41.58	
360	48.05	49.71	41.88	41.75	37.91	39.61	

Green Passed; Yellow-Partial failure; Red – Complete failure

Days	Predicted strength N/MM^2	Observed strength N/MM^2					
	BS8110	S2	S3	S4	S5	S6	S7
7	24	24.76	25.40	20.89	21.89	20.89	20.03
28	36	41.90	34.75	28.68	33.64	28.19	25.91
56	39.6	53.70	46.85	34.47	40.78	33.23	36.64
112	41.76	47.60	43.74	40.46	41.35	33.20	34.48
180	43.2	40.3	41.84	34.4	45.04	37.98	41.58
360	44.64	48.05	49.71	41.88	41.75	37.91	39.61

Green Passed; Yellow-Acceptable; Red – failure

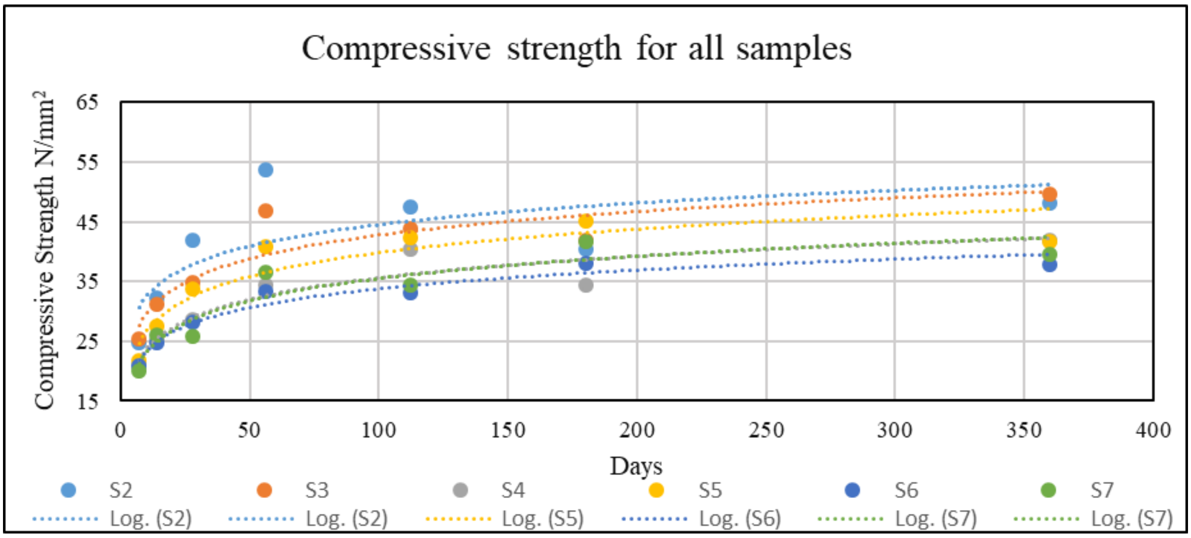


Figure 4.36: Strength development for all the fine aggregates

From Figure 4.36, it was observed that all samples reported a progressive strength gain with curing age. At 7 days curing, samples S2 and S3 were able to attain early strength of 65% of the characteristic strength (24.05N/mm^2). Besides the properties of the fine aggregates, the hot climate of the area promoted early strength development as it has been pointed out that the temperature during the early period of hydration influence the rate of gain of strength of concrete (Shetty, 2006).

At 28 days curing, samples S2 obtained the characteristic strength (37N/mm^2) while sample S3 did not achieve the strength but fell within the acceptable limits. The high strength may be on account of the silica and alumina concentrations in the sands which fell within the recommended limits for high strength development (Penn State University, 2000). Samples S4, S5, S6 and S7 did not attain the characteristic strength. The low strength in sample S5 can be attributed to the high silt and clay content and the smooth texture of the aggregates that reduce bond in the concrete. The low strength in S4, S6 and S7 is due to the silica and alumina concentrations in the sands which fell out of the recommended limits for high strength development. The samples also did not conform to the physical properties' requirements recommended for sand used in construction yet attained the strength over time which could be associated with the high aluminum oxide.

At 56 days, samples S3 and S5 surpassed the target 28-day strength while samples S4 and S7 did not achieve but fell within the acceptable deviation limits but surpassed at 112 days. Sample S6 attained the target 28- day strength at 180 days' age.

Despite S2 and S5, failing to attain the required physical properties, they still attained sufficient strength. This shows that the chemical properties of concrete could have a significant influence on concrete strength.

The summary of the strength development of concrete made from different fine aggregate material is as shown in table 4.27.

Table 4.27: Percentage increase in compressive strength over one year

	Percentage increase in strength					
Age(days)	S2	S3	S4	S5	S6	S7
25-56	24.36	26.05	28.46	21.22	17.30	32.41
56-112	13.27	17.67	41.06	25.87	16.85	24.65
112-180	5.44	18.58	28.34	25.64	33.68	42.36
180-360	14.68	33.73	46.01	24.09	33.43	43.20

Table 4.27 shows the percentage gain in strength after 28 days to one year. S2 has the highest rate of strength development between 28 and 56 days, S3 between 180 and 360 days, S4 180 to 360 days, S5 56 to 112 days, S6 112 to 180 days and S7 112 to 180 days.

4.3.8 Concrete quality in construction

There are eight dimensions of quality in construction namely; durability, aesthetics, conformance, serviceability, perception, reliability, performance and physical features. The materials used for construction should be tested to ascertain that they meet the quality requirements in all dimensions. The processes, practices and procedures should be reviewed to help identify possible areas of change in order to improve construction quality (Hendrickson, 2008). The resultant concrete used in this research were tested for performance and reliability. Performance refers to the basic functions of the facility while reliability is the level of confidence with which occupants can use the facility without failure (Garvin, 1984).

Table 4-28 shows the performance of the concrete made from the samples. The performance was determined by comparison again the set target strengths at 7, 14 and 28 days.

Table 4.28: Performance and reliability of the resultant concrete

Performance and reliability-Compressive strength						
Days	S2	S3	S4	S5	S6	S7
7	V	V	V	V	V	V
14	V	V	X	V	X	X
28	V	V	X	V	X	X

From Table 4.28, it was observed that samples S2 and S3 satisfied the performance and reliability dimensions in quality by attaining the requisite compressive strength after 28 days despite the fact that the samples failed to attain the required physical properties. This could possibly mean that the chemical properties of concrete have a significant influence on concrete strength. Sample S7 failed to satisfy the performance and reliability dimensions in quality. This can be attributed to high silt and clay content in the aggregate samples. A high and clay concentration reduces the bond between the aggregates and the cement paste.

Samples S4 and S6 did not satisfy the quality requirements in terms of performance and reliability. This can be attributed to their failure to meet the fine aggregate physical and the inherent chemical properties. This indicates that the quality of the rock and Naivasha sand is not satisfactory for use in construction. The loading on concrete from the rock sand and Quarry dust should be done after concrete has gained sufficient strength. For Naivasha sand, the resultant concrete should be loaded after six months. Further, the sands should be modified to improve the physical properties for concrete manufacture.

4.3.9 Concrete Strength Prediction Models

Early prediction of strength is key in effective and efficient planning for concrete construction projects. Table 4.29 shows various empirical correlations that have been developed to determine concrete strength estimation though each model has its own limitations when applied. A number of prediction techniques have been used to predict concrete strength development with more accuracy, e.g. statistical methods, computational models and simulations. Apart from speed, statistical modeling has advantages over the other techniques and can be used to define confidence interval for the prediction (Palika, 2014). However, the correlations developed in the existing models may result in different predictions of the strength in locations other than where they were originally developed. This discrepancy could be a consequence of using aggregates having different mineralogy as well as difference in preparation of concrete (Hossein, 2016).

Table 4.29: Prediction models and their limitations

Model	Limitation
British standards (BS 8100) Modification factors for permissible compressive strength; 1.0, 1.10, 1.16, 1.2 and 1.24 for 1, 2, 3,6, and 12 months as minimum age of member when full design load is applied	Does not specify; type of cement used, constituent material properties, quantities of materials used and curing conditions.
German model $fc28= 1.4fc7 + 150$ $fc28= 1.7fc7 + 850$ fc is being expressed in psi where, fc7 and fc28 - strengths at 7 and 28 days, respectively.	Does not take into account the constituent material properties, curing conditions and the cement type and hydration regime Requires use of observed 7 days' compressive strength as a constant employed to predict concrete strength at 28days which is not a good representation and therefore casts doubt on the model.
Abrams' model Fc=A/(B^w/c) A and B are constants Fc- Strength	Concrete at a given age and cured in water at a prescribed temperature is assumed to depend primarily on the water/cement ratio and the degree of compaction only. Uses aggregate sizes which are out of normally used range. Different coefficients of proportionality values are needed whenever any factor affecting the strength of concrete changes - model incomplete
Bolomey's model fc28=24.6(c/w-0.5) fc28- strength at 28days c- mass of cement w- mass of water	Model doesn't take into account other factors like quantities of constituent materials, material physical and chemical properties and curing conditions Model limited to predicting 28 days' age only
ACI model fcm(t)=fc28 (t/(4+0.85t)) Where fcm (t) is the mean compressive strength at an age of t days (MPa) fc28 is the mean 28-day compressive strength (MPa)	Model does not take into account the constituent material properties, curing conditions and the cement type and hydration regime Requires use of observed 28 days compressive strength as a constant employed to predict concrete strength throughout the lifetime of concrete which may be erroneous.

4.3.10 Concrete strength gain prediction based on the British standards BS8110

For grade C30/37 concrete, the compressive strength results obtained from the samples compared to the British standards (BS) cube strength at the given ages are as shown in Table 4.30.

Table 4.30: Observed vs predicted compressive strength using BS 8110 (N/mm2)

Days	S2	S3	S4	S5	S6	S7	Target strength N/MM^2
7	24.76	25.49	20.89	21.79	20.89	20.03	24.05
14	32.15	31.19	25.12	27.62	24.75	26.06	33.30
28	41.90	34.75	28.68	33.66	28.19	25.91	37
56	53.73	46.85	34.47	40.78	33.23	36.64	
112	47.46	43.74	40.46	42.35	33.20	34.48	
180	40.30	41.84	34.40	45.04	37.98	41.58	
360	48.05	49.71	41.88	41.75	37.91	39.61	

Green- Achieved strength; Yellow – Failed but within the deviation limits; Red- Complete failure

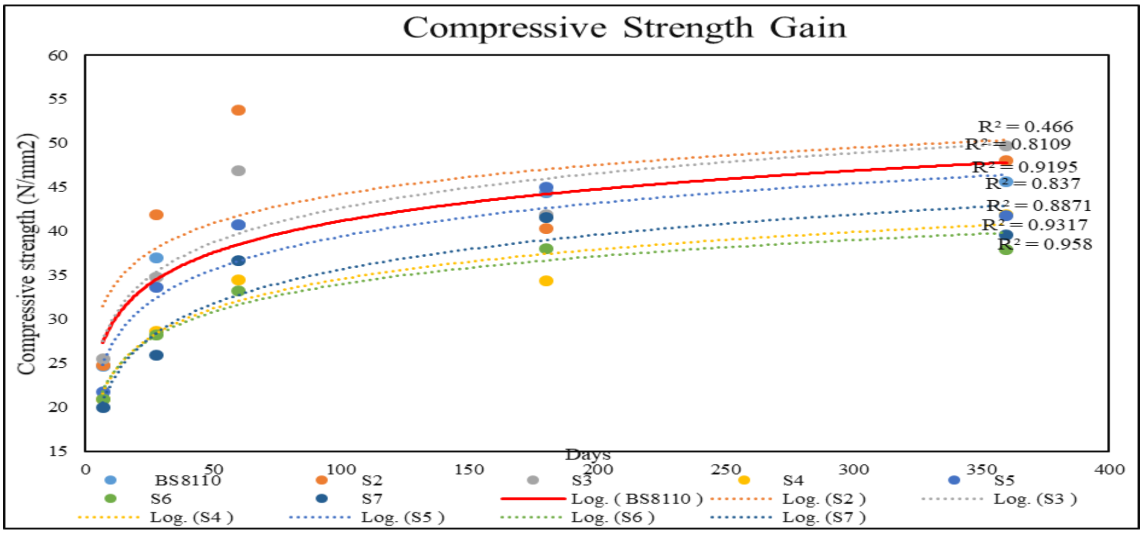


Figure 4.37: Observed vs predicted compressive strength gain based on BS 8110 (N/mm^2)

From Figure 4.39, samples S2 was observed to have strength surpassing the predicted at all ages. The coefficient of determination of S2 was lower than the expected 75%. This could be attributed to a high reading of strength at the 56th day. However, the prediction curve yields better results than the control curve (BS8110). Samples S3 was also observed to exceed the predicted strength at 7, 28 and 360 days. Sample S5 strength results exceeded predicted strength at two months and six months' age. Samples S7, S4 and S6 did not attain the predicted strength at 28days with sample S7 being the lowest in strength. However, the coefficient of determination of S4, S5, S6, and S7 was above acceptable minimum of 75% and therefore curve reasonable acceptable for use in concrete prediction although lower than the control curve.

The deviations from the predicted values could be explained by the use of different constituent materials, curing conditions and hydration regimes. Further, the BS strength prediction does not specify the criteria used to come up with the modification factors; i.e. type of cement used, constituent material properties, quantities of materials used and curing conditions. However, the difference in the curves qualifies the need for a refined model that would reduce this gap.

4.3.11 Concrete strength gain prediction based on the German model

Using this model, a comparison was made to the compressive strength observed from the samples as tabulated in Table 4.31.

Table 431: Observed vs predicted compressive strength using German model (N/mm^2)

Samples	Observed strength		Predicted at 28 days	
	7 days	28 days	Lower range	Upper range
S2	24.76	41.90	35.70	47.95
S3	25.49	34.75	36.72	49.19
S4	20.89	28.68	30.28	41.37
S5	21.78	33.66	31.53	42.89
S6	20.89	28.19	30.28	41.37
S7	20.03	25.91	29.08	39.91

Green-within range; Red – Outside the range

It was observed that, samples S2 and S5 fell within the range predicted values of the German model while samples S3, S4, S6 and S7 fell below the predicted range. The deviation of the observed compressive strength values from the predicted values of the German model could be explained by the model not taking into account the constituent material properties, curing conditions and the cement type and hydration regime. The model also requires use of observed compressive strength at the age of 7 days as a constant employed to predict concrete strength at 28 days which may not be a good representation. Should the 7-day strength be erroneous, then the 28-day strength would follow the trend giving faulty results.

4.3.12 Concrete strength gain prediction based on the Abrams' model

Table 4.32 shows the comparison of the actual strength results to the predicted strength by Abrams' model.

Table 4.32: Observed vs predicted compressive strength using Abrams' model (N/mm^2)

	Days	7 days	28 days
Predicted strength N/MM^2	Bolomeys's Model	16.09	34.93
Observed strength	S2	24.76	41.90
	S3	25.49	37.17
	S4	20.89	28.68
	S5	21.78	33.64
	S6	20.89	28.41
	S7	20.03	25.91

Green –above predicted value; Red- below predicted value

As observed in Table 4.32, the actual strength results varied from values obtained from Abrams' prediction model. Samples S2, S3 and S5 had observed strengths that surpassed the predicted strength at 7 and 28 days while samples S7, S4 and S6 had observed strength results that were lower than the predicted strength at 28 days. This can be attributed to the fact that in Abrams' equation the strength of concrete at a given age, cured in water at a prescribed temperature, is assumed to depend primarily on two factors only: the water-cement ratio and the degree of compaction (Neville, 2011). This model is incomplete because different coefficients of proportionality values are required whenever any factor affecting the strength of concrete changes. The coefficients of proportionality parameters depend on cement type and strength, aggregate gradations and proportions, admixtures, curing conditions, testing conditions, and age of concrete (Moutassen, 2015). The model is also limited to predict for 7- and 28-days age only.

4.3.13 Concrete strength gain prediction based on the Bolomey's model

Table 4.33: Observed vs predicted compressive strength using Bolomey's model (N/mm^2)

		28 days
Predicted strength N/MM^2	Bolomeys's Model	34.93
Observed strength	S2	41.90
	S3	37.17
	S4	28.68
	S5	33.64
	S6	28.41
	S7	25.91

Green –above predicted value; Red- below predicted value

From Table 4.33, it was observed that all actual compressive strength values deviated from the predicted values. Samples S2 and S3 strength results exceeded the predicted values of Bolomey's model while samples S4, S5, S6 and S7 fell below the predicted values. This could be due to the fact that Bolomey's prediction model is assumed to depend primarily on water-cement ratio. It doesn't take into account other factors like quantities of constituent materials, material physical and chemical properties and curing conditions. The model is also limited to predict 28 days age only.

4.3.14 Concrete strength gain prediction based on the ACI model

Table 4.34: Observed vs predicted compressive strength using ACI model (N/mm²)

Days	S2		S3		S4		S5		S6		S7	
	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual
7	29.48	24.76	25.39	25.49	20.18	20.89	23.68	21.79	19.83	20.89	18.23	20.03
14	36.89	32.15	31.77	31.19	25.25	25.12	29.64	27.62	24.82	24.75	22.81	26.06
28	42.20	41.89	36.35	36.09	28.89	28.68	33.90	33.66	28.39	28.19	26.09	25.91
56	45.47	53.73	39.16	46.85	31.13	34.47	36.53	40.78	30.60	33.23	28.12	36.64
112	47.31	47.46	40.74	43.74	32.38	40.458	38.00	42.35	31.83	33.203	29.25	34.48
180	48.04	40.30	41.37	41.84	32.88	34.40	38.59	45.04	32.32	37.98	29.70	41.58
360	48.66	48.05	41.91	49.71	33.31	41.88	39.09	41.75	32.74	37.91	30.09	39.61

All the samples had their strengths predicted at the respective days and compared to the actual compressive strength results as indicated in Table 4.34. This was used to plot the graphs in Figure 4.38 to Figure 4.43.

