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Effect Of Mixing Methods on the Rheology and Hardened Properties of Concrete with Low Water-Binder Ratio

MSc Thesis

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A thesis submitted in partial fulfilment of the requirements for the award of the Degree of Master of Science in Civil Engineering (Structural Engineering) of the University of Nairobi

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DECLARATION AND APPROVAL

This thesis is my original work. I also affirm that to the best of my knowledge; this has not been presented for a degree in any other university.

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DEDICATION

I dedicate this research to my dear wife, Sarah, whose persistent encouragement, and loving support culminated into this great achievement. Together with our children, they gave me easy moments during my study, while enduring long durations alone.

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ABBREVIATIONS & ACRONYMS

Item	**Meaning**
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
BCA	Building and Construction Authority
BS	British Standard
EN	European Standards (European Norm)
FM	Fineness Modulus
HPC	High Performance Concrete
HSC	High Strength Concrete
IS	Indian Standard
KEBS	Kenya Bureau of Standards
KS	Kenya Standards
PCA	Portland Cement Association
PMC	Paste Mortar Concrete

ABSTRACT

This thesis presents a review of conventional methods outlined in some existing design codes to assess their suitability in preparation of concrete with low water-binder ratio. The amount of water used in concrete mixing is often reduced to a minimum required to hydrate the cementing paste, which increases its strength and durability. Workability is enhanced by addition of a plasticizing admixture. Any loss of moisture during mixing can result in incomplete hydration of the paste and loss of strength. Concrete mixing methods based on three codes namely American Concrete Institute (ACI), British Standard (BS) and Indian Standard (IS) were considered. An additional method of preparing a cement paste followed by aggregates, referred to as Paste Mortar Aggregate (PMC) was also included in the study. The sequences of charging the mixer with individual components of concrete were systematically varied in accordance with the guidelines provided in the four methods. On the other hand, the effectiveness of active (forced action) and passive (free fall) mixing was investigated using a paddle mixer and a rotating drum mixer, respectively.

The Results obtained show that PMC mixing method produced concrete with a slump of 140mm signifying better workability than other methods with the BS method having the lowest slump of 35mm. Similarly, PMC mixing method produced concrete with the highest compressive strength of 65 MPa at day 28 compared to IS (52MPa), ACI (52MPa) and BS-(42MPa). Overall, the BS method had the lowest workability, strength, and durability results for concrete prepared using both active and passive mixers. Active mixing produced concrete with high ultimate strength, better homogeneity, and high durability than passive mixing. For instance, on day 90, PMC results for active mixer were almost 30% higher than those of passive mixer for all mixing methods. The study findings show that there is significant influence of mixing methods and particularly, the sequence of charging mixers, on both plastic and hardened characteristics of concrete with low water-binder ratio.

CHAPTER ONE

1. Introduction

1.1 Background of the Study

The main purpose of mixing concrete is to attain a uniform blend of all constituent materials. Essentially components of any concrete mix may be the same, but the relative proportioning of the components and mixing method that is applied during preparation makes the difference in its performance properties. Proper mixing of materials is particularly of great importance for concrete with low water-binder ratio in order to achieve the workability, strength and durability requirements as well as protection of steel from rust (Chang & Peng, 2001). Concrete with low water-binder ratio may be described as any concrete with special combination of performance and consistency requirements (ACI CT-13, 2013). Such concrete cannot always be attained routinely with conventional ingredients and normal mixing, placing, as well as curing procedures. It's application is primarily in structures which require prolonged service life such as oil drilling stands, bridges with wide spans and any structure with wide spaces between columns (Ephraim & Ode, 2017). Many products are now available for use to improve the properties of concrete with low water-binder ratio due to advancement in technology. However, mix proportions for concrete with low water-binder ratio are dictated by other dynamics, such as performance properties required, locally available materials, experience of the personnel involved and overall cost (Nuraan, 2017). Investigations done on methods of concrete mixing from different countries concluded that in order to reduce the amount of water and cement required for conventional concrete, the binder must be mixed first followed by addition of aggregate. This process has led to an increase in strength of between 10 to 20% and shows the impact of an optimized mixing method on the overall characteristics of concrete (Amr, 2015; Nuraan, 2017).