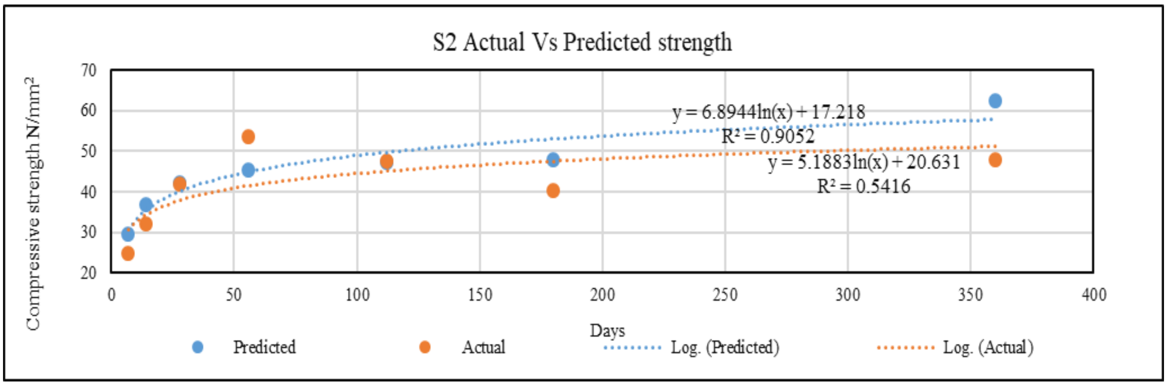


Figure 4.38: Observed vs predicted compressive strength gain for S2 (N/mm2)

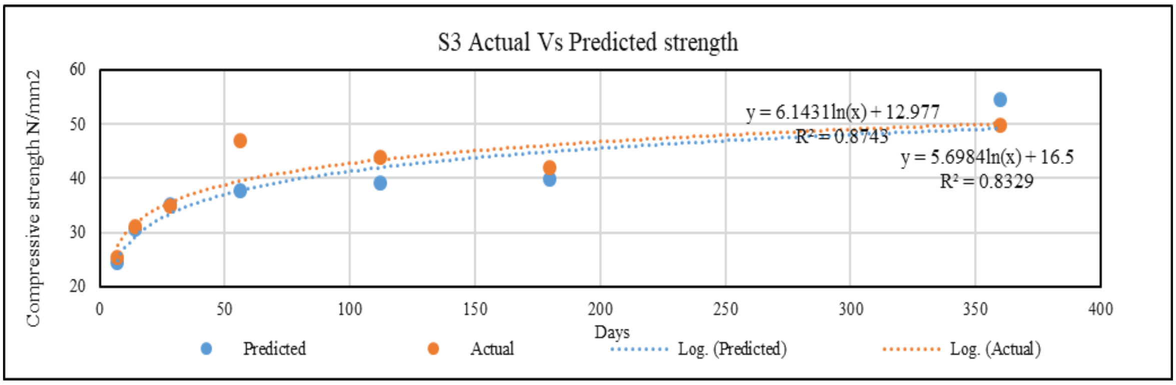


Figure 4.39: Observed vs predicted compressive strength gain for S3 (N/mm2)

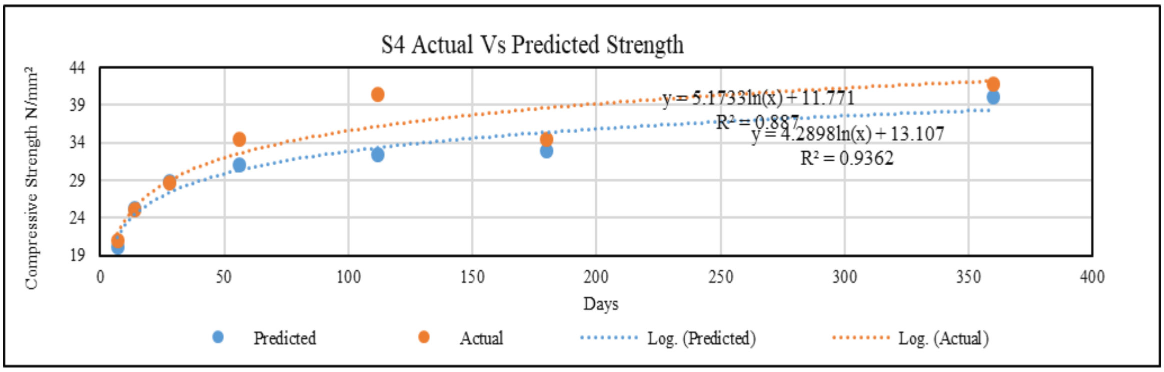


Figure 4.40: Observed vs predicted compressive strength gain for S4 (N/mm2)

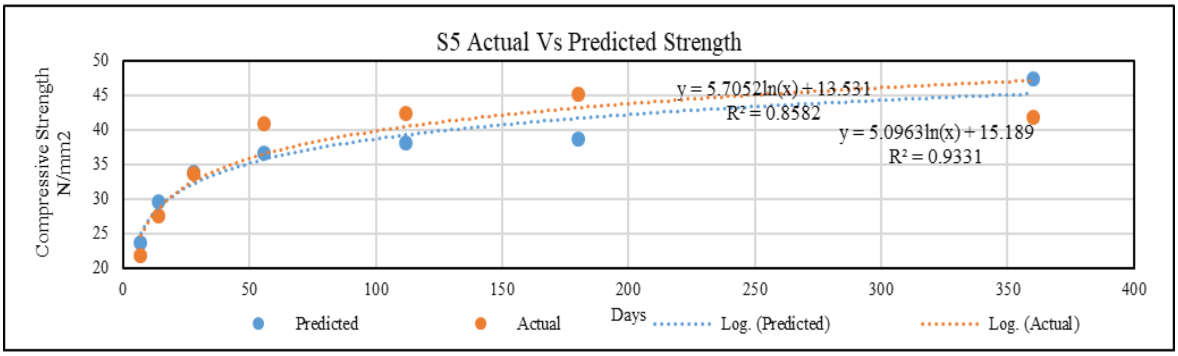


Figure 4.41: Observed vs predicted compressive strength gain for S5 (N/mm2)

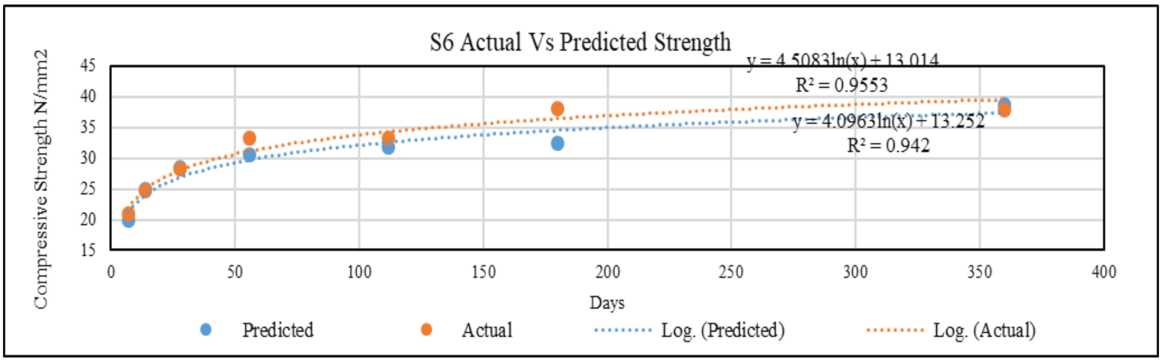


Figure 4.42: Observed vs predicted compressive strength gain for S6 (N/mm2

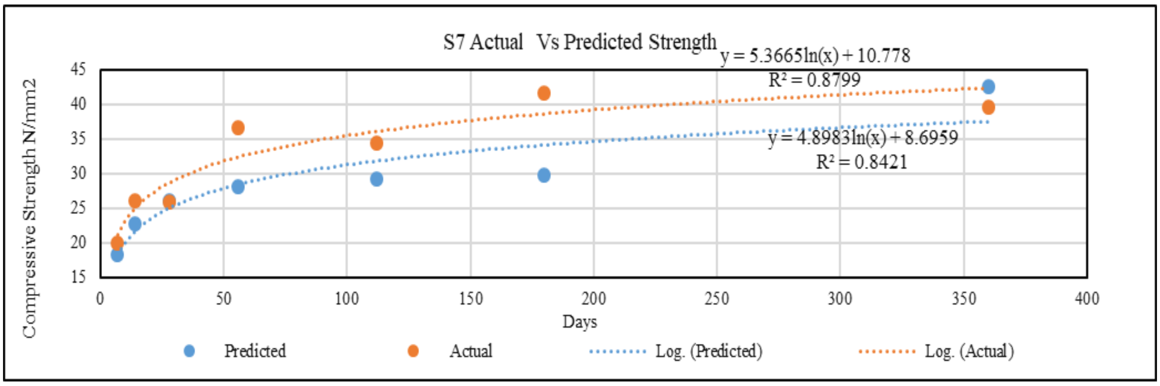


Figure 4.43: Observed vs predicted compressive strength gain for S7 (N/mm2

It was observed that at 7, 14, 28, 56, 112, 180 and 360 days the concrete strength observed from concrete made from all the samples attained higher compressive strength than the predicted ACI values at the various stages except for S2 which incidentally showed a low coefficient of determination partially explained by high reading at the 56th day. The Coefficient of determination of all the other samples were well above the acceptable minimum of 75%. This indicates their acceptability in predicting concrete strength development. A deviation of the observed compressive strength values from the predicted values of the ACI model values could be explained by the failure to consider the constituent material properties, curing conditions and the cement type and hydration regime. The model also requires use of observed 28 days' compressive strength as a constant employed to predict concrete strength throughout the lifetime of concrete which may be erroneous.

In all the above models, it is evident that there is need to have a model that is all inclusive by considering all the physical and chemical properties of the fine aggregate material used in concrete production.

4.4 Concrete Performance Model Using Multi-Linear Regression Model (Objective 3)

In this study, a multiple linear regression technique was used to come up with a strength development curve for the various fine aggregate materials. This statistical method was preferred because it enables incorporation of all the physical and chemical parameters affecting concrete strength and has only one outcome variable (concrete compressive strength). The model takes into account the quantities and qualities of the constituent materials while bringing cognizance to the fact that their effects on concrete are interdependent. The data on compressive strength was obtained from concrete made from six different samples of fine aggregates whose physical and chemical properties had been determined. The variables used to predict were water-cementations ratio, quantities of mix design constituents, physical and chemical properties of the fine aggregates.

Multiple-linear regression models developed for this study yielded coefficients of determination (CODs) for concrete strength prediction at 7, 14, 28, 56, 112, 180 and 360-days curing. This model used to predict the compressive strength of various types of concrete is the form shown in Equation 4-1.

$$f = b1 + b2\,x1 + b3x2 + b4\,x3 + b5\,x4 + b6\,x5 + b7\,x6 + b8\,x7 + b9x8 \;\ldots\ldots\ldots\ldots..$$

Equation 0-1

where: *f*: compressive strength of concrete (N/mm^2)

b1: intercept

b2, b3…b9: coefficients

x1: quantity of fine aggregate in the mix (kg)

x2: quantity of coarse aggregate in the mix (kg)

x3: quantity of water in the mix (kg)

x4: quantity of cement in the mix (kg)

x5: Concentration of Silica (%)

x6: Concentration of Alumina (%)

x7: Concentration of Silt and Clay (%)

*x*8: water/cement ratio

The above parameters used in the multilinear regression model are derived from the degree of their importance in strength gain as captured in concrete theory and experimental observations. A regression analysis carried out on the data on compressive strength given on Table 4.35 below give values of regression coefficients b1 to b9 as shown in Table 4.36. The regression coefficients represent the expected change in the response variable accompanying a unit change in the corresponding explanatory variable. The remaining explanatory variables are held constant. The values of these coefficients are reflective of the effects of various qualities and quantities of the constituents on the compressive strength of concrete.

Table 4.35: Mix proportions of concrete and properties of fine aggregates used for model formulation

	7	14	28	56	112	180	360	FA (kg)	CA (Kg)	Water (kg)	Cement (kg)	SiO (%)	AiO (%)	Silt & Clay	W/C ratio
S2	23.64	33.24	43.61	56.96	43.78	41.49	46.88	656	1218	190	365	76	11	4.85	0.52
	24.98	33.72	38.74	56.97	50.24	39.11	49.85	656	1218	190	365	76	11	4.85	0.52
	25.65	29.48	43.35	47.26	48.37	40.30	47.41	656	1218	190	365	76	11	4.85	0.52
S3	25.51	32.82	29.91	43.77	39.21	44.00	48.35	525	1350	190	365	78	9	4.16	0.52
	25.56	30.85	37.17	56.17	48.38	40.32	49.75	525	1350	190	365	78	9	4.16	0.52
	25.42	29.92	37.18	40.59	43.63	41.21	51.01	525	1350	190	365	78	9	4.16	0.52
S4	21.67	23.31	28.47	29.72	41.32	35.00	40.91	788	1087	190	365	67	17	2.06	0.52
	22.36	26.52	29.78	38.02	40.75	36.81	42.94	788	1087	190	365	67	17	2.06	0.52
	18.65	25.53	27.80	35.67	39.30	31.40	41.80	788	1087	190	365	67	17	2.06	0.52
S5	22.16	27.36	34.49	38.20	43.38	45.04	43.61	656	1218	190	365	80	10	6.66	0.52
	21.96	27.16	34.35	41.02	43.32	46.70	36.78	656	1218	190	365	80	10	6.66	0.52
	21.26	28.33	32.14	43.14	40.34	43.37	44.85	656	1218	190	365	80	10	6.66	0.52
S6	21.29	27.33	28.93	30.29	29.77	36.17	36.93	562	1312	190	365	69	14	9.37	0.52
	20.79	22.73	30.44	34.21	33.56	41.14	36.38	562	1312	190	365	69	14	9.37	0.52
	20.58	24.19	25.21	35.21	36.27	36.62	40.44	562	1312	190	365	69	14	9.37	0.52
S7	20.47	26.59	29.09	35.23	35.03	40.66	38.12	788	1087	190	365	65	19	11.9	0.52
	20.13	27.35	22.40	36.19	33.71	41.58	40.72	788	1087	190	365	65	19	11.9	0.52
	19.50	24.26	26.23	38.50	34.70	42.50	40.00	788	1087	190	365	65	19	11.9	0.52

Table 4.36: Regression coefficients for samples

Parameters	Coefficients	7 days	14 days	28 days	56 days	112 days	180 days	360 days
Intercept	b1	-5024.48	-8030.2	-3311.87	-16679.3	-6070.75	-3724.56	-13620.88
FA (kg)	b2	2.87616	4.631307	2.31528	9.836197	3.622564	1.978976	7.698436
CA (kg)	b3	2.809214	4.498898	2.100821	9.465922	3.462695	1.969591	7.539971
Water (kg)	b4	0	0	0	0	0	0	0
Cement (kg)	b5	0	0	0	0	0	0	0
SiO (%)	b6	-2.56299	-4.50006	-7.15002	-12.3691	-4.60904	0.818243	-5.569614
AlO (%)	b7	-6.13269	-10.9314	-17.1793	-29.7428	-11.7803	0.115372	-13.48403
Silt & Clay	b8	0.638083	1.403025	1.756569	3.751478	0.849671	0.87223	1.378134
w/c ratio	b9	0	0	0	0	0	0	0

From the coefficients displayed in Table 4.36, it is observed that the major independent variables influencing concrete strength development at 7, 14, 28, 56 and

112 days were; alumina, Silicon dioxide, silt & clay, fine and coarse aggregate quantities. Silt & clay, fine and course aggregate showed a positive relationship while the chemical properties show a negative relation. Water and cement quantities were constant for all samples.

The equations generated from this coefficient yields the following models for predicting compressive strength of concrete corresponding to grade C30/37 using the data set in Table 4.35 were formulated in equations 4-2 to 4-8.

$$f\,7 = -5024.48 + 2.88x1 + 2.81\,x2 + -2.56x5 + -6.13\,x6 + 0.64\,x7 \ldots\ldots\ldots\ldots$$
Equation 0-2

$$f14 = -8030.2 + 4.63\,x1 + 4.50\,x2 + -4.50\,x5 + -10.93\,x6 + 1.40\,x7 \ldots\ldots\ldots\ldots$$
Equation 0-3

$$f\,28 = -5024.48 + 2.88\,x1 + 2.81x2 + -2.56\,x5 + -6.13x6 + 0.64x7 \ldots\ldots\ldots\ldots$$
Equation 0-4

$$f\,56 = -16679.3 + 9.84x1 + 9.50x2 + -12.37x5 + -29.75x6 + 3.75\,x7 \ldots\ldots\ldots\ldots$$
Equation 0-5

$$f\,112 = -6070.75 + 3.62\,x1 + 3.46x2 + -4.61x5 + -11.78x6 + 0.85\,x7 \ldots\ldots\ldots\ldots$$
Equation 0-6

$$f\,180 = -3724.56 + 1.98x1 + 1.97x2 + 0.82x5 + 0.12x6 + 0.87x7 \ldots\ldots\ldots\ldots$$
Equation 0-7

$$f\,360 = -13620.9 + 7.70x1 + 7.54x2 - -5.57x5 - -13.48x6 + 1.38x7 \ldots\ldots\ldots\ldots$$
Equation 0-8

4.4.1 Validation of the model

The acceptance and reliability of any model is mainly dependent on its performance. A popular method of performance analysis is the use of statistical parameters, where output results obtained from the model are compared to observed field or laboratory results. The validation of the developed model was done using a different set of compressive strength data given on Table 4.37 not included in the formulation of the model. This data was obtained from run 2 which was carried out for a period of 180 days. The results obtained in the Table 4.37 were incorporated in equations 4-2 to 4-8 to predict the compressive strength of concrete at 7, 14, 28, 56, 112, 180 and 360-days curing.

Table 4.37: Mix proportions of concrete and properties of fine aggregates used for validation

Column1	7	14	28	56	112	180	FA(kg)	CA(kg)	Water (kg)	Cement	Sio (%)	AIO (%)	Silt & clay	W/C ratio
S2	22.72	30.75	35.89	46.53	41.00	38.39	656	1218	190	365	76	11	4.85	0.52
	23.89	31.75	37.01	48.16	43.78	39.92	656	1218	190	365	76	11	4.85	0.52
	21.24	27.28	38.87	46.41	44.10	39.79	656	1218	190	365	76	11	4.85	0.52
S3	21.55	27.23	33.19	41.26	40.00	38.35	525	1350	190	365	78	9	4.16	0.52
	23.46	29.03	34.69	41.39	42.10	38.55	525	1350	190	365	78	9	4.16	0.52
	21.42	28.43	33.27	39.79	40.78	37.06	525	1350	190	365	78	9	4.16	0.52
S4	16.02	19.68	23.94	26.37	35.50	33.60	788	1087	190	365	67	17	2.06	0.52
	15.89	20.35	24.60	32.94	35.30	32.30	788	1087	190	365	67	17	2.06	0.52
	16.28	20.90	20.67	33.23	36.78	33.86	788	1087	190	365	67	17	2.06	0.52
S5	20.88	23.71	29.60	36.29	38.56	41.93	656	1218	190	365	80	10	6.66	0.52
	18.97	24.47	30.99	35.47	39.11	43.21	656	1218	190	365	80	10	6.66	0.52
	19.82	23.63	29.04	36.20	36.00	43.66	656	1218	190	365	80	10	6.66	0.52
S6	16.08	20.88	26.20	33.26	32.89	36.86	562	1312	190	365	69	14	9.37	0.52
	16.04	21.88	26.49	30.21	33.33	36.47	562	1312	190	365	69	14	9.37	0.52
	16.77	20.30	23.38	32.30	32.00	32.82	562	1312	190	365	69	14	9.37	0.52
S7	15.63	20.28	21.94	31.97	29.33	38.55	788	1087	190	365	65	19	11.9	0.52
	15.13	19.17	23.82	28.50	29.78	37.48	788	1087	190	365	65	19	11.9	0.52
	16.95	20.71	24.84	32.01	31.11	38.29	788	1087	190	365	65	19	11.9	0.52

The relationship between the observed compressive strength results obtained from the experimental work and those predicted from the model are shown in Figures 4.44 to 4.49.

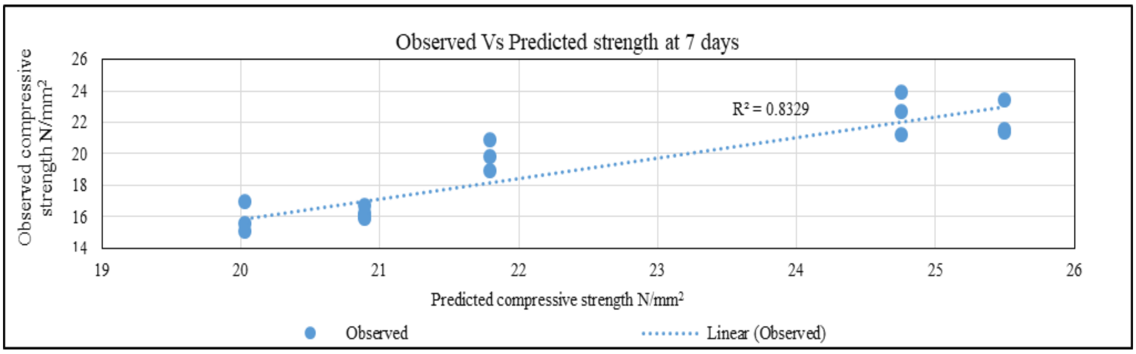


Figure 4.44: Observed vs predicted compressive strength (N/mm^2) at 7 days

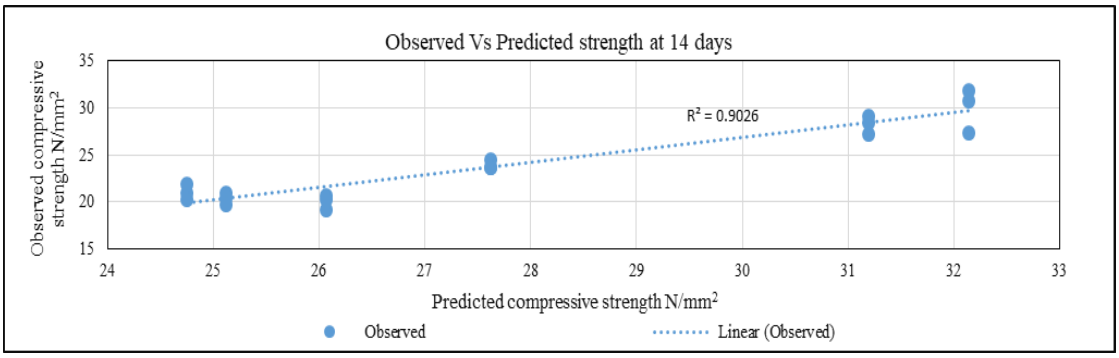


Figure 4.45: Observed vs predicted compressive strength (N/mm^2) at 14 days

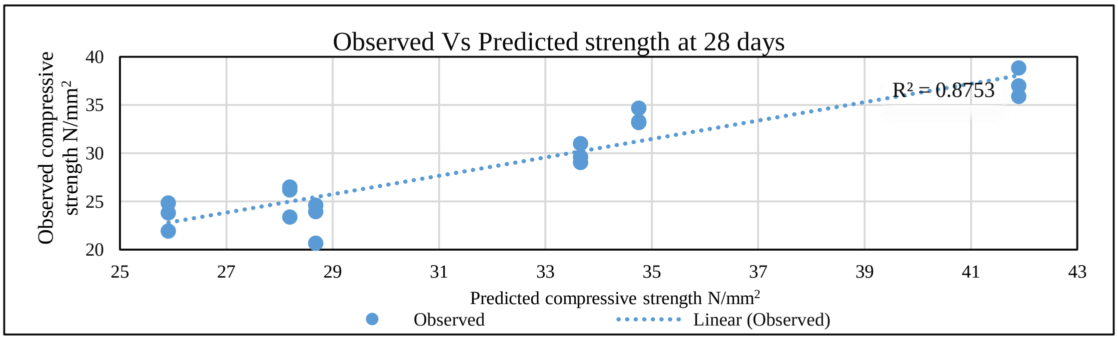


Figure 4.46: Observed vs predicted compressive strength (N/mm^2) at 28 days

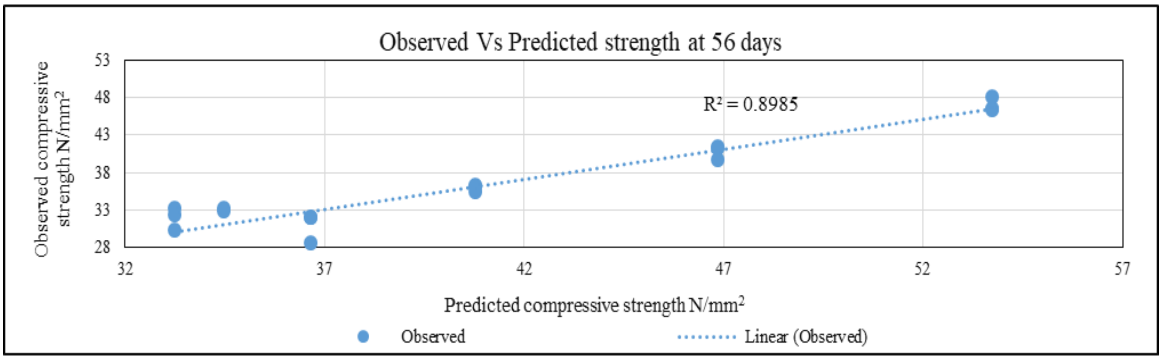


Figure 4.47: Observed vs predicted compressive strength (N/mm^2) at 56 days

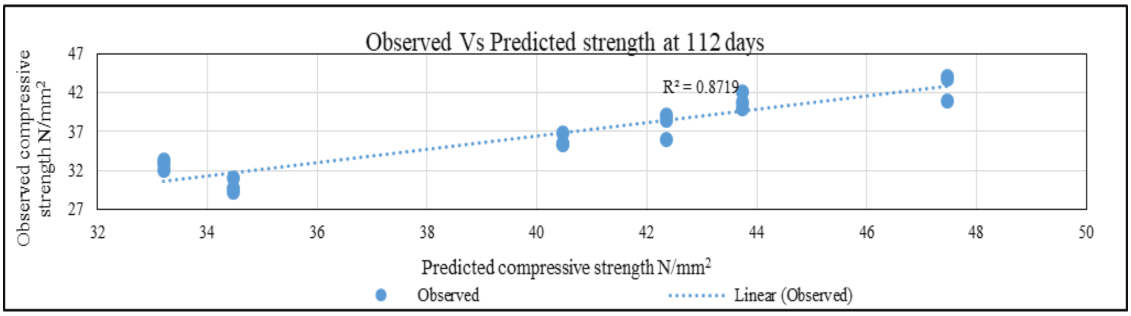


Figure 4.48: Observed vs predicted compressive strength(N/mm^2) at112 days

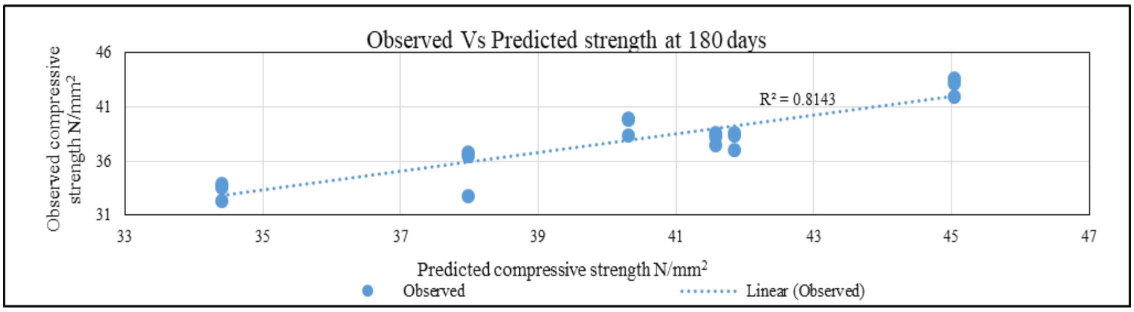


Figure 4.49: Observed vs predicted compressive strength (N/mm^2) at 180 days

It is observed that the model has 83.29, 90.26, 87.53, 89.85, 87.19 and 81.43 percent coefficient of determination with the experimental data for 7, 14, 28, 56, 112 and 180 days respectively. This is above the expectation of COD of 75% for acceptability. The observed and the predicted values for the compressive strength of concrete using MLRM is in close correlation and therefore reliable for compressive strength prediction.

4.4.2 Comparison between MLR, BS and ACI Models

The prediction curves of the British standards model, ACI model and the Multi-linear regression model were compared to establish if the models had any similarities. Figure 4.50 to 4.55 show the comparisons.

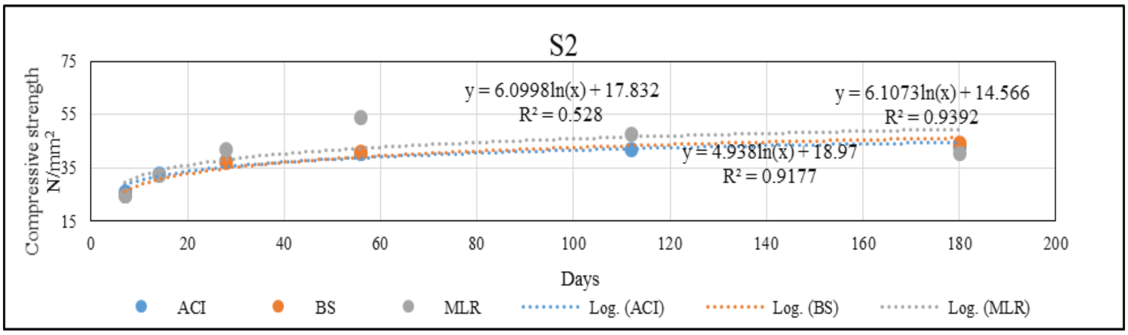


Figure 4.50: Comparison of multi-linear regression, BS and ACI models for S2 concrete compressive strength prediction

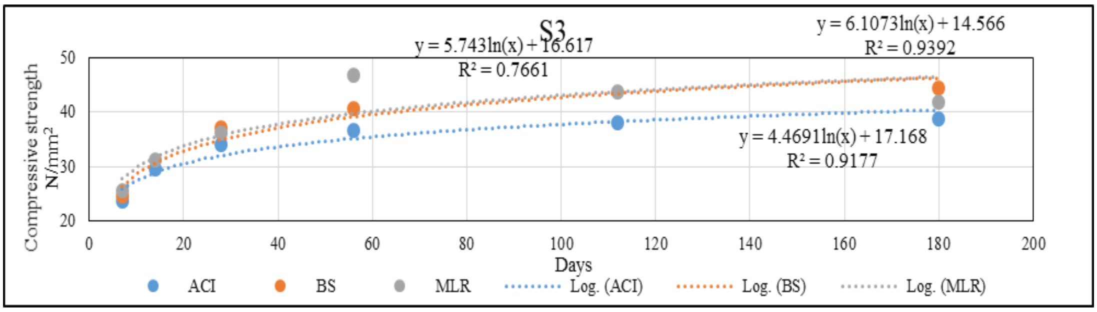


Figure 4.51: Comparison of multi-linear regression, BS and ACI models for S3 concrete compressive strength prediction

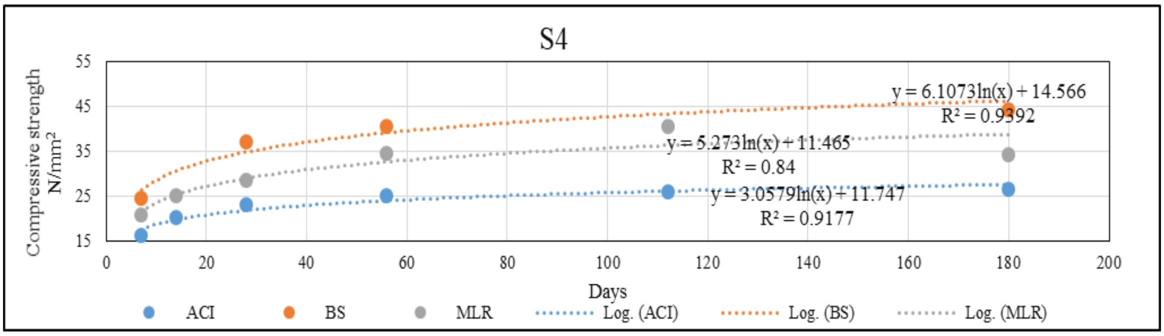


Figure 4.52: Comparison of multi-linear regression, BS and ACI models for S4 concrete compressive strength prediction

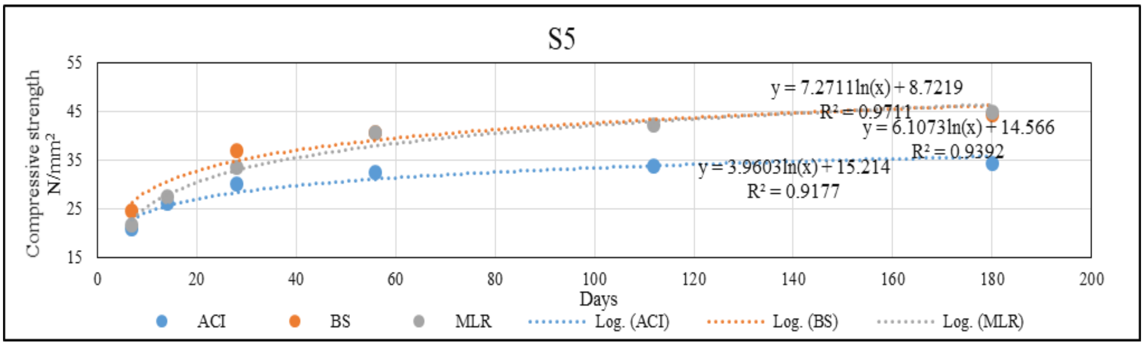


Figure 4.53: Comparison of multi-linear regression, BS and ACI models for S5 concrete compressive strength prediction

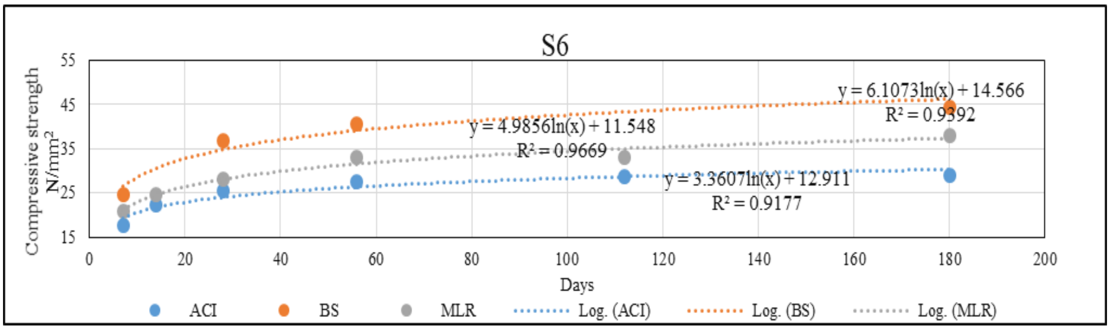


Figure 4.54: Comparison of multi-linear regression, BS and ACI models for S6 concrete compressive strength prediction

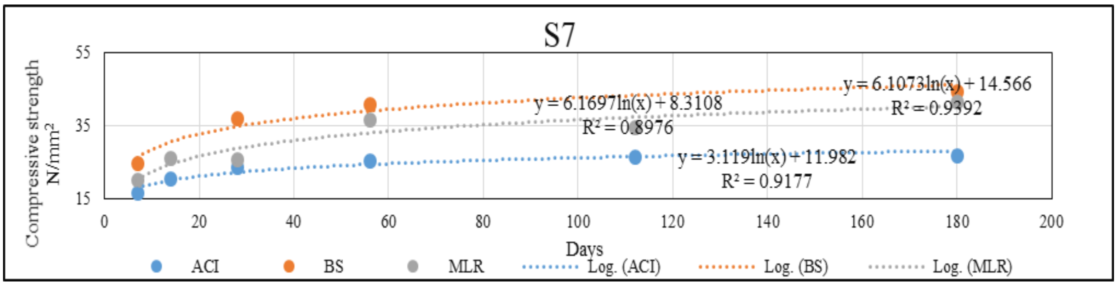


Figure 4.55: Comparison of multi-linear regression, BS and ACI models for S7 concrete compressive strength prediction

The multi-linear regression model was observed to favorably agree with the British Standard and American Concrete Institute (ACI) prediction curves as attested by the COD. Overall, the MLRM curve lies between the two presenting a more harmonized model for use.

4.4.3 Model Hypothesis testing

In this study, the researcher hypothesized that chemical properties of fine aggregate have no significant effect on concrete strength development. The hypothesis testing equations is as follows;

$$f = b1 + b2\,x1 + b3\,x2 + b4\,x3 + b5\,x4 + b6\,x5 + b7\,x6 + b8\,x7 + b9\,x8$$

where: f: compressive strength of concrete (N/mm^2)

b1: intercept

b2, b3…b9: coefficients

x1: quantity of fine aggregate in the mix (kg)

x2: quantity of coarse aggregate in the mix (kg)

x3: quantity of water in the mix (kg)

x4: quantity of cement in the mix (kg)

x5: Concentration of Silica (%)

x6: Concentration of Alumina (%)

x7: Concentration of Silt and Clay (%)

*x*8: water/cement ratio

The null hypothesis stated as follows:

H0: b2=b3=, . . ., =b9 = 0

Alternative hypothesis as below: -

H_1: $b_j \neq 0$ For at least one j, j = 1, . . ., n

Rejection of H0 would imply that at least one of the repressors/factors, b2, b3, . . ., b9, contributes significantly to the model. A regression analysis was used to test this hypothesis at level of significance α=0.05 and F-table, Table 6-24 in the Appendix 6.8, used to get the critical F-factor. The F significance were used to reject or accept the Null hypothesis. For a small F Significance Null hypothesis was rejected.

Table 4.38 to 4.44 shows the summary output of the regression results obtained at different concrete strength age.