According to Rana, Tiwari, & Srivastava (2016) the efficiency of mixing coupled with the type of mixer used also largely influences homogeneity and consistency of concrete. Various constituents of concrete with low water-binder ratio can be mixed by either using hands or mechanical methods. In many countries, factors such as nearness to the batching plant, proposed construction schedule and the amount of concrete required greatly influence the choice of mixing method for the project. Ferraris (2001) investigated the effects of both passive and active mixers on the strength characteristics of concrete and concluded that the type and configuration of mixer, mixing cycle, mixing duration, loading method and energy of mixing concrete constituents directly affect various strength characteristics of concrete.

There are various well-defined traditional mix design procedures for producing concrete mixes. The common methods available in conventional design codes include Indian Standard (IS), American Concrete Institute (ACI), and British Standard (BS) method which give specific indications of the mixing methods to be adopted to achieve the desired concrete strengths. (Chang, P. K., & Peng, Y. N., 2001). This study investigates effects of mixing methods outlined in the three codes on the properties of concrete with low water-binder ratio. Additionally, a method involving progressively making paste followed by aggregate recommended by Mass, G. R. (1989) also known as Paste-mortar-concrete (PMC) was used.

1.2 Problem Statement

Of major importance in production of concrete is the mixing of various constituents particularly in optimizing the rheological parameters at any given target strength (Aminul, 2011). Compared to normal concrete, concrete with low water-binder ratio is a multi-constituent scheme comprising of aggregates, cement, additives, and water. Proper mixing of these constituents is therefore critical in achieving the desired characteristics either in fresh or hardened state. The main problems encountered during the preparation of concrete with low water-binder ratio include reduced performance due to loss of workability caused by reduced mixing water to achieve the required high strength and durability. Introduction of appropriate admixtures to address this problem may either improve the quality of concrete or worsen the situation completely depending on the stage of addition and method of mixing (A. Rasheed, et al, 2018).

Whereas existing conventional design codes and standards provide sequences of mixing various materials for preparation of concrete there is little literature available regarding guidelines of mixing constituents of concrete with low water-binder ratio. Additionally, from industry experience, many users of concrete with low water-binder ratio lack the expertise to properly mix its materials leading to poor quality concrete in construction projects. To fill this gap, this research investigated the effects of four concrete mixing methods and passive versus active mixing on the rheology and hardened properties of concrete with low water/binder ratio.

1.3 Research Objectives

1.3.1 Overall Objective

To assess effects of mixing methods and mixer types on plastic and hardened properties of concrete with low water-binder ratio.

1.3.2 Specific Objectives

i. To evaluate the effectiveness of various mixing methods on plastic properties.

ii. To evaluate the effects of various mixing methods on strength properties.

iii. To establish the effects of various mixing methods on durability properties.

iv. To compare effects of passive and active mixing on the rheology, strength, and durability characteristics.

1.4 Justification

There is merit in adopting concrete with low water-binder ratio in order to produce durable structures with low maintenance and life cycle costs (Koteng', 2013). Of major importance in the production of concrete with low water-binder ratio is the order of mixing various concrete constituents particularly in optimizing consolidation and strength related characteristics. The aim of this research is to investigate the effectiveness of different mixing methods in producing concrete with low water-binder ratio and further to investigate the effects of passive and forced mixing methods. Most of the available previous research concerns the mixing of normal concrete as opposed to low water/binder ratio concrete. Though opinion on optimum charging sequence of concrete constituents into mixers during mixing varies, there is general consensus among many authors that mixing methods affect various properties of the resulting concrete (Chang and Peng, 2001) The most preferred method of mixing concrete using large mixers is by adding layers of coarse aggregate, followed by cement and then fine aggregate. Generally, there is limited research done on concrete with low water-binder ratio mixing using traditional concrete design codes such as ACI, BS and IS. Some studies such as Aguwa (2010), investigated the relationship between mixing concrete by hand and its compressive strength through measurement of the number of times concrete is turned over in a mixing tray. The conclusion that concretes strength increases with increase in the number of turnings was however limited to only small-scale production of concrete and may not be applicable to modern large-scale concrete production methods. Through experiment, this study highlights effects of mixing concrete with low water-binder ratio materials using different methods with specific emphasis on the sequence of charging the mixer and the mixing process.