Table 4.38: Testing of effects of the explanatory variables on concrete strength development- 7 days D

Regression Statistics								
Multiple R	0.9348186							
R Square	0.8738858							
Adjusted R Square	0.5713382							
Standard Error	0.9611613							
Observations	18							
ANOVA								
	df	**SS**	**MS**	**F**	**Significance F**			
Regression	8	76.81824	9.6022801	16.630365	0.0001546			
Residual	12	11.085973	0.9238311					
Total	20	87.904213						
	Coefficients	**Standard Error**	**t Stat**	**P-value**	**Lower 95%**	**Upper 95%**	**Lower 95.0%**	**Upper 95.0%**
Intercept	-5024.4753	1218.6816	-4.1228778	0.0014134	-7679.7544	-2369.1962	-7679.7544	-2369.1962
FA (kg)	2.8761605	0.6724422	4.2771861	0.0010743	1.4110348	4.3412862	1.4110348	4.3412862
CA (kg)	2.8092139	0.6635075	4.2338839	0.00116	1.3635551	4.2548726	1.3635551	4.2548726
Water (kg)	0	0	65535	#NUM!	0	0	0	0
Cement (kg)	0	0	65535	#NUM!	0	0	0	0
SiO (%)	-2.562989	0.5789512	-4.4269517	#NUM!	-3.8244152	-1.3015627	-3.8244152	-1.3015627
AlO (%)	-6.1326918	1.2877482	-4.7623379	0.0004623	-8.9384541	-3.3269296	-8.9384541	-3.3269296
Silt & Clay	0.6380832	0.1882385	3.3897589	0.0053704	0.2279467	1.0482198	0.2279467	1.0482198
w/c ratio	0	0	65535	#NUM!	0	0	0	0

Table 4.39: Testing of effects of proposed explanatory variables on concrete strength development-14 days

Regression Statistics								
Multiple R	0.8941354							
R Square	0.7994781							
Adjusted R Square	0.4659274							
Standard Error	1.7698467							
Observations	18							
ANOVA								
	df	**SS**	**MS**	**F**	**Significance F**			
Regression	8	149.86404	18.733005	9.5687701	0.0013565			
Residual	12	37.588289	3.1323574					
Total	20	187.45233						
	Coefficients	**Standard Error**	**t Stat**	**P-value**	**Lower 95%**	**Upper 95%**	**Lower 95.0%**	**Upper 95.0%**
Intercept	-8030.2023	2244.035	-3.5784657	0.0037929	-12919.535	-3140.87	-12919.535	-3140.87
FA (kg)	4.6313068	1.2382101	3.7403238	0.0028203	1.9334787	7.3291349	1.9334787	7.3291349
CA (kg)	4.4988978	1.2217581	3.6823146	0.0031355	1.8369155	7.1608801	1.8369155	7.1608801
Water (kg)	0	0	65535	#NUM!	0	0	0	0
Cement (kg)	0	0	65535	#NUM!	0	0	0	0
SiO (%)	-4.5000644	1.0660592	-4.2212143	#NUM!	-6.8228079	-2.1773209	-6.8228079	-2.1773209
AlO (%)	-10.931449	2.3712116	-4.6100687	0.0006004	-16.097875	-5.7650222	-16.097875	-5.7650222
Silt & Clay	1.4030252	0.3466154	4.0477863	0.0016167	0.6478151	2.1582354	0.6478151	2.1582354
w/c ratio	0	0	65535	#NUM!	0	0	0	0

Table 4.40: Testing of effects of proposed explanatory variables on concrete strength development-28 days

Regression Statistics									
Multiple R	0.9201405								
R Square	0.8466585								
Adjusted R Square	0.5327662								
Standard Error	2.7804934								
Observations	18								
ANOVA									
	df	**SS**	**MS**	**F**	**Significance F**				
Regression	8	512.23994	64.029992	13.251337	0.0003846				
Residual	12	92.773723	7.7311436						
Total	20	605.01366							
	Coefficients	**Standard Error**	**t Stat**	**P-value**	**Lower 95%**	**Upper 95%**	**Lower 95.0%**	**Upper 95.0%**	
Intercept	-3311.8699	3525.4604	-0.9394149	0.366043	-10993.188	4369.4485	-10993.188	4369.4485	
FA (kg)	2.3152799	1.945273	1.1902082	0.2569787	-1.9231059	6.5536657	-1.9231059	6.5536657	
CA (kg)	2.1008211	1.9194263	1.0945047	0.2952165	-2.0812496	6.2828919	-2.0812496	6.2828919	
Water (kg)	0	0	65535	#NUM!	0	0	0	0	
Cement (kg)	0	0	65535	#NUM!	0	0	0	0	
SiO (%)	-7.150015	1.6748177	-4.2691303	#NUM!	-10.799129	-3.5009007	-10.799129	-3.5009007	
AlO (%)	-17.179336	3.7252595	-4.6115811	0.0005988	-25.295979	-9.062693	-25.295979	-9.062693	
Silt & Clay	1.7565693	0.5445454	3.2257535	0.0072764	0.5701068	2.9430319	0.5701068	2.9430319	
w/c ratio	0	0	65535	#NUM!	0	0	0	0	

Table 4.41: Testing of effects of proposed explanatory variables on concrete strength development-56 days

Regression Statistics								
Multiple R	0.8841929							
R Square	0.7817971							
Adjusted R Square	0.4408792							
Standard Error	4.7120208							
Observations	18							
ANOVA								
	df	**SS**	**MS**	**F**	**Significance F**			
Regression	8	954.61698	119.32712	8.5989367	0.0020231			
Residual	12	266.43768	22.20314					
Total	20	1221.0547						
	Coefficients	**Standard Error**	**t Stat**	**P-value**	**Lower 95%**	**Upper 95%**	**Lower 95.0%**	**Upper 95.0%**
Intercept	-16679.28	5974.4946	-2.7917474	0.0162917	-29696.585	-3661.9741	-29696.585	-3661.9741
FA (kg)	9.8361968	3.2965972	2.9837424	0.0114062	2.6535285	17.018865	2.6535285	17.018865
CA (kg)	9.4659224	3.2527957	2.9100882	0.0130789	2.3786895	16.553155	2.3786895	16.553155
Water (kg)	0	0	65535	#NUM!	0	0	0	0
Cement (kg)	0	0	65535	#NUM!	0	0	0	0
SiO (%)	-12.369149	2.8382645	-4.3579974	#NUM!	-18.553196	-6.1851021	-18.553196	-6.1851021
AlO (%)	-29.742755	6.3130883	-4.7112845	0.0005045	-43.497793	-15.987717	-43.497793	-15.987717
Silt & Clay	3.7514781	0.9228252	4.0652099	0.001567	1.7408148	5.7621415	1.7408148	5.7621415
w/c ratio	0	0	65535	#NUM!	0	0	0	0

Table 4.42: Testing of effects of proposed explanatory variables on concrete strength development-112 days

Regression Statistics								
Multiple R	0.9098644							
R Square	0.8278533							
Adjusted R Square	0.5061255							
Standard Error	2.8081778							
Observations	18							
ANOVA								
	df	**SS**	**MS**	**F**	**Significance F**			
Regression	8	455.07714	56.884642	11.541594	0.0006613			
Residual	12	94.630351	7.8858626					
Total	20	549.70749						
	Coefficients	**Standard Error**	**t Stat**	**P-value**	**Lower 95%**	**Upper 95%**	**Lower 95.0%**	**Upper 95.0%**
Intercept	-6070.7524	3560.5622	-1.7049983	0.1139227	-13828.551	1687.0462	-13828.551	1687.0462
FA (kg)	3.6225645	1.9646414	1.8438808	0.0900207	-0.6580214	7.9031504	-0.6580214	7.9031504
CA (kg)	3.4626954	1.9385374	1.7862412	0.0993307	-0.7610148	7.6864056	-0.7610148	7.6864056
Water (kg)	0	0	65535	#NUM!	0	0	0	0
Cement (kg)	0	0	65535	#NUM!	0	0	0	0
SiO (%)	-4.6090395	1.6914933	-2.7248347	#NUM!	-8.2944868	-0.9235923	-8.2944868	-0.9235923
AlO (%)	-11.780254	3.7623506	-3.1310888	0.0086743	-19.977712	-3.582796	-19.977712	-3.582796
Silt & Clay	0.8496709	0.5499673	1.5449481	0.1483115	-0.3486048	2.0479467	-0.3486048	2.0479467
w/c ratio	0	0	65535	#NUM!	0	0	0	0

Table 4.43: Testing of effects of proposed explanatory variables on concrete strength development-180 days

Regression Statistics								
Multiple R	0.8983859							
R Square	0.8070973							
Adjusted R Square	0.4767211							
Standard Error	1.9940589							
Observations	18							
ANOVA								
	df	**SS**	**MS**	**F**	**Significance F**			
Regression	8	199.63868	24.954835	10.041503	0.0011299			
Residual	12	47.715251	3.9762709					
Total	20	247.35393						
	Coefficients	**Standard Error**	**t Stat**	**P-value**	**Lower 95%**	**Upper 95%**	**Lower 95.0%**	**Upper 95.0%**
Intercept	-3724.5556	2528.3195	-1.4731349	0.1664551	-9233.2907	1784.1794	-9233.2907	1784.1794
FA (kg)	1.9789763	1.3950722	1.4185476	0.1814768	-1.0606248	5.0185774	-1.0606248	5.0185774
CA (kg)	1.9695909	1.376536	1.4308314	0.1780007	-1.0296234	4.9688051	-1.0296234	4.9688051
Water (kg)	0	0	65535	#NUM!	0	0	0	0
Cement (kg)	0	0	65535	#NUM!	0	0	0	0
SiO (%)	0.8182425	1.2011124	0.6812372	#NUM!	-1.7987566	3.4352416	-1.7987566	3.4352416
AlO (%)	0.1153724	2.6716074	0.0431846	0.9662646	-5.7055602	5.936305	-5.7055602	5.936305
Silt & Clay	0.8722297	0.3905262	2.2334726	0.0453266	0.0213461	1.7231133	0.0213461	1.7231133
w/c ratio	0	0	65535	#NUM!	0	0	0	0

Table 4.44: Testing of effects of proposed explanatory variables on concrete strength development-360 days

Regression Statistics									
Multiple R	0.9180972								
R Square	0.8429025								
Adjusted R Square	0.5274451								
Standard Error	2.2684779								
Observations	18								
ANOVA									
	df	**SS**	**MS**	**F**	**Significance F**				
Regression	8	331.32811	41.416013	12.877132	0.0004307				
Residual	12	61.751906	5.1459922						
Total	20	393.08001							
	Coefficients	**Standard Error**	**t Stat**	**P-value**	**Lower 95%**	**Upper 95%**	**Lower 95.0%**	**Upper 95.0%**
Intercept	-13620.882	2876.2626	-4.7356184	0.0004839	-19887.72	-7354.0442	-19887.72	-7354.0442
FA (kg)	7.6984361	1.5870597	4.8507541	0.0003977	4.2405302	11.156342	4.2405302	11.156342
CA (kg)	7.5399713	1.5659725	4.8148809	0.0004227	4.1280102	10.951932	4.1280102	10.951932
Water (kg)	0	0	65535	#NUM!	0	0	0	0
Cement (kg)	0	0	65535	#NUM!	0	0	0	0
SiO (%)	-5.5696138	1.3664075	-4.0761002	#NUM!	-8.54676	-2.5924677	-8.54676	-2.5924677
AlO (%)	-13.484033	3.0392696	-4.4366031	0.0008117	-20.106032	-6.8620333	-20.106032	-6.8620333
Silt & Clay	1.3781339	0.4442698	3.1020202	0.0091556	0.4101532	2.3461147	0.4101532	2.3461147
w/c ratio	0	0	65535	#NUM!	0	0	0	0

From the above tables, the coefficient of determination and the significance F were tabulated and the summary of the obtained results shown in table 4.45.

Table 4.45: Summary of the Coefficient of determination and Significance F for the concrete at Different ages

Concrete Age (days)	R^2 (%)	Significance F	Remarks
7	87.3	0.00016	Reject Null Hypothesis
14	79.9	.0014	Reject Null Hypothesis
28	89.2	.00007	Reject Null Hypothesis
56	78.2	.002	Reject Null Hypothesis
112	82.8	.0006	Reject Null Hypothesis
180	80.7	.001	Reject Null Hypothesis
360	84.29	.004	Reject Null Hypothesis

From Table 4.45, the test results show that the physical and chemical properties of concrete have a significant influence on the strength of concrete as supported by a high Coefficient of determination. The significance F was below 5% level showing a statistically significant model at all the different ages of concrete. The Null hypothesis is rejected and therefore, chemical properties found to have significant influence on the strength of concrete.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

In the Nairobi Metropolitan region, different types of fine aggregate are used, including river sand, rock sand, Naivasha sand and quarry dust. While different research has been done on various materials to determine their suitability for use as fine aggregates, there is still much to be understood about the effects of the physical and chemical properties of different fine aggregates to concrete production and strength development.

The primary aim of this study was to investigate the chemical, physical and mineralogical characteristics of the various fine aggregates supplied in Nairobi Metropolitan and assess their suitability for use in concrete through evaluation of the strength of the resultant concrete produced. The study also formulated a strength development model for concrete made from the various fine aggregates to guide future concrete strength predictions.

5.2 Establishing the Relationship between Physical Chemical and Mineralogical Properties of Fine Aggregates

The research established that, fine aggregates from different catchment areas exhibit different chemical, physical and mineralogical properties due to variation in geological formations. The formation processes of the parent rocks and their crystalline structures influence the chemical and physical properties of the fine aggregates which subsequently affect the strength of the resultant concrete. Therefore, the selection of the fine aggregates sources is important in obtaining quality materials.

5.3 Concrete Strength from Different Materials and Comparison with Existing Strength Prediction Models

The river sands; S2, S3 and S5 (Mwingi, Machakos and Kajiado respectively), attained higher strengths compared to the other fine aggregates; S4, S6 and S7 (Naivasha sand, Rock sand and quarry dust respectively) in accordance to the D.O.E method/ British standards. Samples S2, S3 and S5 had higher strengths compared to S4, S6 and S7. Despite the fact that it did not conform to the pre-defined standards for aggregates physical properties, sample S2 attained the 28-day target strength while S3 failed to achieve the target strength at 28 days but was within the acceptable deviation limits. Therefore, Mwingi and Kajiado river sands are suitable for use in the construction industry. The other fine aggregates; S4, S5, S6 and S7 attained 78%, 91%, 76% and 70% of the target strength at 28 days respectively. A further observation at 56 days indicated a strength gain, with S5 surpassing the characteristic target strength and S7 marginally attaining the target strength. If Machakos river sand and quarry dust are used in construction, the resultant concrete should be loaded after two months. Rock sand attained the target strength at 112 days while Naivasha sand attained at 180 days. Hence, the concrete produced from rock sand and Naivasha sand should be loaded after three and six months respectively to avoid failure. Modifications can be made for the sands that failed to attain the target strength within 28 days, e.g. improving the physical properties by washing to reduce the silt & clay content or by use of admixtures. The strength obtained fairly agreed with the existing models with a high coefficient of determination of over 75% for all the aggregates.

In summary; -

- Concrete made from different fine aggregates developed strength at different rates
- Concrete from River sands yielded higher compressive strength than that made from other fine aggregates
- Sand from Naivasha, Rock sand and quarry dust, had lowest strength development curve

- All fine aggregates yielded acceptable concrete strength after 180days curing.
- Loading and striking of formwork depends on the type of fine aggregate material used.

5.4 Concrete Performance Model Using Multi-Linear Regression Model

A concrete performance model was formulated incorporating the physical and chemical parameters of the fine aggregates and validated with a different set of test results. The model was also compared with the existing ACI and British model and the following was concluded:

- The multi-linear regression models were developed for strength prediction at 7,14, 28, 56, 112 ,180 and 360 days yielded satisfactory coefficients of determination (CODs) of 83.29, 90.26, 87.53, 89.85, 87.19 and 81.43 respectively
- The validation of the model showed that the observed and the predicted values for the compressive strength of concrete using MLRM is in close correlation with over 80% C.O.D and therefore reliable for compressive strength prediction.
- The MLRM compares favourably to the ACI and BS model at average of 88.8% of strength explained by the variables which includes chemical properties. ACI and BS are at 93% and 92% respectively.

Broadly speaking, the multilinear prediction model is valuable for concrete practice and research purposes. In construction, the prediction models can be useful in estimating the strength of concrete at different ages. It may help to spot risks of failure in concrete and allow preventive interventions. In research the prediction model can be used in the design and analysis of concrete mixes.

5.5 Recommendations

This study brings to the fore areas that will need further research. From this study, it is recommended to have the following:

- Establish the effect of blending different fine aggregates material to concrete quality
- Investigate the strength development curve for the concrete made from the same aggregates using varied water/cement ration
- Replication of this study with standard sand as control

For Further research:

- Establish the distribution of different fine aggregates used in the metropolitan region and associated concrete delivery and application
- Establish concrete quality control mechanism and its effectiveness in Kenya
- Formulation of a concrete strength development life cycle predication model
- Replication of the prediction model developed to other regions in the country

For Policy and Practice

- The government should have a policy that regulates and controls concrete mix design and this should be achieved by accrediting concrete mix designers and manufacturers. On site batching of concrete should be banned and replaced by ready mix concrete manufactured within a controlled environment for quality assurance.

5.6 Contribution to Knowledge

This research unmasks the usability of the different types of fine aggregates in Nairobi Metropolitan. The study has revealed that: Fine aggregates materials have different properties which influence the strength of concrete

  - Quarry dust, Rock sand and Sand from Naivasha are suitable for concrete production when proper Concrete mix design and curing of concrete is done although there is delay in strength development.
  - The study has developed a MLRM for strength prediction modelling beyond the normal 28 days. This is useful in early warning of concrete quality.

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APPENDICES

Appendix I: Bulk density

Table 0-1 Bulk density of coarse aggregates (10mm)

coarse aggregate 10mm						
	Container Weight (g)	Container + Material (g)	Container + Water (g)	Material Weight (g)	Water weight (g)	Bulk -Density (Kg/m3)
Run 1	4,550.00	18,300.00	14,400.00	13,750.00	9,850.00	1,395.94
Run 2	4,550.00	18,700.00	14,400.00	14,150.00	9,850.00	1,436.55
Run 3	4,550.00	18,600.00	14,400.00	14,050.00	9,850.00	1,426.40
					Average	1,419.63

Table 0-2 Bulk density of coarse aggregates (20mm)

Coarse aggregates 20mm						
Sand-6	Container Weight (g)	Container + Material (g)	Container + Water (g)	Material Weight (g)	Water weight (g)	Bulk -Density (Kg/m3)
Run 1	4,550.00	18,500.00	14,400.00	13,950.00	9,850.00	1,416.24
Run 2	4,550.00	18,900.00	14,400.00	14,350.00	9,850.00	1,456.85
Run 3	4,550.00	18,800.00	14,400.00	14,250.00	9,850.00	1,446.70
					Average	1,439.93

Fine aggregates

Table 0-3 Bulk density of Mwingi river sand

S2- Mwingi river sand						
Column1	Container Weight (g)	Container + Material (g)	Container + Water (g)	Material Weight (g)	Water weight (g)	Bulk -Density (Kg/m3)
Run 1	1,552.00	4,548.00	3,592.00	2,996.00	2,040.00	1,468.63
Run 2	1,552.00	4,644.00	3,592.00	3,092.00	2,040.00	1,515.69
Run 3	1,552.00	4,627.00	3,592.00	3,075.00	2,040.00	1,507.35
					Average	1,497.22

Table 0-4 Bulk density of kajiado river sand

S3- Kajiado river sand						
Column1	**Container Weight (g)**	**Container + Material (g)**	**Container + Water (g)**	**Material Weight (g)**	**Water weight (g)**	**Bulk - Density (Kg/m3)**
Run 1	1,552.00	4,579.00	3,592.00	3,027.00	2,040.00	1,483.82
Run 2	1,552.00	4,556.00	3,592.00	3,004.00	2,040.00	1,472.55
Run 3	1,552.00	4,514.00	3,592.00	2,962.00	2,040.00	1,451.96
					Average	1,469.44

Table 0-5 Bulk density of rock sand

S4- Rock sand						
Column1	**Container Weight (g)**	**Container + Material (g)**	**Container + Water (g)**	**Material Weight (g)**	**Water weight (g)**	**Bulk - Density (Kg/m3)**
Run 1	1,552.00	4,400.00	3,592.00	2,848.00	2,040.00	1,396.08
Run 2	1,552.00	4,406.00	3,592.00	2,854.00	2,040.00	1,399.02
Run 3	1,552.00	4,462.00	3,592.00	2,910.00	2,040.00	1,426.47
					Average	1,407.19

Table 0-6 Bulk density of machakos river sand

S5- Machakos river sand						
	Container Weight (g)	**Container + Material (g)**	**Container + Water (g)**	**Material Weight (g)**	**Water weight (g)**	**Bulk -Density (Kg/m3)**
Run 1	1,552.00	4,815.00	3,592.00	3,263.00	2,040.00	1,599.51
Run 2	1,552.00	4,840.00	3,592.00	3,288.00	2,040.00	1,611.76
Run 3	1,552.00	4,873.00	3,592.00	3,321.00	2,040.00	1,627.94
					Average	1,613.07

Table 0-7 Bulk density of Naivasha sand

S6- Naivasha sand						
Column1	**Container Weight (g)**	**Container + Material (g)**	**Container + Water (g)**	**Material Weight (g)**	**Water weight (g)**	**Bulk -Density (Kg/m3)**
Run 1	1,552.00	4,303.00	3,592.00	2,751.00	2,040.00	1,348.53
Run 2	1,552.00	4,277.00	3,592.00	2,725.00	2,040.00	1,335.78
Run 3	1,552.00	4,202.00	3,592.00	2,650.00	2,040.00	1,299.02
					Average	1,327.78

Table 0-8 Bulk density of quarry dust

S7- Quarry dusr						
Column1	**Container Weight (g)**	**Container + Material (g)**	**Container + Water (g)**	**Material Weight (g)**	**Water weight (g)**	**Bulk -Density (Kg/m3)**
Run 1	1,552.00	4,989.00	3,592.00	3,437.00	2,040.00	1,684.80
Run 2	1,552.00	4,976.00	3,592.00	3,424.00	2,040.00	1,678.43
Run 3	1,552.00	4,997.00	3,592.00	3,445.00	2,040.00	1,688.73
					Average	1,683.99

Appendix II: Particle Density and Water Absorption

Fineness modulus

The fineness modulus was calculated by adding the cumulative percentage of aggregates retained on each sieve

X-Ray Diffraction

The mineral composition was determined. The raw data and reduced dI lists of the samples were as follows. **S2- Mwingi river sand**

Table 0-9 Pattern list and 2theta results for mwingi river sand

Pattern List #1

Index	Compound Name	Formula	Pattern #	I/Ic DB	S-Q
6	Labradorite	Al0.814 Ca0.32 Na0.18 O4 Si1.184	COD 9000748	0.750	16.7 %
1	Berzelianite	Cu1.95 Se	COD 9015206	5.620	25.4 %
3	Berzelianite	Cu2 Se	COD 9015293	6.080	23.4 %
5	Perryite	Fe0.24 Ni7.76 P0.63 Si2.37	COD 9011074	4.140	5.2 %
4	Monipite	Mo Ni P	COD 9013392	6.810	2.6 %
2	Quartz low	O2 Si	COD 1011176	4.820	26.7 %

2Theta

Index	Angle	d Value	Rel. Intensity
1	17.217 °	5.14625 Å	0.3 %
2	20.880 °	4.25107 Å	25.6 %
3	22.077 °	4.02318 Å	2.9 %
4	23.000 °	3.86372 Å	0.8 %
5	23.683 °	3.75700 Å	2.9 %
6	23.934 °	3.71506 Å	1.9 %
7	24.005 °	3.70422 Å	1.7 %
8	24.303 °	3.65947 Å	1.1 %
9	25.545 °	3.48424 Å	1.9 %
10	25.625 °	3.47353 Å	2.5 %
11	25.693 °	3.46446 Å	1.8 %
13	26.666 °	3.34024 Å	93.5 %
12	26.679 °	3.33872 Å	100.0 %
14	27.118 °	3.28566 Å	3.6 %
15	27.536 °	3.23682 Å	6.9 %
16	27.751 °	3.21212 Å	3.0 %
17	27.870 °	3.19866 Å	7.8 %
18	28.024 °	3.18141 Å	13.9 %
19	28.092 °	3.17388 Å	7.1 %
20	28.385 °	3.14182 Å	1.8 %
21	28.463 °	3.13335 Å	1.2 %
22	28.603 °	3.11833 Å	0.8 %
23	29.618 °	3.01373 Å	0.4 %
24	29.801 °	2.99567 Å	2.8 %
25	30.374 °	2.94038 Å	1.7 %
26	30.853 °	2.89582 Å	2.1 %
27	33.081 °	2.70574 Å	0.5 %
28	34.261 °	2.61517 Å	0.9 %
29	34.348 °	2.60874 Å	0.8 %
30	36.577 °	2.45471 Å	7.9 %
31	36.669 °	2.44870 Å	3.6 %
32	37.092 °	2.42182 Å	0.5 %

S3- Kajiado river sand

Table 0-10 Pattern list and 2theta results for kajiado river sand

Pattern List #1

Index	Compound Name	Formula	Pattern #	I/Ic DB	S-Q
6	Albite	Al Na O8 Si3	COD 9002199	0.830	15.7 %
4	Labradorite	Al0.814 Ca0.32 Na0.18 O4 Si1.184	COD 9000748	0.750	16.4 %
3	Oligoclase	Al1.277 Ca0.277 Na0.723 O8 Si2.723	COD 9011423	0.630	14.8 %
5	Anorhtite sodian	Al1.52 Ca0.52 Na0.48 O8 Si2.48	COD 1008757	0.640	13.9 %
2	Berzelianite	Cu1.95 Se	COD 9015206	5.620	18.1 %
1	Quartz low	O2 Si	COD 1011159	4.820	21.0 %

2Theta

Index	Angle	d Value	Rel. Intensity
1	20.876 °	4.25174 Å	32.8 %
2	21.046 °	4.21787 Å	3.1 %
3	22.022 °	4.03304 Å	4.6 %
4	22.970 °	3.86872 Å	1.8 %
5	23.620 °	3.76362 Å	3.5 %
6	23.961 °	3.71087 Å	1.7 %
7	24.345 °	3.65326 Å	1.7 %
8	25.618 °	3.47444 Å	2.3 %
9	26.462 °	3.36553 Å	4.3 %
10	26.665 °	3.34034 Å	100.0 %
11	27.113 °	3.28626 Å	2.6 %
12	27.499 °	3.24099 Å	10.4 %
13	27.828 °	3.20333 Å	9.2 %
14	28.009 °	3.18304 Å	17.4 %
15	28.321 °	3.14869 Å	1.8 %
16	28.538 °	3.12522 Å	0.8 %
17	29.817 °	2.99406 Å	1.9 %
18	30.449 °	2.93334 Å	2.2 %
19	30.833 °	2.89767 Å	1.2 %
20	31.405 °	2.84616 Å	1.6 %
21	33.882 °	2.64353 Å	0.6 %
22	36.574 °	2.45493 Å	5.2 %
23	39.485 °	2.28038 Å	4.5 %

S4- Rock sand

Table 0-11Pattern list and 2theta results for rock sand

Pattern List #1

Index	Compound Name	Formula	Pattern #	I/Ic DB	S-Q
11	Polybasite	Ag31 As0.203 Cu S22 Sb3.797	COD 9013299	2.030	2.6 %
5	Sanidine	Al Ba0.014 Fe0.003 K0.789 Na0.16 O8 Si3	COD 9005264	0.740	14.6 %
3	Augite	Al Ca0.61 Fe0.13 K0.17 Mg0.43 Mn0.01 Na0.05 O6 Si1.61	COD 9002901	1.240	6.0 %
10	Orthoclase	Al K O8 Si3	COD 9000161	0.810	13.0 %
12	Orthoclase	Al K O8 Si3	COD 9000311	0.820	12.6 %
13	Microcline	Al K O8 Si3	COD 9000701	0.780	17.3 %
6	Sanidine	Al K0.65 Na0.35 O8 Si3	COD 9000682	0.780	13.3 %
1	Diopside	Al0.078 Ca Fe0.024 Mg0.976 O6 Si1.922	COD 9004317	1.290	5.8 %
8	Augite	Al0.7 Ca Fe0.2 Mg0.6 O6 Si1.5	COD 1200006	1.320	4.8 %
9	Bushmakinite	Al0.74 Cr0.26 Cu0.26 H O9 P1.22 Pb2 V0.52	COD 9012901	10.670	1.1 %
2	Nepheline	Al3.84 K0.57 Na3.24 O16 Si4.16	COD 9013313	1.040	7.5 %
7	Thorikosite	As0.2 Cl H0.5 O2 Pb1.5 Sb0.3	COD 9009973	14.440	0.5 %
4	Smirnite	Bi2 O5 Te	COD 9013141	23.130	1.0 %

2Theta

Index	Angle	d Value	Rel. Intensity
1	20.548 °	4.31896 Å	12.2 %
2	21.054 °	4.21631 Å	18.1 %
3	21.206 °	4.18632 Å	35.4 %
4	21.968 °	4.04276 Å	13.8 %
5	23.108 °	3.84593 Å	18.4 %
6	23.585 °	3.76911 Å	40.1 %
7	25.784 °	3.45256 Å	18.7 %
8	27.564 °	3.23346 Å	100.0 %
9	27.733 °	3.21417 Å	63.1 %
10	28.339 °	3.14680 Å	13.8 %
11	29.691 °	3.00648 Å	23.1 %
12	29.857 °	2.99017 Å	26.3 %
13	30.900 °	2.89152 Å	25.5 %
14	33.026 °	2.71009 Å	11.6 %
15	38.356 °	2.34488 Å	5.9 %

S5-Machakos river sand

Table 0-12 Pattern list and 2theta results for machakos river sand

2Theta

Index	Angle	d Value	Rel. Intensity
1	18.571 °	4.77395 Å	0.6 %
2	20.877 °	4.25166 Å	32.2 %
3	22.030 °	4.03161 Å	4.1 %
4	22.911 °	3.87854 Å	8.1 %
5	23.247 °	3.82319 Å	1.0 %
6	23.573 °	3.77103 Å	2.5 %
7	23.627 °	3.76261 Å	2.7 %
8	23.916 °	3.71775 Å	2.3 %
9	24.280 °	3.66281 Å	2.0 %
10	25.553 °	3.48322 Å	3.0 %
11	26.645 °	3.34289 Å	100.0 %
12	26.682 °	3.33836 Å	67.8 %
13	27.465 °	3.24483 Å	11.7 %
14	27.522 °	3.23829 Å	12.1 %
15	27.792 °	3.20744 Å	12.4 %
16	27.874 °	3.19814 Å	17.0 %
17	27.959 °	3.18871 Å	10.8 %
18	28.254 °	3.15607 Å	1.5 %
19	29.724 °	3.00318 Å	1.7 %
20	29.895 °	2.98645 Å	2.0 %
21	30.427 °	2.93544 Å	2.2 %
22	30.832 °	2.89781 Å	1.8 %
23	31.380 °	2.84836 Å	1.3 %
24	35.057 °	2.55758 Å	1.4 %
25	35.146 °	2.55136 Å	1.3 %
26	35.558 °	2.52268 Å	1.4 %
27	35.729 °	2.51101 Å	2.0 %
28	36.494 °	2.46013 Å	8.4 %
29	36.554 °	2.45622 Å	6.8 %
30	37.652 °	2.38708 Å	1.1 %
31	38.602 °	2.33052 Å	0.7 %
32	39.438 °	2.28302 Å	6.9 %
33	39.516 °	2.27869 Å	6.0 %

S6- Naivasha sand

Table 0-13Pattern list and 2theta results for naivasha sand

Pattern List #1

Index	Compound Name	Formula	Pattern #	I/Ic DB	S-Q
1	Anorthoclase	Al K0.333 Na0.667 O8 Si3	COD 9000855	0.680	46.5 %
2	Sanidine	Al1.04 Ca0.04 K0.65 Na0.31 O8 Si2.96	COD 9010841	0.740	37.9 %
3	Diopside	Ca Fe0.26 Mg0.74 O6 Si2	COD 9004211	1.440	10.5 %
4	Boulangerite	Pb10.159 S22 Sb7.841	COD 9014250	2.810	5.2 %

2Theta

Index	Angle	d Value	Rel. Intensity
1	21.463 °	4.13688 Å	33.9 %
2	22.824 °	3.89313 Å	16.5 %
3	23.503 °	3.78220 Å	27.6 %
4	25.499 °	3.49039 Å	13.2 %
5	27.337 °	3.25979 Å	86.4 %
6	27.573 °	3.23237 Å	100.0 %

Appendix III: S7- Quarry dust

Table 0-14 Pattern list results for quarry dust

Pattern List #1

Index	Compound Name	Formula	Pattern #	I/Ic DB	S-Q
6	Andorite VI	Ag Pb S6 Sb3	COD 9008385	4.750	2.4 %
1	Sanidine	Al K O8 Si3	COD 1011187	0.880	22.4 %
3	Sanidine	Al K O8 Si3	COD 9009662	0.810	19.7 %
4	Sanidine	Al1.04 Ca0.04 K0.65 Na0.31 O8 Si2.96	COD 9010841	0.740	28.1 %
5	Feldspar	Al1.9 O8 Si2.1 Sr	COD 9002563	1.290	13.8 %
2	Baricite	Mg3 O16 P2	COD 9001027	1.930	13.6 %

Table 0-15 2theta results for quarry dust

2Theta

Index	Angle	d Value	Rel. Intensity
1	17.828 °	4.97129 Å	9.1 %
2	20.585 °	4.31116 Å	17.4 %
3	21.264 °	4.17503 Å	25.6 %
4	22.089 °	4.02104 Å	19.1 %
5	23.216 °	3.82826 Å	28.0 %
6	23.667 °	3.75638 Å	47.2 %
7	24.648 °	3.60892 Å	12.5 %
8	25.855 °	3.44319 Å	36.1 %
9	27.313 °	3.26262 Å	53.1 %
10	27.605 °	3.22870 Å	100.0 %
11	27.695 °	3.21851 Å	93.3 %
12	28.419 °	3.13813 Å	14.8 %
13	29.756 °	3.00010 Å	29.4 %
14	29.977 °	2.97847 Å	37.4 %
15	30.984 °	2.88389 Å	29.8 %
16	32.533 °	2.75003 Å	15.2 %
17	34.956 °	2.56478 Å	22.9 %
18	35.379 °	2.53504 Å	22.9 %
19	38.440 °	2.33993 Å	15.0 %

Appendix IV: X-Ray Fluorescence

Chemical analysis of Fine aggregate material							
Sno.	Test Parameter (%)	S-2	S-3	S-4	S-5	S-6	S-7
1	Sio2	91.545	55.58	84.46	87.34	80.05	82.07
2	Al2O3						
3	Fe2O3	0.031	0.2	0.41	0.35	0.17	0.37
4	CaO	0.008	0.002	0.01	0.0034	0.0016	0.006
5	MgO	0.02	0.01	0.01	0.01	0.01	0.01
6	Na2O	0.03	0.02	0.67	0.04	0.01	0.32
7	K2O	0.03	0.03	0.18	0.04	0.02	0.08
8	TiO2						
9	LoI						
10	Cl	0.083	0.274	0.45	0.16	0.24	0.461
11	So4	0.068	0.08	0.073	0.0711	0.0721	0.07

Appendix V: Mix design of concrete

The process of mix design involves the selection of concrete constituents and determination of their relative proportions in order to attain concrete of a given minimum strength and durability. The various steps in mix design include;

I. Determining the margin strength for the mix design.
II. Determining the water cement ratio.
III. Determining the free water content.
IV. Determining the cement content.
V. Determining the total aggregate content.

The necessity for mix design to have a mean strength greater than the specified characteristic strength comes as a result of the variability of concrete in production. Thus the margin;

$F_m = f_c + k_s$

Where F_m = the target mean strength

f_c = specified characteristic strength

k_s = The margin which is the product of ;

s = the standard deviation and

k = A constant

The constant k is derived from the normal distribution and increases as the proportion of defectives is decreased, thus

K for 10% defective = 1.28

K for 5% defective = 1.64

K for 2.5% defective = 1.96

K for 1% defective = 2.33

For the 2.5% defective level specified in BS 5328, k = 1.96 and thus fm = fc + 1.96s.

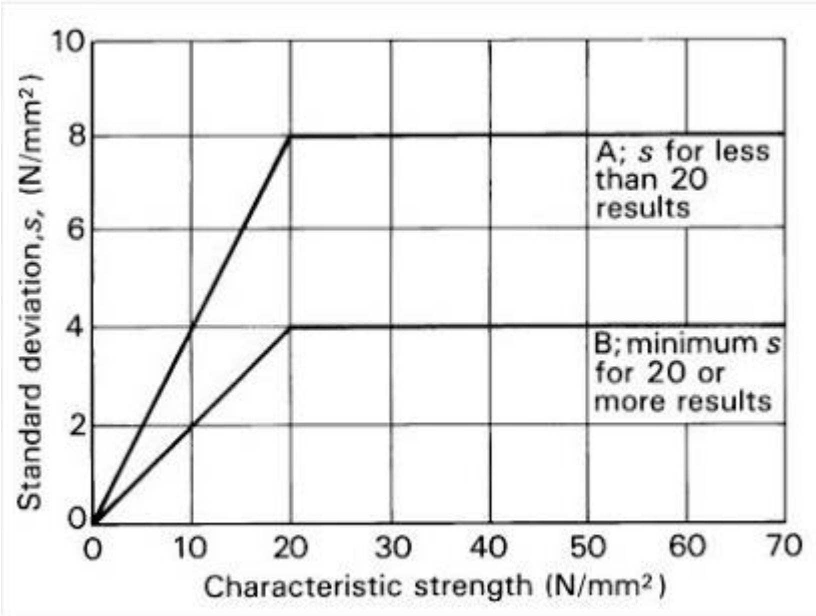


Figure 0-1 Relationship between standard deviation and characteristic strength

Figure 7-1 relates to a concrete having a specified characteristic strength of 30 N/mm2 and a standard deviation of 8 N/mm2 is used. Hence

fm =30 +1.96(8)= 46 N/mm2.

Determination of Water-Cement Ratio

For the target strength of 46N/mm^2 and cement class of 42.5N the water- cement ratio was determined from the graph

Table 0-16 Approximate compressive strengths(n/mm²) of concrete mixes made with free water/cement ratio of 0.5

Cement strength class	Type of coarse aggregate	Compressive strengths (N/mm^2) Age (days) 3	7	28	91
42.5	Uncrushed	22	30	42	49
	Crushed	27	36	49	56
52.5	Uncrushed	29	37	48	54
	Crushed	34	43	55	61

Throughout this publication concrete strength is expressed in the units N/mm^2.
1 N/mm^2 = 1 MN/m^2 = 1 MPa. (N = newton; Pa = pascal.)

Table 1 was used to determine the approximate compressive strength that corresponds to a free water/cement ratio of 0.5 at the specified age.

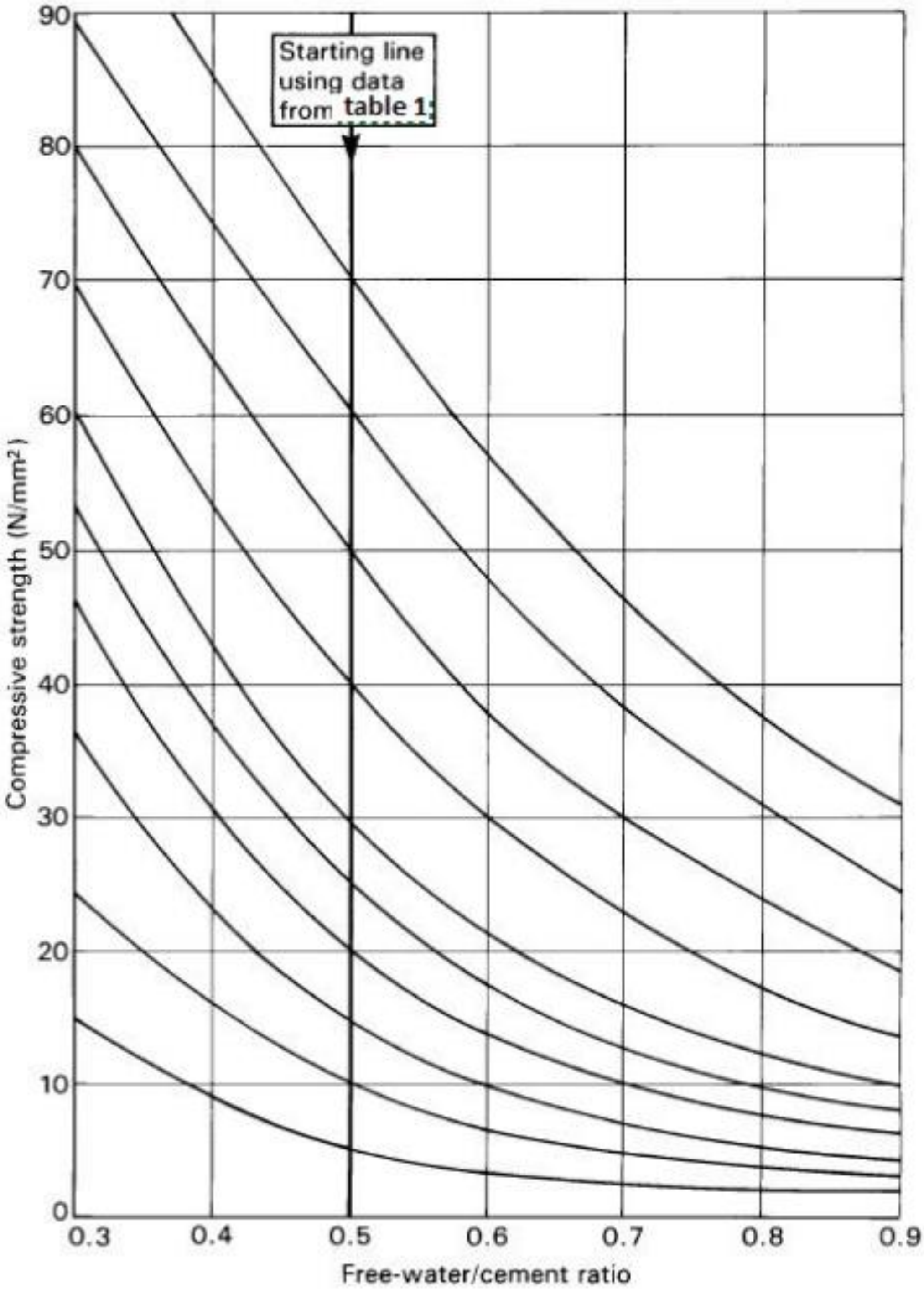


Figure 0-2 Relationship between compressive strength and free water/cement ratio

The strength value obtained from Figure 7-1 was used to plot on Figure 7-2 and a curve drawn from this point parallel to the printed curves until it intersects a horizontal line passing through the ordinate representing the target strength. This obtained 0.52 as the free water/cement ratio.