1.5 Scope and Limitations of the Study

The study evaluated effects of mixing methods on the plastic and hardened properties of concrete with low water-binder ratio. Three mixing methods based on traditional design codes namely Indian Standard (IS), American Concrete Institute (ACI), and British Standard (BS) Codes. A fourth method by the name Paste-Mortar Concrete (PMC) based on recommendations by Mass, (1989) was also used. The key parameter considered for each method was the sequence of adding various concrete materials into the mixer i.e. cement, fine and coarse aggregates, water and superplasticizer. Other parameters such as mixing time and mixing energy were outside the scope of this study. Properties investigated were workability in the fresh state which was tested using slump and flow table tests, and hardened properties such as density, water absorption, abrasion resistance, compressive and split tensile strengths. In this study a concrete strength of 60 MPa at 28 days was targeted based on recommendations in literature and the fact that concrete with low water binder ratio is synonymous with high to ultra-high strengths. Whereas higher strengths could have been achieved, they were avoided due to various risks including cracking caused by high early age temperature rise. (Gidion Turuallo, & Marios N. Soutsos, 2015). The effect of active mixing was investigated using a paddle mixer and the effect of passive mixing was investigated using a rotating drum mixer. Effort was made during mixing to keep factors such as mixing time, mixer power and size of the batch constant for each mixing method to ensure consistency for all specimens.

Tests were carried out using EN CEM IV/B-P 32.5R cement at a water/binder ratio of 0.3 and a design workability of 55mm. Aggregates consisted of river sand and crushed stone of maximum size 12.7 mm. The super-plasticizing admixture was polycarboxylate based.

CHAPTER TWO

2. Literature Review

2.1 Description of concrete with low water-binder ratio

It is common knowledge that when the water/binder ratio of concrete is reduced, the strength is increased subject to the concrete being capable of good consolidation and there being enough water for the complete hydration of the binder. Concrete with low water/binder ratio is a necessary requirement in the production of high performance concrete with the highest durability characteristics designed to meet special requirements for a particular application. (ACI 318, 2005; ACI CT-13, 2013). Water/binder ratio in concrete refers to the proportion of the weight of water to the weight of the binding material. For example, a 0.3 water/binder ratio indicates that for each 100 kg of binder content in the concrete, 30 kg of water must be added during mixing. The binder is made up of cement mixed together with a range of additives such as blast furnace slag, silica fume and fly ash (Sephaku Cement, 2018). In this research, the binder used consisted of Portland cement intermixed with natural pozzolana.

Depending on its use, low water/ binder ratio concrete is prepared using other ingredients such as fine and coarse aggregates, and plasticizers. Mixing of these ingredients, to a great extent, is not only a science but also an art but the most consideration is to accord the binder greatest opportunity to access the water. Depending on the mix design, too much or too little water can have serious and disparaging effect on the strength and durability of low water/binder ratio concrete. (Scezy and Mohler, 2009). For instance, limited access to water interrupts the chemical reactions that take place during early hydration with a negative impact on particles bond during curing. Although there are limitations to how low water/binder ratio should be, 0.28 to 0.30 are recommended for full hydration of the binder which is synonymous with high strength and durability (Sephaku Cement, 2018).