Determination of free- water content.

Table 0-17 Approximate free water content (kg/m^3) required to give various levels of workability

Slump (mm)		0–10	10–30	30–60	60–180
Vebe time (s)		>12	6–12	3–6	0–3
Maximum size of aggregate (mm)	Type of aggregate				
10	Uncrushed	150	180	205	225
	Crushed	180	205	230	250
20	Uncrushed	135	160	180	195
	Crushed	170	190	210	225
40	Uncrushed	115	140	160	175
	Crushed	155	175	190	205

The free-water content was determined from Table 2 above using a chosen slump of 10-30mm and vebe time of 6-12s with a maximum size of crushed aggregates of 20mm to obtain 190kg of water.

Determination of cement content

The cement content was determined from equation C3

$$Cement\ content = \frac{Free\ water\ content}{free\ water/cement\ ratio} \quad \ldots\ldots\ldots \text{(C3)}$$

Equation 0-1 cement content

The result obtained was checked against the maximum or minimum values specified.

Determination of total aggregate content

From the Figure 7-3, using free water content of 190kg/m^3 and assumed relative density of 2.7 for crushed aggregates, the aggregate density of 2430kg/m^3 in the saturated surface dry conditions (SSD) was obtained.

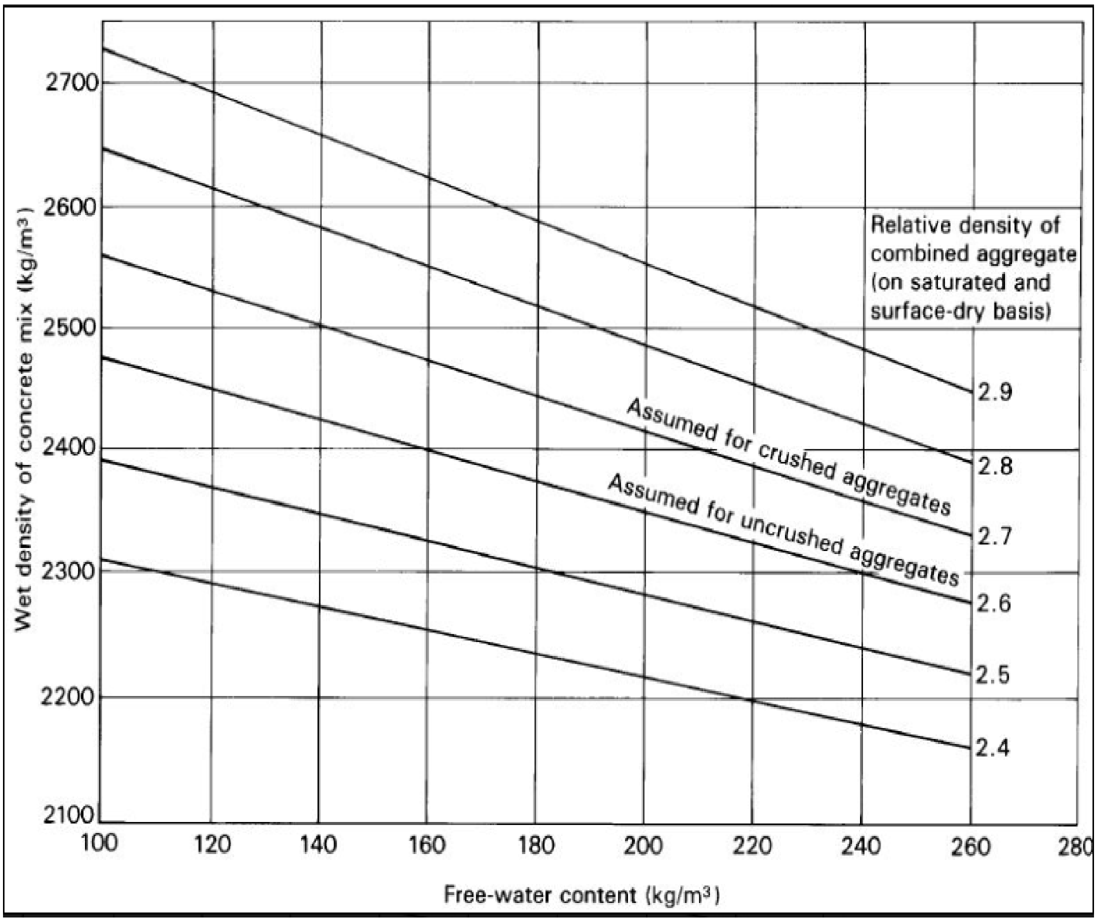


Figure 0-3 estimated wet density of fully compacted concrete

The total aggregate content was calculated using equation 4:

$Total\ aggregate\ content = D - C - W$ ………..(C4)

$=2430\ - 265\ - 190$

= 1875 kg/m^3

Where;

D= the wet density of concrete (in kg/m^3)

C= the cement content (in kg/m^3)

W = the free-water content (in kg/m^3)

Determination of the fine and coarse aggregate contents

The step involved the determination of how much of the total aggregate consists of fine aggregate. (Materials smaller than 5 mm, i.e. the sand or fine aggregate content).

$$Fine\ aggregate\ content\ =\ total\ aggregate\ content\ *\ proportion\ of\ fines$$

$$Coarse\ aggregate\ content\ =\ total\ aggregate\ content - fine\ aggregate\ content$$

The Figure 7-4 shows recommended values for the proportion of fine aggregate depending on the maximum size of aggregate, the workability level, the grading of the fine aggregate (defined by the percentage passing a 600 µm sieve) and the free-water/ cement ratio. The best proportion of fines to use in a given concrete mix design depends on the shape of the particular aggregate, the grading and the usage of the concrete. A maximum aggregate size of 20mm was used to determine the fine and course aggregate contents.

A ratio of 1:2 was used in the combination of 10mm and 20mm coarse aggregates.

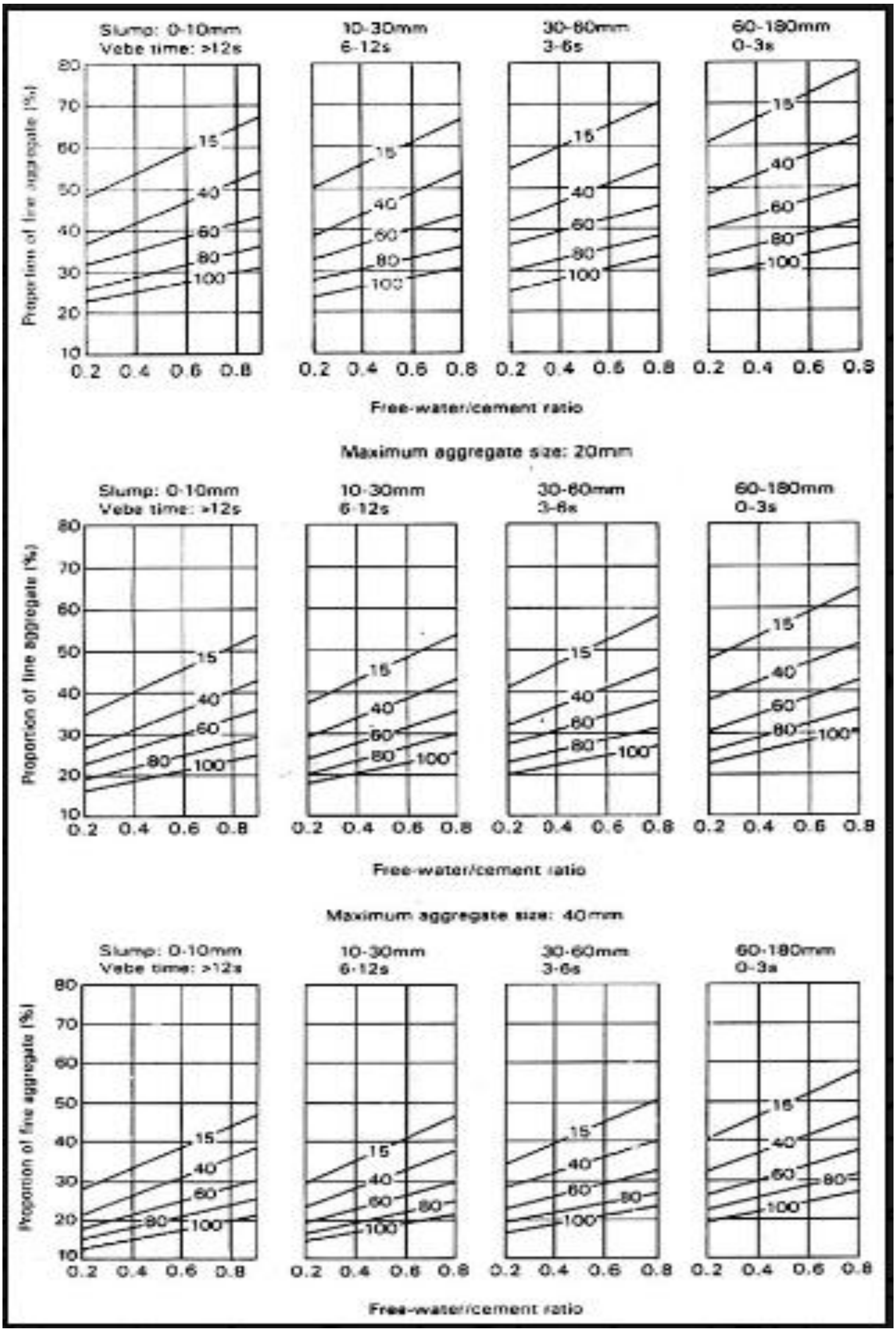


Figure 0-4 Recommended proportions of fine aggregates according to percentage passing a 600µm sieve

Appendix VI: Production of Trial Mix Design

Using the calculated batch weights of the aggregates, the proportions of the different constituents of concrete were determined to produce a trial mix of $0.025m^3$. The volume mix enough to produce 3 cubes of concrete was calculated by multiplying the volume mix by the constituents contents obtained from the concrete mix design process. The concrete mixing procedure was done as per the laboratory guidelines; Hand mixing was used where the aggregate was spread in a uniform layer on a hard, clean, non-porous base. Cement was then spread over the aggregate and the dry materials were mixed by turning over from one end of the tray to the other three times and cutting by shovel till a uniform mix was obtained. Clean water was then added gradually, mix turned over again three times till it appeared uniform in colour and consistency.

Table 1. Characteristic compressive strength compliance requirements

Specified grade	group of test results	A	B
		The mean of the group of test results exceeds the specified characteristic compressive strength by at least:	Any individual test result is not less than the characteristic compressive strength less:
		N/mm^2	N/mm^2
C20 and above	first 2	1	3
	first 3	2	3
	any consecutive 4	3	3
C7.5 to C15	first 2	0	2
	first 3	1	2
	any consecutive 4	2	2

Table 0-18 Completed concrete mix design for s2

Table 1 Concrete mix design form

Sand type ....S2...................

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	... .30...............................N/mm² at ....28 days; Proportion defective ......2.5................................. %
	1.2	Standard deviation	Fig 3	.... N/mm² or no data ......8...... N/mm²
	1.3	Margin	C1 Or Specified	(k = ... 1.96............) ......1.96 × 8...= 16......... N/mm²; .... N/mm²
	1.4	Target mean strength	C2	.........30...... + ...16...... = 46... N/mm²
	1.5	Cement strength class	Specified	42.5/52.5
	1.6	Aggregate type: coarse Aggregate type: fine		Crushed/uncrushed Crushed/uncrushed
	1.7	Free-water/cement ratio	Table 2, Fig 4	............0.52................................. Use the lower value 0.52
	1.8	Maximum free-water/ Cement ratio	Specified	..................0.55.....................
2	2.1	Slump or Vebe time	Specified	Slump ... 10-30........... mm or Vebe time .... s
	2.2	Maximum aggregate size	Specified	......20............ mm
	2.3	Free-water content	Table 3	.....................190.. 190 kg/m³
3	3.1	Cement content	C3	......190......... ÷ ....0.52..................... = ...365.4 kg/m³
	3.2	Maximum cement content	Specified	.... kg/m³
	3.3	Minimum cement content	Specified	...............290......kg/m³
				Use 3.1 if ≤ 3.2 Use 3.3 if > 3.1 kg/m³ — 365 kg/m³
	3.4	Modified free-water/cement ratio		....
4	4.1	Relative density of known/assumed aggregate (SSD)		.................................2.7............
	4.2	Concrete density	Fig 5	...2430 kg/m³
190	4.3	Total aggregate content	C4	............2430......... − ...365...... − ...190... =...1875 kg/m³
5	5.1	Grading of fine aggregate	Percentage passing 600 µm sieve	....40.............................. %
	5.2	Proportion of fine aggregate	Fig 6	....35................................ %
	5.3	Fine aggregate content	C5	...............1875............... × ....0.35... = 656 kg/m³
	5.4	Coarse aggregate content	C5	..................1875........... − ....656...... = 1219 kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	...365.........	.........190.........	............656.........	.........406......	......812......	....
per trial mix of ....0.025...... m³	...10.1...............	...4.75.........	......16.125............	.......10......	......20......	....

Items in italics are optional limiting values that may be specified (see Section 7).Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.) The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water. SSD = based on the saturated surface-dry condition.

Table 0-19 Completed concrete mix design for s3

Table 1 Concrete mix design form

Sand type ....S3...................

Stage	Item	Reference or calculation	Values
1	1.1 Characteristic strength	Specified	... .30.............................. N/mm² at ....28 days; Proportion defective ......2.5................................ %
	1.2 Standard deviation	Fig 3	.... N/mm² or no data ......8...... N/mm²
	1.3 Margin	C1 Or Specified	(k = ... 1.96...........) ......1.96 × 8...= 16......... N/mm²; .... N/mm²
	1.4 Target mean strength	C2	.........30...... □ ...16...... = 46... N/mm²
	1.5 Cement strength class	Specified	42.5/52.5
	1.6 Aggregate type: coarse; Aggregate type: fine		Crushed/uncrushed; Crushed/uncrushed
	1.7 Free-water/cement ratio	Table 2, Fig 4	...........0.52...... } Use the lower value 0.52
	1.8 Maximum free-water/ Cement ratio	Specified	....
2	2.1 Slump or Vebe time	Specified	Slump ... 10-30........... mm or Vebe time .... s
	2.2 Maximum aggregate size	Specified	......20........... mm
	2.3 Free-water content	Table 3	....................190.. 190 kg/m³
3	3.1 Cement content	C3	......190......... ÷ ....0.52..................... = ...365 kg/m³
	3.2 Maximum cement content	Specified	.... kg/m³
	3.3 Minimum cement content	Specified	...............290......kg/m³
			Use 3.1 if ≤ 3.2; Use 3.3 if > 3.1; kg/m³ — 365 kg/m³
	3.4 Modified free-water/cement ratio		....
4	4.1 Relative density of known/assumed aggregate (SSD)		................................2.7...........
	4.2 Concrete density	Fig 5	...2430 kg/m³
190	4.3 Total aggregate content	C4	...........2430......... − ...365...... − ...190... =...1875 kg/m³
5	5.1 Grading of fine aggregate	Percentage passing 600 µm sieve	....70............................... %
	5.2 Proportion of fine aggregate	Fig 6	....28................................ %
	5.3 Fine aggregate content	C5	...............1875............... × ....0.28... = 525 kg/m³
	5.4 Coarse aggregate content	C5	...................1875............ − ....525..... = 1350 kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	...365.........	.........190.........	............525.........	.........450......	......900......	....
per trial mix of ....0.025...... m³	...9.125............	...4.75.........	.........13.12............	.....11.25......	...22.5......	....

Items in italics are optional limiting values that may be specified (see Section 7).Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

Table 0-20 Completed concrete mix design for s4

Table 1 Concrete mix design form

Sand type ....S4..................

Stage	Item	Reference or calculation	Values
1	1.1 Characteristic strength	Specified	... .30............................ N/mm² at ....28 days; Proportion defective ......2.5................................ %
	1.2 Standard deviation	Fig 3	.... N/mm² or no data ......8...... N/mm²
	1.3 Margin	C1 Or Specified	(k = ... 1.96............) ......1.96 × 8...= 16......... N/mm²; .... N/mm²
	1.4 Target mean strength	C2	.........30...... □ ...16...... = 46... N/mm²
	1.5 Cement strength class	Specified	42.5/52.5
	1.6 Aggregate type: coarse Aggregate type: fine		Crushed/uncrushed Crushed/uncrushed
	1.7 Free-water/cement ratio	Table 2, Fig 4	............0.52......; Use the lower value 0.52
	1.8 Maximum free-water/Cement ratio	Specified	....
2	2.1 Slump or Vebe time	Specified	Slump ... 10-30............ mm or Vebe time .... s
	2.2 Maximum aggregate size	Specified	......20............ mm
	2.3 Free-water content	Table 3	....................190.. 190 kg/m³
3	3.1 Cement content	C3	......190......... ÷ ....0.52..................... = ...365 kg/m³
	3.2 Maximum cement content	Specified	.... kg/m³
	3.3 Minimum cement content	Specified	...............290......kg/m³; Use 3.1 if ≤ 3.2; Use 3.3 if > 3.1 kg/m³; 365 kg/m³
	3.4 Modified free-water/cement ratio		....
4	4.1 Relative density of known/assumed aggregate (SSD)		.................................2.7............
	4.2 Concrete density	Fig 5	...2430 kg/m³
190	4.3 Total aggregate content	C4	...........2430......... − ...365...... − ...190... =...1875 kg/m³
5	5.1 Grading of fine aggregate	Percentage passing 600 µm sieve	....25.............................. %
	5.2 Proportion of fine aggregate	Fig 6	....42................................. %
	5.3 Fine aggregate content	C5	...............1875............... × ....0.42... = 788 kg/m³
	5.4 Coarse aggregate content	C5	..................1875............ − ....788...... = 1087 kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	...365.........	.........190.........	............788.........	.........362......	......725......	....
per trial mix of ....0.025...... m³	...9.125...........	...4.75.........	.........19.7............	.....9.05......	.....18.125......	....

Items in italics are optional limiting values that may be specified (see Section 7).Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water. SSD = based on the saturated surface-dry condition.

Table 0-21 Completed concrete mix design for s5

Table 1 Concrete mix design form

Sand type ....S5...................

Stage	Item	Reference or calculation	Values
1	1.1 Characteristic strength	Specified	... .30............................. N/mm² at ....28 days
			Proportion defective ......2.5................................ %
	1.2 Standard deviation	Fig 3	.... N/mm² or no data ......8...... N/mm²
	1.3 Margin	C1 Or Specified	(k = ... 1.96...........) ......1.96 × 8...= 16......... N/mm²
			.... N/mm²
	1.4 Target mean strength	C2	.........30...... □ ... 16...... = 46... N/mm²
	1.5 Cement strength class	Specified	42.5/52.5
	1.6 Aggregate type: coarse		Crushed/uncrushed
	Aggregate type: fine		Crushed/uncrushed
	1.7 Free-water/cement ratio	Table 2, Fig 4	............0.52...... } Use the lower value 0.52
	1.8 Maximum free-water/ Cement ratio	Specified	....
2	2.1 Slump or Vebe time	Specified	Slump ... 10-30........... mm or Vebe time .... s
	2.2 Maximum aggregate size	Specified	......20............ mm
	2.3 Free-water content	Table 3	.....................190.. 190 kg/m³
3	3.1 Cement content	C3	......190......... ÷ ....0.52..................... = ...365 kg/m³
	3.2 Maximum cement content	Specified	.... kg/m³
	3.3 Minimum cement content	Specified	...............290......kg/m³
			Use 3.1 if ≤ 3.2 Use 3.3 if > 3.1 kg/m³ — 365 kg/m³
	3.4 Modified free-water/cement ratio		....
4	4.1 Relative density of known/assumed aggregate (SSD)		.................................2.7............
	4.2 Concrete density	Fig 5	...2430 kg/m³
190	4.3 Total aggregate content	C4	............2430......... − ...365...... − ...190... =...1875 kg/m³
5	5.1 Grading of fine aggregate	Percentage passing 600 µm sieve	....45.............................. %
	5.2 Proportion of fine aggregate	Fig 6	....35................................ %
	5.3 Fine aggregate content	C5	...............1875............... × ....0.35... = 656 kg/m³
	5.4 Coarse aggregate content	C5	...................1875............ − ....656...... = 1219 kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	...365.........	.........190.........	............656.........	.........406......	......813......	....
per trial mix of ....0.025...... m³	...9.125............	...4.75.........	.........16.4............	.....10.15......	.....20.3......	....

tems in italics are optional limiting values that may be specified (see Section 7).Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water. SSD = based on the saturated surface-dry condition.

Table 0-22 Completed concrete mix design for s6

Table 1 Concrete mix design form

Sand type ....S6...................

Stage	Item	Reference or calculation	Values
1	1.1 Characteristic strength	Specified	... .30...................................... N/mm² at ....28 days; Proportion defective ......2.5................................ %
	1.2 Standard deviation	Fig 3	.... N/mm² or no data ......8...... N/mm²
	1.3 Margin	C1 Or Specified	(k = ... 1.96............) ......1.96 × 8...= 16......... N/mm²; .... N/mm²
	1.4 Target mean strength	C2	.........30...... + ... 16...... = 46... N/mm²
	1.5 Cement strength class	Specified	42.5/52.5
	1.6 Aggregate type: coarse; Aggregate type: fine		Crushed/uncrushed; Crushed/uncrushed
	1.7 Free-water/cement ratio	Table 2, Fig 4	............0.52......; Use the lower value 0.52
	1.8 Maximum free-water/ Cement ratio	Specified	....
2	2.1 Slump or Vebe time	Specified	Slump ... 10-30............ mm or Vebe time .... s
	2.2 Maximum aggregate size	Specified	......20............ mm
	2.3 Free-water content	Table 3	.....................190... 190 kg/m³
3	3.1 Cement content	C3	......190......... ÷ ....0.52..................... = ...365 kg/m³
	3.2 Maximum cement content	Specified	.... kg/m³
	3.3 Minimum cement content	Specified	...............290......kg/m³
			Use 3.1 if ≤ 3.2; Use 3.3 if > 3.1 kg/m³: 365 kg/m³
	3.4 Modified free-water/cement ratio		....
4	4.1 Relative density of known/assumed aggregate (SSD)		...................................2.7............
	4.2 Concrete density	Fig 5	...2430 kg/m³
	4.3 Total aggregate content	C4	............2430......... − ...365...... − ...190... =...1875 kg/m³
5	5.1 Grading of fine aggregate	Percentage passing 600 μm sieve	....60................................ %
	5.2 Proportion of fine aggregate	Fig 6	....30...................... %
	5.3 Fine aggregate content	C5	...............1875............... × ....0.30... = 562.5 kg/m³
	5.4 Coarse aggregate content	C5	...............1875............ − ....562.5...... = 1312 kg/m³

190

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	...365.........	.........190.........	.............562.........	.........437......	......875......	....
per trial mix of ....0.025...... m³	...9.125............	...4.75.........	.........14.05............	.....11......	.......21.8......	....

Items in italics are optional limiting values that may be specified (see Section 7).Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water. SSD = based on the saturated surface-dry condition.

Table 0-23 Completed concrete mix design for s7

Table 1 Concrete mix design form

Sand type ....S7...................

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	... .30...............................N/mm² at ....28 days; Proportion defective ......2.5................................ %
	1.2	Standard deviation	Fig 3	.... N/mm² or no data ......8...... N/mm²
	1.3	Margin	C1 Or Specified	(k = ... 1.96............) ......1.96 × 8...= 16......... N/mm²; .... N/mm²
	1.4	Target mean strength	C2	.........30...... + ... 16...... = 46... N/mm²
	1.5	Cement strength class	Specified	42.5/52.5
	1.6	Aggregate type: coarse Aggregate type: fine		Crushed/uncrushed Crushed/uncrushed
	1.7	Free-water/cement ratio	Table 2, Fig 4	............0.52...... } Use the lower value 0.52
	1.8	Maximum free-water/ Cement ratio	Specified	....
2	2.1	Slump or Vebe time	Specified	Slump ... 10-30........... mm or Vebe time .... s
	2.2	Maximum aggregate size	Specified	......20............ mm
	2.3	Free-water content	Table 3	.....................190... 190 kg/m³
3	3.1	Cement content	C3	......190......... ÷ ....0.52..................... = ...365 kg/m³
	3.2	Maximum cement content	Specified	.... kg/m³
	3.3	Minimum cement content	Specified	..............290......kg/m³
				Use 3.1 if ≤ 3.2 Use 3.3 if > 3.1 kg/m³ — 365 kg/m³
	3.4	Modified free-water/cement ratio		....
4	4.1	Relative density of known/assumed aggregate (SSD)		.................................2.7............
	4.2	Concrete density	Fig 5	...2430 kg/m³
190	4.3	Total aggregate content	C4	...........2430......... − ...365...... − ...190... =...1875 kg/m³
5	5.1	Grading of fine aggregate	Percentage passing 600 µm sieve	....25............................. %
	5.2	Proportion of fine aggregate	Fig 6	....42................................. %
	5.3	Fine aggregate content	C5	...............1875..............× ....0.42... = 787.5 kg/m³
	5.4	Coarse aggregate content	C5	...............1875............ − ....787.5 = 1087.5 kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	...365.........	.........190.........	............788.........	.........362......	......725......	....
per trial mix of ....0.025...... m³	...9.125............	...4.75.........	.........19.7............	.......9.05......	.......18.125......	....

Items in italics are optional limiting values that may be specified (see Section 7).Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.) The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water. SSD = based on the saturated surface-dry condition.

Appendix VII: Raw compressive strength data.

RUN1

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S2	7988	2366.8	06/12/2017	13/12/2017	7	531.96	23.64	
	8180	2423.7				561.94	24.98	
	8116	2404.7				577.15	25.65	
Average Strength at …7… days							24.76	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S2	8275	2451.9	06/12/2017	20/12/2017	14	747.78	33.24	
	7932	2350.2				758.8	33.72	
	8335	2469.6				663.3	29.48	
Average Strength at …14… days							32.15	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S2	8089	2396.7	06/12/2017	03/01/2018	28	981.25	43.61	
	8473	2510.5				871.54	38.74	
	8165	2419.3				975.42	43.35	
Average Strength at …28… days							41.9	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S2	7446	2206.2	06/12/2017	31/01/2018	56	1281.54	56.96	
	8226	2437.3				1281.83	56.97	
	7874	2333				1063.37	47.26	
Average Strength at …56… days							53.73	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S2	7829	2319.7	06/12/2017	28/03/2018	112	985.13	43.78	
	7983	2365.3				1130.32	50.24	
	8301	2459.6				1088.37	48.37	
Average Strength at …112… days							47.46	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S2	8354	2475.3	06/12/2017	04/06/2018	180	933.54	41.49	
	8326	2467				879.98	39.11	
	8501	2518.8				906.75	40.30	
Average Strength at …180… days							40.30	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S2	7991	2367.7	06/12/2017	21/11/2018	360	1054.87	46.88	
	8139	2411.6				1121.61	49.85	
	8023	2377.2				1056.63	47.41	
Average Strength at …360… days							48.05	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S3	8299	2459	07/12/2017	14/12/2017	7	574	25.11	
	8281	2453.6				568.24	25.56	
	8287	2455.4				571.9	25.42	
Average Strength at …7… days							25.36	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S3	7879	2334.5	07/12/2017	21/12/2017	14	738.6	32.82	
	8275	2451.9				694.03	30.85	
	7813	2315				693.1	29.92	
Average Strength at …14… days							31.2	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S3	8107	2402.1	07/12/2017	04/01/2018	28	762.975	33.91	
	8105	2401.5				836.29	37.17	
	8287	2455.4				836.46	37.18	
Average Strength at …28… days							36.09	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S3	8233	2439.4	07/12/2017	01/02/2018	56	984.9	43.77	
	8431	2498.1				1263.91	56.17	
	8110	2403				913.39	40.59	
Average Strength at …56… days							46.84	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S3	7916	2345.5	07/12/2017	29/03/2018	112	882.16	39.21	
	8395	2487.4				1088.65	48.38	
	8124	2407.1				981.64	43.63	
Average Strength at 112…… days							43.74	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S3	8172	2421.3	07/12/2017	05/06/2018	180	990.00	44.00	
	8029	2379				907.20	40.32	
	7886	2336.6				927.23	41.21	
Average Strength at …180… days							41.84	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S3	8256	2446.2	07/12/2017	22/11/2018	360	1087.89	48.35	
	8367	2479.1				1119.43	49.75	
	8014	2374.5				1147.77	51.01	
Average Strength at …360… days							49.71	

Cube	Wt. (g)	Density (Kg/m³)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm²)	P-Pass F-Fail
S4	8335	2469.6	09/01/2018	16/01/2018	7	487.66	21.67	
	8400	2488.9				507	22.36	
	7989	2367.1				419.62	18.65	
Average Strength at …7… days							20.89	

Cube	Wt. (g)	Density (Kg/m³)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm²)	P-Pass F-Fail
S4	7973	2362.3	09/01/2018	23/01/2018	14	524.57	23.31	
	8488	2515				596.63	26.52	
	8199	2429.3				574.43	25.53	
Average Strength at …14… days							25.12	

Cube	Wt. (g)	Density (Kg/m³)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm²)	P-Pass F-Fail
S4	8494	2516.7	09/01/2018	06/02/2018	28	640.56	28.47	
	8098	2399.4				670.07	29.78	
	8330	2468.1				625.42	27.80	
Average Strength at …28… days							28.68	

Cube	Wt. (g)	Density (Kg/m³)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm²)	P-Pass F-Fail
S4	7834	2321.2	09/01/2018	06/03/2018	56	668.64	29.72	
	8190	2426.7				855.54	38.02	
	7888	2337.2				802.51	35.67	
Average Strength at …56… days							36.85	

Cube	Wt. (g)	Density (Kg/m³)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm²)	P-Pass F-Fail
S4	8262	2448	09/01/2018	01/05/2018	112	929.69	41.32	
	7928	2349				916.94	40.75	
	8000	2370.4				884.34	39.3	
Average Strength at …112… days							40.46	

Cube	Wt. (g)	Density (Kg/m³)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm²)	P-Pass F-Fail
S4	7900	2340.7	09/01/2018	08/07/2018	180	787.50	35.00	
	8423	2495.7				828.23	36.81	
	8033	2380.1				706.50	31.40	
Average Strength at …180… days							34.40	

Cube	Wt. (g)	Density (Kg/m³)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm²)	P-Pass F-Fail
S4	8213	2433.5	09/01/2018	25/12/2018	360	920.40	40.91	
	8115	2404.4				966.12	42.94	
	7211	2136.6				940.43	41.80	
Average Strength at …360… days							41.88	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S5	8145	2413.3	08/12/2017	15/12/2017	7	498.6	22.16	
	8491	2515.9				494.03	21.96	
	8221	2435.9				478.28	21.26	
Average Strength at …7… days							21.79	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S5	8163	2418.7	08/12/2017	22/12/2017	14	615.55	27.36	
	8061	2388.4				611.12	27.16	
	8409	2491.6				637.46	28.33	
Average Strength at …14… days							27.62	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S5	8081	2394.4	08/12/2017	05/01/2018	28	775.93	34.49	
	8153	2415.7				772.93	34.35	
	7543	2235				722.17	32.14	
Average Strength at …28… days							33.64	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S5	8236	2440.3	08/12/2017	02/02/2018	56	859.46	38.20	
	7934	2350.8				922.93	41.02	
	8324	2466.4				970.56	43.14	
Average Strength at …56… days							40.78	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S5	8018	2375.7	08/12/2017	30/03/2018	112	975.93	43.38	
	8068	2390.5				974.78	43.32	
	8621	2554.4				907.65	40.34	
Average Strength at …112… days							42.35	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S5	7900	2340.7	08/12/2017	06/06/2018	180	1013.4	45.04	
	8423	2495.7				1050.78	46.7	
	8033	2380.1				795.79	43.37	
Average Strength at …180… days							45.04	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S5	8548	2532.7	08/12/2017	23/11/2018	360	981.22	43.61	
	7983	2365.3				827.46	36.78	
	8347	2473.2				1009.18	44.85	
Average Strength at …360… days							41.75	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S6	8392	2486.5	12/01/2018	19/01/2018	7	479.12	21.29	
	8440	2500.7				469.86	20.79	
	8211	2432.9				463.11	20.58	
Average Strength at …7… days							20.89	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S6	8150	2414.8	12/01/2018	26/01/2018	14	614.83	27.33	
	7654	2267.8				511.4	22.73	
	8096	2398.8				544.23	24.19	
Average Strength at …14… days							24.75	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S6	7650	2266.7	12/01/2018	09/02/2018	28	650.91	28.93	
	8372	2480.6				864.94	30.44	
	7750	2296.3				567.23	25.21	
Average Strength at …28… days							28.19	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S6	8448	2503.1	12/01/2018	09/03/2018	56	681.58	30.29	
	8459	2506.4				769.66	34.21	
	8217	2434.7				792.11	35.21	
Average Strength at …56… days							33.23	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S6	7399	2192.3	12/01/2018	04/05/2018	112	669.82	29.77	
	7888	2337.2				755.11	33.56	
	7740	2293.3				816.04	36.27	
Average Strength at …112… days							33.2	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S6	7376	2185.5	12/01/2018	11/07/2018	180	813.87	36.17	
	7836	2321.8				925.7	41.14	
	6967	2064.3				824.08	36.62	
Average Strength at …180… days							37.98	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S6	7819	2316.7	12/01/2018	28/12/2018	360	830.94	36.93	
	7479	2216				818.45	36.38	
	7438	2203.9				909.88	40.44	
Average Strength at …360… days							37.91	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S7	8381	2483.3	16/01/2018	23/01/2018	7	460.66	20.47	
	8372	2480.6				452.88	20.13	
	8355	2475.6				438.63	19.50	
Average Strength at ...7... days							20.03	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S7	7757	2298.4	16/01/2018	30/01/2018	14	598.17	26.59	
	7750	2296.3				615.38	27.35	
	7799	2310.8				545.75	24.26	
Average Strength at ...14... days							26.06	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S7	8211	2432.9	16/01/2018	13/02/2018	28	654.61	29.09	
	8324	2466.4				504.06	22.40	
	8001	2370.7				540.12	26.23	
Average Strength at ...28... days							25.91	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S7	7882	2335.4	16/01/2018	13/03/2018	56	792.61	35.23	
	8011	2373.6				814.17	36.19	
	7923	2347.6				866.21	38.50	
Average Strength at ...56... days							36.64	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S7	7823	2317.9	16/01/2018	08/05/2018	112	788.11	35.03	
	8202	2430.2				758.36	33.71	
	7148	2117.9				780.72	34.70	
Average Strength at ...112... days							34.48	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S7	7753	2297.2	16/01/2018	15/07/2018	180	914.85	40.66	
	7651	2267				935.55	41.58	
	7977	2363.6				956.25	42.50	
Average Strength at ...180... days							41.58	

Cube	Wt. (g)	Density (Kg/m^3)	Casting Date	Testing Date	Age (days)	Load (KN)	Compressive Strength (N/mm^2)	P-Pass F-Fail
S7	8107	2402.1	16/01/2018	01/01/2019	360	857.76	38.12	
	8133	2409.8				916.13	40.72	
	7869	2331.6				899.95	40.00	
Average Strength at ...360... days							39.61	

Appendix VIII: Run 2 Multilinear-regression analysis raw data

At 7 days curing

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.9348186
R Square	0.8738858
Adjusted R Square	0.5713382
Standard Error	0.9611613
Observations	18

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	8	76.81824	9.6022801	16.630365	0.0001546
Residual	12	11.085973	0.9238311		
Total	20	87.904213			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-5024.4753	1218.6816	-4.1228778	0.0014134	-7679.7544	-2369.1962	-7679.7544	-2369.1962
FA (kg)	2.8761605	0.6724422	4.2771861	0.0010743	1.4110348	4.3412862	1.4110348	4.3412862
CA (kg)	2.8092139	0.6635075	4.2338839	0.00116	1.3635551	4.2548726	1.3635551	4.2548726
Water (kg)	0	0	65535	#NUM!	0	0	0	0
Cement (kg)	0	0	65535	#NUM!	0	0	0	0
SiO (%)	-2.562989	0.5789512	-4.4269517	#NUM!	-3.8244152	-1.3015627	-3.8244152	-1.3015627
AlO (%)	-6.1326918	1.2877482	-4.7623379	0.0004623	-8.9384541	-3.3269296	-8.9384541	-3.3269296
Silt & Clay	0.6380832	0.1882385	3.3897589	0.0053704	0.2279467	1.0482198	0.2279467	1.0482198
w/c ratio	0	0	65535	#NUM!	0	0	0	0

At 14 days curing

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.8941354
R Square	0.7994781
Adjusted R	0.4659274
Standard Er	1.7698467
Observatio	18

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	8	149.86404	18.733005	9.5687701	0.0013565
Residual	12	37.588289	3.1323574		
Total	20	187.45233			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-8030.2023	2244.035	-3.5784657	0.0037929	-12919.535	-3140.87	-12919.535	-3140.87
FA (kg)	4.6313068	1.2382101	3.7403238	0.0028203	1.9334787	7.3291349	1.9334787	7.3291349
CA (kg)	4.4988978	1.2217581	3.6823146	0.0031355	1.8369155	7.1608801	1.8369155	7.1608801
Water (kg)	0	0	65535	#NUM!	0	0	0	0
Cement (kg	0	0	65535	#NUM!	0	0	0	0
SiO (%)	-4.5000644	1.0660592	-4.2212143	#NUM!	-6.8228079	-2.1773209	-6.8228079	-2.1773209
AlO (%)	-10.931449	2.3712116	-4.6100687	0.0006004	-16.097875	-5.7650222	-16.097875	-5.7650222
Silt & Clay	1.4030252	0.3466154	4.0477863	0.0016167	0.6478151	2.1582354	0.6478151	2.1582354
w/c ratio	0	0	65535	#NUM!	0	0	0	0