2.2 Properties of Low water/binder ratio concrete

Bickley and Mitchell (2001) observe that it is wrong to consider mechanical properties of low water/binder ratio concrete as similar to those of high strength concrete (HSC). Additional properties of concrete with low water/binder ratio include workability, curing, strength, ductility and creep. Other important properties include toughness, volume stability, early age strength and long life in severe environments (Rana et al., 2016). Table 2.2 gives a summary of the criteria used in specifying various key properties.

Table 2.2: Criteria used to specify properties of concrete with low water binder/ratio (Bickley & Mitchel, 2001).

Property	Criteria that may be specified
High strength	70 and 140 MPa at 28 and 91 days respectively
High-early compressive strength	20 and 28 MPa at 3 to 12 hours and 1 to 3 days respectively
High-early flexural strength	2 and 4 MPa at 3 to 12 hours or 1 to 3 days respectively
Abrasion resistance	0 to 1 mm depth of wear
Low permeability	500 to 2000 coulombs
Chloride penetration	Less than 0.07% Cl at 6 months
Low absorption	2% to 5%
Resistance to chemical attack	No deterioration after 1 year
High modulus of elasticity	More than 40 GPa

2.2.1 Workability

Concrete workability is the overall measure of effective internal effort needed for complete compaction and ease of handling freshly mixed concrete minimizing segregation during handling. (Gordana et al., 2010). In preparing low water/binder ratio concrete, workability is influenced by factors such as water/binder ratio, size of aggregates and mixing water quantity which determine the overall consistency, flowability and stability during placement.

Concrete workability, method of placement and consolidation type are key considerations in choosing a suitable mixing method. For instance, self-consolidating low water/binder ratio concrete with unique high workability requirements requires special mixing method for rigorous construction schedule (Scezy and Mohler, 2009). The most common test used to determine workability is slump test whose procedure is detailed in ASTM C143, (1990). The concrete slump testing apparatus consist of a standard cone of 100mm upper diameter, 200mm lower diameter, and of height 300mm. Each cone is filled with concrete samples in three stages with each stage tamped 25 times with a standard tamping rod. The mold is then carefully lifted upwards and the difference in height between the top of the cone and top of highest point of concrete is recorded as slump. BS EN 206-1:2000 categorizes shape of concrete slump as either true, shear or collapse. The test is also widely used to assess consistency of low water/binder ratio concrete with a low slump indicating stiff consistency. Concrete with poor consistency is characterized by excessive drying shrinkage, segregation, and bleeding. ASTM C143 (1990) states that proportioning of ingredients, batching, and mixing of low water/binder ratio concrete requires correct specification to ensure accuracy in dispersion and uniformity of structural form throughout the casting process. As a result of using low water-binder ratio and water reducing plasticizers in preparing low water/binder ratio concrete, the risk of poor performance caused by excessive mixing water is low. However, it is common to have poorly consolidated concrete, which is also porous, weak and with deprived durability. This risk is minimized by using properly graded aggregate which are easier to consolidate during placing either through mechanical vibration or free physical settling due to self-weight (Kosmatka et al, 2003).

To enhance workability, Hoy (1998) recommends a concrete mixing approach known as a two-stage mixing process where a cohesive binder of fine particles is first mixed followed by aggregate in the later stages of mixing. The procedure of charging the mixer plays a key role in developing a homogenous concrete. A small change in mix procedure may affect the rheological behavior of freshly mixed concrete. Dry aggregates have the capacity to absorb mixing water during the initial stages of loading materials in the mixer. This can lead to lower workability since less quantity of mixing water is available for providing lubrication per unit surface area of aggregate and hence restraining mobility of particles (Ahmed, 2002). Adding aggregates after mixing cement and superplasticizer to form a uniform paste minimizes loss of free water which enhances concrete fluidity. Superplasticizer aids in the dispersion of concrete constituents with fine cement particles absorbing mixing water during the initial stages of mixing and later forming a lubrication zone around the aggregates in the later stages of mixing resulting for a more workable mix. (Abibasheer, 2015).