At 28 days curing

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.9201405							
R Square	0.8466585							
Adjusted R	0.5327662							
Standard Er	2.7804934							
Observatio	18							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	8	512.23994	64.029992	13.251337	0.0003846			
Residual	12	92.773723	7.7311436					
Total	20	605.01366						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-3311.8699	3525.4604	-0.9394149	0.366043	-10993.188	4369.4485	-10993.188	4369.4485
FA (kg)	2.3152799	1.945273	1.1902082	0.2569787	-1.9231059	6.5536657	-1.9231059	6.5536657
CA (kg)	2.1008211	1.9194263	1.0945047	0.2952165	-2.0812496	6.2828919	-2.0812496	6.2828919
Water (kg)	0	0	65535	#NUM!	0	0	0	0
Cement (kg	0	0	65535	#NUM!	0	0	0	0
SiO (%)	-7.150015	1.6748177	-4.2691303	#NUM!	-10.799129	-3.5009007	-10.799129	-3.5009007
AlO (%)	-17.179336	3.7252595	-4.6115811	0.0005988	-25.295979	-9.062693	-25.295979	-9.062693
Silt & Clay	1.7565693	0.5445454	3.2257535	0.0072764	0.5701068	2.9430319	0.5701068	2.9430319
w/c ratio	0	0	65535	#NUM!	0	0	0	0

At 56 days

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.8841929							
R Square	0.7817971							
Adjusted R	0.4408792							
Standard Er	4.7120208							
Observatio	18							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	8	954.61698	119.32712	8.5989367	0.0020231			
Residual	12	266.43768	22.20314					
Total	20	1221.0547						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-16679.28	5974.4946	-2.7917474	0.0162917	-29696.585	-3661.9741	-29696.585	-3661.9741
FA (kg)	9.8361968	3.2965972	2.9837424	0.0114062	2.6535285	17.018865	2.6535285	17.018865
CA (kg)	9.4659224	3.2527957	2.9100882	0.0130789	2.3786895	16.553155	2.3786895	16.553155
Water (kg)	0	0	65535	#NUM!	0	0	0	0
Cement (kg	0	0	65535	#NUM!	0	0	0	0
SiO (%)	-12.369149	2.8382645	-4.3579974	#NUM!	-18.553196	-6.1851021	-18.553196	-6.1851021
AlO (%)	-29.742755	6.3130883	-4.7112845	0.0005045	-43.497793	-15.987717	-43.497793	-15.987717
Silt & Clay	3.7514781	0.9228252	4.0652099	0.001567	1.7408148	5.7621415	1.7408148	5.7621415
w/c ratio	0	0	65535	#NUM!	0	0	0	0

At 112 days

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.9098644							
R Square	0.8278533							
Adjusted R	0.5061255							
Standard Er	2.8081778							
Observatio	18							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	8	455.07714	56.884642	11.541594	0.0006613			
Residual	12	94.630351	7.8858626					
Total	20	549.70749						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-6070.7524	3560.5622	-1.7049983	0.1139227	-13828.551	1687.0462	-13828.551	1687.0462
FA (kg)	3.6225645	1.9646414	1.8438808	0.0900207	-0.6580214	7.9031504	-0.6580214	7.9031504
CA (kg)	3.4626954	1.9385374	1.7862412	0.0993307	-0.7610148	7.6864056	-0.7610148	7.6864056
Water (kg)	0	0	65535	#NUM!	0	0	0	0
Cement (kg	0	0	65535	#NUM!	0	0	0	0
SiO (%)	-4.6090395	1.6914933	-2.7248347	#NUM!	-8.2944868	-0.9235923	-8.2944868	-0.9235923
AlO (%)	-11.780254	3.7623506	-3.1310888	0.0086743	-19.977712	-3.582796	-19.977712	-3.582796
Silt & Clay	0.8496709	0.5499673	1.5449481	0.1483115	-0.3486048	2.0479467	-0.3486048	2.0479467
w/c ratio	0	0	65535	#NUM!	0	0	0	0

At 180 days

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.8983859							
R Square	0.8070973							
Adjusted R	0.4767211							
Standard Er	1.9940589							
Observatio	18							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	8	199.63868	24.954835	10.041503	0.0011299			
Residual	12	47.715251	3.9762709					
Total	20	247.35393						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-3724.5556	2528.3195	-1.4731349	0.1664551	-9233.2907	1784.1794	-9233.2907	1784.1794
FA (kg)	1.9789763	1.3950722	1.4185476	0.1814768	-1.0606248	5.0185774	-1.0606248	5.0185774
CA (kg)	1.9695909	1.376536	1.4308314	0.1780007	-1.0296234	4.9688051	-1.0296234	4.9688051
Water (kg)	0	0	65535	#NUM!	0	0	0	0
Cement (kg	0	0	65535	#NUM!	0	0	0	0
SiO (%)	0.8182425	1.2011124	0.6812372	#NUM!	-1.7987566	3.4352416	-1.7987566	3.4352416
AlO (%)	0.1153724	2.6716074	0.0431846	0.9662646	-5.7055602	5.936305	-5.7055602	5.936305
Silt & Clay	0.8722297	0.3905262	2.2334726	0.0453266	0.0213461	1.7231133	0.0213461	1.7231133
w/c ratio	0	0	65535	#NUM!	0	0	0	0

At 360 days

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.9180972							
R Square	0.8429025							
Adjusted R	0.5274451							
Standard Er	2.2684779							
Observatio	18							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	8	331.32811	41.416013	12.877132	0.0004307			
Residual	12	61.751906	5.1459922					
Total	20	393.08001						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-13620.882	2876.2626	-4.7356184	0.0004839	-19887.72	-7354.0442	-19887.72	-7354.0442
FA (kg)	7.6984361	1.5870597	4.8507541	0.0003977	4.2405302	11.156342	4.2405302	11.156342
CA (kg)	7.5399713	1.5659725	4.8148809	0.0004227	4.1280102	10.951932	4.1280102	10.951932
Water (kg)	0	0	65535	#NUM!	0	0	0	0
Cement (kg)	0	0	65535	#NUM!	0	0	0	0
SiO (%)	-5.5696138	1.3664075	-4.0761002	#NUM!	-8.54676	-2.5924677	-8.54676	-2.5924677
AlO (%)	-13.484033	3.0392696	-4.4366031	0.0008117	-20.106032	-6.8620333	-20.106032	-6.8620333
Silt & Clay	1.3781339	0.4442698	3.1020202	0.0091556	0.4101532	2.3461147	0.4101532	2.3461147
w/c ratio	0	0	65535	#NUM!	0	0	0	0

Appendix IX: Calculations

S2 (Mwingi river sand)

$$f\,7 = -5024.48 + 2.87616\,(656) + 2.809214\,(1218) + -2.56299\,(76) + -6.13269\,(11) + 0.638083\,(4.85)$$

$$f14 = -8030.2 + 4.631307\,(656) + 4.498898\,(1218) + -4.50006\,(76) + -10.9314\,(11) + 1.403025\,(4.85)$$

$$f\,28 = -3311.87 + 2.31528(656) + 2.100821(1218) + -7.15002(76) + -17.1793\,(11) + 1.756569\,(4.85)$$

$$f\,56 = -16679.3 + 9.836197(656) + 9.465922\,(1218) + -12.3691(76) + -29.7428\,(11) + 3.751478\,(4.85)$$

$$f\,112 = -6070.75 + 3.622564(656) + 3.462695(1218) + -4.60904\,(76) + -11.7803\,(11) + 0.849671\,(4.85)$$

$$f\,180 = -3724.56 + 1.978976(656) + 1.969591\,(1218) + 0.818243\,(76) + 0.115372\,(11) + 0.87223\,(4.85)$$

S3 (Kajiado river sand)

$$f\,7 = -5024.48 + 2.87616\,(525) + 2.809214\,(1350) + -2.56299\,(78) + -6.13269\,(9) + 0.638083\,(4.16)$$

$$f14 = -8030.2 + 4.631307(525) + 4.498898(1350) + -4.50006\,(78) + -10.9314\,(9) + 1.403025\,(4.16)$$

$$f\,28 = -3311.87 + 2.31528(525) + 2.100821(1350) + -7.15002\,(78) + -17.1793(9) + 1.756569\,(4.16)$$

$$f\,56 = -16679.3 + 9.836197(525) + 9.465922\,(1350) + -12.3691(78) + -29.7428\,(9) + 3.751478\,(4.16)$$

$$f\,112 = -6070.75 + 3.622564\,FA + 3.462695(1350) + -4.60904\,(78) + -11.7803\,(9) + 0.849671\,(4.16)$$

$$f\ 180 = -3724.56 + 1.978976\ (525) + 1.969591\ CA + 0.818243(78) + 0.115372\ (9) + 0.87223\ (4.16)$$

S4 (Rock sand)

$$f\ 7 = -5024.48 + 2.87616\ (788) + 2.809214\ (1087) + -2.56299\ (67) + -6.13269\ (17) + 0.638083\ (2.06)$$

$$f14 = -8030.2 + 4.631307\ (788) + 4.498898(1087) + -4.50006\ (67) + -10.9314\ (17) + 1.403025\ (2.06)$$

$$f\ 28 = -3311.87 + 2.31528(788) + 2.100821(1087) + -7.15002\ (67) + -17.1793\ (17) + 1.756569\ (2.06)$$

$$f\ 56 = -16679.3 + 9.836197(788) + 9.465922\ (1087) + -12.3691(67) + -29.7428\ (17) + 3.751478\ (2.06)$$

$$f\ 112 = -6070.75 + 3.622564\ (788) + 3.462695(1087) + -4.60904\ (67) + -11.7803\ (17) + 0.849671\ (2.06)$$

$$f\ 180 = -3724.56 + 1.978976\ (788) + 1.969591\ (1087) + 0.818243(67) + 0.115372(17) + 0.87223\ (2.06)$$

S5 (Machakos river sand)

$$f\ 7 = -5024.48 + 2.87616\ (656) + 2.809214\ (1218) + -2.56299\ (80) + -6.13269\ (10) + 0.638083\ (6.56)$$

$$f14 = -8030.2 + 4.631307\ (656) + 4.498898\ (1218) + -4.50006\ (80) + -10.9314\ (10) + 1.403025\ (6.56)$$

$$f\ 28 = -3311.87 + 2.31528(656) + 2.100821(1218) + -7.15002\ (80) + -17.1793\ (10) + 1.756569\ (6.56)$$

$$f\ 56 = -16679.3 + 9.836197(656) + 9.465922\ (1218) + -12.3691(80) + -29.7428\ (10) + 3.751478\ (6.56)$$

$$f\ 112 = -6070.75 + 3.622564\ (656) + 3.462695(1218) + -4.60904\ (80) + -11.7803\ (10) + 0.849671\ (6.56)$$

$$f\ 180 = -3724.56 + 1.978976\ (656) + 1.969591\ (1218) + 0.818243\ (80) + 0.115372\ (10) + 0.87223\ (6.56)$$

S6 (Naivasha sand)

$$f\ 7 = -5024.48 + 2.87616\ (562) + 2.809214\ (1312) + -2.56299\ (69) + -6.13269\ (14) + 0.638083\ (9.57)$$

$$f 14 = -8030.2 + 4.631307\ (562) + 4.498898\ (1312) + -4.50006\ (69) + -10.9314\ (14) + 1.403025\ (9.57)$$

$$f\ 28 = -3311.87 + 2.31528(562) + 2.100821C(1312) + -7.15002\ (69) + -17.1793\ (14) + 1.756569\ (9.57)$$

$$f\ 56 = -16679.3 + 9.836197(562) + 9.465922(1312) + -12.36915(69) + -29.7428\ (14) + 3.751478\ (9.57)$$

$$f\ 112 = -6070.75 + 3.622564(562) + 3.462695(1312) + -4.60904\ (69) + -11.7803\ (14) + 0.849671(9.57)$$

$$f\ 180 = -3724.56 + 1.978976\ (562) + 1.969591\ (1312) + 0.818243\ (69) + 0.115372\ (14) + 0.87223\ (9.57)$$

S7 (Quarry dust)

$$f\ 7 = -5024.48 + 2.87616\ (788) + 2.809214\ (1087) + -2.56299\ (65) + -6.13269\ (19) + 0.638083\ (11.9)$$

$$f 14 = -8030.2 + 4.631307\ (788) + 4.498898\ (1087) + -4.50006\ (65) + -10.9314\ (19) + 1.403025\ (11.9)$$

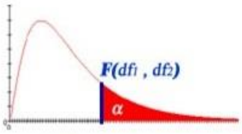
$$f\ 28 = -3311.87 + 2.31528(788) + 2.100821(1087) + -7.15002\ (65) + -17.1793\ (19) + 1.756569(11.9)$$

$$f\ 56 = -16679.3 + 9.836197(788) + 9.465922\ (1087) + -12.3691(65) + -29.7428\ (19) + 3.751478\ (11.9)$$

$$f\ 112 = -6070.75 + 3.622564\ (788) + 3.462695(1087) + -4.60904\ (65) + -11.7803(19) + 0.849671\ (11.9)$$

$$f\ 180 = -3724.56 + 1.978976\ (788) + 1.969591(1087) + 0.818243\ (65) + 0.115372\ (19) + 0.87223\ (11.9)$$

Table 0-24 f- test table



F Table for α = 0.05

/	df_1=1	2	3	4	5	6	7	8	9	10	12	15	20	24	30	40	60	120	∞
df_2=2	18.51	19.00	19.16	19.25	19.30	19.33	19.35	19.37	19.38	19.40	19.41	19.43	19.45	19.45	19.46	19.47	19.48	19.49	19.50
3	10.13	9.55	9.28	9.12	9.01	8.94	8.89	8.85	8.81	8.79	8.74	8.70	8.66	8.64	8.62	8.59	8.57	8.55	8.53
4	7.71	6.94	6.59	6.39	6.26	6.16	6.09	6.04	6.00	5.96	5.91	5.86	5.80	5.77	5.75	5.72	5.69	5.66	5.63
5	6.61	5.79	5.41	5.19	5.05	4.95	4.88	4.82	4.77	4.74	4.68	4.62	4.56	4.53	4.50	4.46	4.43	4.40	4.37
6	5.99	5.14	4.76	4.53	4.39	4.28	4.21	4.15	4.10	4.06	4.00	3.94	3.87	3.84	3.81	3.77	3.74	3.70	3.67
7	5.59	4.74	4.35	4.12	3.97	3.87	3.79	3.73	3.68	3.64	3.57	3.51	3.44	3.41	3.38	3.34	3.30	3.27	3.23
8	5.32	4.46	4.07	3.84	3.69	3.58	3.50	3.44	3.39	3.35	3.28	3.22	3.15	3.12	3.08	3.04	3.01	2.97	2.93
9	5.12	4.26	3.86	3.63	3.48	3.37	3.29	3.23	3.18	3.14	3.07	3.01	2.94	2.90	2.86	2.83	2.79	2.75	2.71
10	4.96	4.10	3.71	3.48	3.33	3.22	3.14	3.07	3.02	2.98	2.91	2.85	2.77	2.74	2.70	2.66	2.62	2.58	2.54
11	4.84	3.98	3.59	3.36	3.20	3.09	3.01	2.95	2.90	2.85	2.79	2.72	2.65	2.61	2.57	2.53	2.49	2.45	2.40
12	4.75	3.89	3.49	3.26	3.11	3.00	2.91	2.85	2.80	2.75	2.69	2.62	2.54	2.51	2.47	2.43	2.38	2.34	2.30
13	4.67	3.81	3.41	3.18	3.03	2.92	2.83	2.77	2.71	2.67	2.60	2.53	2.46	2.42	2.38	2.34	2.30	2.25	2.21
14	4.60	3.74	3.34	3.11	2.96	2.85	2.76	2.70	2.65	2.60	2.53	2.46	2.39	2.35	2.31	2.27	2.22	2.18	2.13
15	4.54	3.68	3.29	3.06	2.90	2.79	2.71	2.64	2.59	2.54	2.48	2.40	2.33	2.29	2.25	2.20	2.16	2.11	2.07
16	4.49	3.63	3.24	3.01	2.85	2.74	2.66	2.59	2.54	2.49	2.42	2.35	2.28	2.24	2.19	2.15	2.11	2.06	2.01
17	4.45	3.59	3.20	2.96	2.81	2.70	2.61	2.55	2.49	2.45	2.38	2.31	2.23	2.19	2.15	2.10	2.06	2.01	1.96
18	4.41	3.55	3.16	2.93	2.77	2.66	2.58	2.51	2.46	2.41	2.34	2.27	2.19	2.15	2.11	2.06	2.02	1.97	1.92
19	4.38	3.52	3.13	2.90	2.74	2.63	2.54	2.48	2.42	2.38	2.31	2.23	2.16	2.11	2.07	2.03	1.98	1.93	1.88
20	4.35	3.49	3.10	2.87	2.71	2.60	2.51	2.45	2.39	2.35	2.28	2.20	2.12	2.08	2.04	1.99	1.95	1.90	1.84
21	4.32	3.47	3.07	2.84	2.68	2.57	2.49	2.42	2.37	2.32	2.25	2.18	2.10	2.05	2.01	1.96	1.92	1.87	1.81
22	4.30	3.44	3.05	2.82	2.66	2.55	2.46	2.40	2.34	2.30	2.23	2.15	2.07	2.03	1.98	1.94	1.89	1.84	1.78
23	4.28	3.42	3.03	2.80	2.64	2.53	2.44	2.37	2.32	2.27	2.20	2.13	2.05	2.01	1.96	1.91	1.86	1.81	1.76
24	4.26	3.40	3.01	2.78	2.62	2.51	2.42	2.36	2.30	2.25	2.18	2.11	2.03	1.98	1.94	1.89	1.84	1.79	1.73
25	4.24	3.39	2.99	2.76	2.60	2.49	2.40	2.34	2.28	2.24	2.16	2.09	2.01	1.96	1.92	1.87	1.82	1.77	1.71
26	4.23	3.37	2.98	2.74	2.59	2.47	2.39	2.32	2.27	2.22	2.15	2.07	1.99	1.95	1.90	1.85	1.80	1.75	1.69
27	4.21	3.35	2.96	2.73	2.57	2.46	2.37	2.31	2.25	2.20	2.13	2.06	1.97	1.93	1.88	1.84	1.79	1.73	1.67
28	4.20	3.34	2.95	2.71	2.56	2.45	2.36	2.29	2.24	2.19	2.12	2.04	1.96	1.91	1.87	1.82	1.77	1.71	1.65
29	4.18	3.33	2.93	2.70	2.55	2.43	2.35	2.28	2.22	2.18	2.10	2.03	1.94	1.90	1.85	1.81	1.75	1.70	1.64
30	4.17	3.32	2.92	2.69	2.53	2.42	2.33	2.27	2.21	2.16	2.09	2.01	1.93	1.89	1.84	1.79	1.74	1.68	1.62
40	4.08	3.23	2.84	2.61	2.45	2.34	2.25	2.18	2.12	2.08	2.00	1.92	1.84	1.79	1.74	1.69	1.64	1.58	1.51
60	4.00	3.15	2.76	2.53	2.37	2.25	2.17	2.10	2.04	1.99	1.92	1.84	1.75	1.70	1.65	1.59	1.53	1.47	1.39
120	3.92	3.07	2.68	2.45	2.29	2.18	2.09	2.02	1.96	1.91	1.83	1.75	1.66	1.61	1.55	1.50	1.43	1.35	1.25
∞	3.84	3.00	2.60	2.37	2.21	2.10	2.01	1.94	1.88	1.83	1.75	1.67	1.57	1.52	1.46	1.39	1.32	1.22	1.00