2.2.2 Curing

Concrete with low water/binder ratio requires proper curing after hardening to achieve the desired physical properties. Hardening and hydration of concrete requires sufficient moisture which contributes to strength gain which is perhaps the most important property of concrete. Consolidation of concrete with low water/binder ratio takes place within 3 to 12 hours of initial setting during which significant high-early compressive strength of up to 28 MPa is achieved (Bickley & Mitchel, 2001). Low water/binder ratio concrete setting, which is the crystallization of cement hydration products is different from hardening which can be described as development of quantifiable strength. The effects of both processes, however, are noticeable at the end of the induction phase when the concentration of ions has reached a crucial state. (Panasyuk, 2014). Ultimately, hardness and strength of HPC is also imparted by tricalcium aluminate, formed by the reaction of calcium oxide and aluminium oxide (KS EAS 18: 2001, 2005, Okumu et al., 2017). Pozzolanic materials such as GGBFS, FA, SF, natural and organic pozzolans which are often used to partially replace Portland cement with technical and environmental advantages, influence the curing process of concrete. The reactive silicates and aluminates in the pozzolans react with Ca(OH)2 to produce more cementitious C-S-H, C-A-H and C-A-S-H phases. Workability enhancing admixtures are increasingly being used to improve the performance of concrete in the fresh and hardened state (Ferraris, Chiara, 1999). Low water/binder ratio concrete prepared using a blended cement has been found to have low bleeding properties (Kosmatka et al, 2003). Since specific gravity of water is the lowest compared to other ingredients, it moves upward to form a layer on the surface of fresh concrete upon placement in a process known as bleeding or water-gain. Evaporation of bled water may lower the surface of initial placed surface through settlement shrinkage. Banfill (2003), while studying rheology of concrete, concluded that bleeding is related to the flow and deformation of particles in suspension as well as sedimentation which is a factor of shape, size and concentration of the particles. Bleeding in low water/binder ratio concrete is therefore reduced by the good particle bonds formed by use of fine cementitious materials such as fly-ash, slag and silica fumes in blended cement.

2.2.3 Strength

In mixing low water/binder ratio concrete, strength gives an indication of quality and is directly related to the composition and distribution of cement paste which affects the physical structure and uniformity of concrete mix. Poor concrete strength is easily detectable by the presence of flaws such as honeycombs, pores, and discontinuities on the surface of hardened concrete (Neville and Brooks, 2010). Compressive strength of low water/binder ratio concrete ranges from 60 to 140 MPa measured from day 28 of casting (Bickley & Mitchel, 2001). Low water/binder ratio concrete can achieve high-early compressive strength of up to 28 MPa within 48 hours of casting. This strength is measured as the maximum resistance to axial loading and may be used to give an indication of the degree to which hydration has happened, the condition of curing and the effect of environmental conditions on curing (Abrams, 1918).

Statistically, compressive strength of concrete is considered to be approximately eight times its direct flexural strength. Another estimate of flexural strength is considered to be 0.45 to 0.68 times the square root of its compressive strength in MPa (Neville and Brooks, 2010). Early flexural strength of low water/binder ratio concrete is estimated to be 4 MPa within 48 hours of casting (Bickley & Mitchel, 2001). Strength of low water/binder ratio concrete is closely related to its density which is dependent on the type and size of aggregates used in mixing, air content allowed in the concrete, water content and cementitious materials. For concrete that is air cured, the weight of dry sample equals the weight of the fresh sample ingredients minus the weight of mixing water evaporates into the air. Part of the mixing water is chemically used during cement hydration adding to the weight of hardened concrete samples. However, some of the water May remain tightly held in pores and capillaries without evaporating under normal conditions hence making the concrete to be denser in the early stages of curing. (Kosmatka et al, 2003).

2.2.4 Durability

Concrete durability can be defined as its ability to resist abrasion and weathering action and also endure chemical attacks within its desired functional duration (Shetty, 2005). Durability of concrete has recently attracted higher importance in modern building construction projects. Concrete structures such as pavements and hydraulic structures are prone to abrasion or wear with prolonged usage due to friction and impact of sand, silt, and rocks during operation of such structures. Low water/binder ratio concrete has been found to be the more suitable for such structures due to its strength and abrasion resistance (Bickley & Mitchel, 2001). According to Liu, (1981), replacing part of the cement in concrete with blast furnace slag, improves workability even without using water reducing agents. The resulting low water/binder ratio concrete with blast furnace slag has a higher strength at old age and better durability, enhanced density, stronger cement-aggregate bondage, and excellent protection of reinforcement against corrosion.

Resistance to abrasion is closely related to compressive strength and generally, a stronger concrete such as low water/binder ratio concrete is expected to have a higher abrasion resistance. This property is further supported by careful selection of aggregate and curing requirements for low water/binder ratio concrete (Kosmatka et al, 2011). Liu, (1981) investigated the impact of water/binder ratio on strength and durability of concrete. He concluded that reducing water-binder ratio from 0.42 to 0.28 resulted in improvement of abrasion resistance of concrete at all ages. A water/binder ratio of 0.35 gave the best abrasion erosion resistance at 3 hours-time of testing. American Society for Testing and Materials (ASTM) has developed different abrasion testing methods as follows:

- Test method for abrasion resistance of concrete by sand blasting (ASTM C 418)
- Test method for obtaining and testing drilled cores and sawed beams of concrete (ASTM C 944)
- Test method for abrasion resistance of horizontal concrete surfaces (ASTM C 779)
- Test method for abrasion resistance of concrete – Underwater method (ASTM C 1138)

The most commonly used test method for evaluating resistance of concrete subjected to abrasive action is ASTM C 779 using a revolving disk machine which is easily adaptable for laboratory testing. (Kumar & Sharma (2014). BS EN 1338:2003, BS EN 1339:2003, IS 1237:2012 and IS 15658:2006 gives standardized procedures for evaluating abrasive loading for concrete pavements. According to Liu, T.C (1981), for low water binder ratio concrete, the loss in volume after 16 cycles of the grinding disc, at a speed of 30 revolutions per minute should be less than or equal to:

a. 18000 mm3/5000 mm2 - In areas subject to very heavy pedestrian and vehicular traffic and

b. 20000 mm3/5000 mm2 - In areas subject to normal pedestrian and vehicle use.

The selection and mixing of ingredients selection also play a role in permeability property of low water/binder ratio concrete. Concrete permeability is generally the rate at which water particles flow in an unsaturated porous concrete due to differences in pressure produced by capillary action measured as a percentage of the mass of water to concrete. Bickley & Mitchel (2001) reported that low water/binder ratio concrete has an absorption rate of between 2 to 5 % which is considerably low compared to normal concrete. Other important durability properties of low water/binder ratio concrete include resistance to chemical attack, volume stability and long life in severe environments. (Bickley & Mitchel, 2001).

2.3 Materials used in production of low water/binder ratio concrete

2.3.1 Aggregates

Diawara and Ghafoori (2011) state that mixing, workability, and strength of low water/binder ratio concrete are significantly influenced by the material characteristics of aggregates. These are grouped in terms of particle size and distribution, and particle nature. In addition, Zhang, Han, Ng, & Wang (2017) proved through laboratory tests that depending on the shape of the aggregate, reduced water/cement ratio and the design slump may be achieved by use of less water during mixing. Similarly, Ke-Ru, Chen, Yao, & Zhang (2001) established that the compressive strength and elastic modulus of low water/binder ratio concrete are directly related to mineralogical characteristics of aggregates used. It is important for the aggregate used in manufacturing low water/binder ratio concrete to be fine grained, unaltered and strong. On the other hand, Choudhary, Bajaj, & Sharma (2014) observed that the larger the aggregates used in making low water/binder ratio concrete, the less the specific surface area and weaker the aggregate-paste bond strength ultimately leading to reduced compressive strength of concrete. They further reported that during mixing, care should be taken not to break down fine aggregates as this considerably reduces concrete workability. Other literature show preference for relatively small aggregate sizes ranging from 10 to 15 mm in the production of low water/binder ratio concrete (Nuraan, 2017). Cizer, Balen, & Gemert (2007) investigated the relationship between low water/binder ratio concrete properties and grading of coarse and fine aggregates. They observed that the maximum size of aggregate used in making low water/binder ratio concrete relies on several factors like the physical properties of the structural member to be cast and the number and spacing of steel used in the member.

2.3.2 Cementing Materials

Compressive strength of concrete highly depends on the properties of the cement used. Different brands and types of cements with varying chemical compositions have different mechanical properties. Both chemical and mechanical properties of cement directly affect the quality of concrete produced (Muller, 2012). According to Okumu et al., (2017), the content and fineness of C_3A in cement affects the adsorption of superplasticizers used in making low water/binder ratio concrete. The main chemical components of cement responsible for early compressive strength development in concrete reaction include CaO, SiO_2, Al_2O_3 and Fe_2O_3 (Cizer et al., 2007).

2.3.3 Admixtures

ACI defines admixtures as materials other than hydraulic cement, water, aggregates and supplementary cementing materials, which form part of concrete ingredients and are added to the batch during or before mixing (ACI CT-13, 2013). Ephraim & Ode, (2017) classified admixtures used in the production of low water/binder ratio concrete as either cementitious or pozzolanic. They also provide chemical composition and particle characteristics of each type of admixtures used in producing low water/binder ratio concrete. On the other hand, ASTM C 494-10 classifies admixtures used in concrete as follows:

Type A	Water-reducing
Type B	Retarding/delaying.
Type C	Quickening/Accelerating
Type D	Water-reducing/retarding
Type E	Water-reducing/accelerating
Type F	High-range water-reducing/super-plasticizing, and
Type G	High-range water-reducing/retarding/super-plasticizing /retarding

In addition to the above list, there are admixtures for other uses which include waterproofing, air detainment, and antiseptic action (Nevile, 2013). BS EN 934-2 (2009) allows variations of admixture dosages for various concrete mixes even though manufacturers may recommend dosage as percentages of cement mass. Overall, the standard recommends measurement of admixtures to within 5% of the specified manufacturer's recommendation during use. Great care is necessary in the sequence of feeding the mixer with admixture while preparing low water/binder ratio concrete because, inappropriate quantities can affect the setting and hardening of cement to a large extent. Cizer et al., (2007) indicated that water reducing admixtures can decrease water contents in a mix up to 10% while increasing air content by up to 1%. During mixing, addition of admixtures has to be done promptly and in timely manner. Delays in introducing admixtures into the mix may either enhance performance of concrete or increase retardation. Water reducing admixtures decrease water contents in concrete by up to 30% while at the same time increasing air void content by up to 1% (Laskar, 2011). In using admixtures and particularly for low water/binder ratio concrete, Neville (2011) emphasizes on the importance of understanding the specific effects of any admixture before use.

2.3.4 Water

For a good result, concrete should be mixed using clean water without any form of harmful substances to the concrete or reinforcement. According to Rana et al., (2016) harmful substances in mixing water may have negative effects on the setting time, volume stability and overall strength of concrete. The ASTM standard further prescribes a criterion for determining questionable water supplies and an additional criterion for accepting concrete mixing water from combined water supplies. Any potable water with the recommended concentrations of dissolved solids and which is natural, and drinkable may be used for mixing concrete. ASTM C1602 (2018) outlines the impacts of impurities in water on various properties of concrete as per Table 2.3.

Table 2.3: Impact of water impurities on concrete properties (PCA, 2017)

Mixing water impurity	Affected Concrete Property
Silt or suspended particles	Workability
High salt content, Sulfates	Admixture Compatibility
Alkalis, Chlorides, Algae, Sulfates	Durability
Sodium Iodate, Sodium Sulfide, Alkali Hydroxides, Salts of Zinc, Copper and Lead, Sugar	Setting time
Calcium/Magnesium Bicarbonate, Inorganic Acids, Oils, Industrial Waste, Seawater, Organic Acids, Borate, Arsenate, Sugar, Algae, Zinc, Copper and Lead	Strength

2.4 Conventional Concrete Mixing Methods

2.4.1 Indian Standard (IS) Method

In this method, dry mixing of ingredients with a quarter of mixing water takes place first, followed simultaneously by other materials (Zahradeen, 2017). IS 10262:2009, suggested a maximum water/cement ratio (w/c) of 0.45 which necessitates use of water reducing plasticizers during mixing to reduce the mix stiffness. In addition, the proportion of fine aggregate suggested by this method are relatively high and may affect the consistency of low water/binder ratio concrete. Khadiranaikar and Awati (2015) reviewed limitations of conventional mix designs and reported that the IS mix design method does not adjust the sand content even with significant adjustments of cement content in a typical mix. Literature on low water/binder ratio concrete however proposes a need to increase sand content in a concrete mix in which water-cement content has been adjusted or lowered by use of plasticizers. IS 456:00 (2000) recommends that mixing should be done in a mechanical mixer with the mixing continued uniformly until all the materials are distributed in the mixer. The resulting concrete mix should be consistent in color. The standard further recommends the following sequence of mixing:

- Cement and sand should be thoroughly mixed first in the mixer
- Fine and coarse aggregates are then added.
- Water and admixtures are then added and mixed together
- The mixing to continue until a uniform color is obtained throughout the mix.

IS 4926 (2003) gives a general description of batching various concrete materials as well as mixing time on ready mixed concrete while IS 4925 (2004) refers to concrete batching and mixing plants.

2.4.2 American Concrete Institute (ACI) method

American Concrete Institute Committee (ACI: 2000) recommends placement of mixing water and fine aggregates in the mixer first, followed by the other aggregates. This mix design method assumes that the characteristic strength of the concrete mix may be defined using the available amount of control during mixing and does not differentiate between different types of hydraulic cements or different types of aggregates (Amr, 2015). ACI 318 (2005), for instance indicates that the percentage of defects in the mix consistency is determined by the water content irrespective of the various proportions added at various stages during mixing. Wadud & Ahmad (2001) state that the ACI mix design method is purely founded on determining the content of coarse aggregate by considering dry coarse aggregate mass density and fineness modulus of fine aggregate, with a typical minimum water cement ratio of 0.3. With regard to the sequence for mixing concrete, ACI 363.2R (2011) notes that in order to increase the compressive strength of the resulting concrete, a paste of cement and water should be made before mixing with aggregate and other materials. Khadiranaikar and Awati (2015) conclude that since low water/binder ratio concretes often have strengths of between 60 to 70 MPa and water/cement ratio of below 0.3, the ACI method is best suited to produce low water/binder ratio concrete but with improvements on material selection and optimized mixing methods.

As a general principle, this method suggests a separate paste mixing approach where cement and water are mixed into a paste before combining with aggregates (ACI 304R-00, 2000). Experimentally, this approach has resulted into concrete of high compressive strength (Laskar, 2011). In ensuring that concrete will be properly mixed, this method emphasizes on the following sequence of mixing (ACI 304R-00, 2000).

- Placing approximately 10% of coarse aggregate and 1/4 to 1/3 of the mixing water in the mixer drum. This prevents materials such as sand and cement from packing in the drumhead.

- Addition of sand and cement (powdered admixtures to be added into the mixer at this stage)
- Addition of 2/3 to 3/4 of the water mixed with liquid chemical admixtures and the remaining coarse aggregate.
- Continue mixing and add the remaining 1/4 to 1/3 of the water just before discharge

2.4.3 British Standard (BS) Method

This method differentiates between crushed and uncrushed aggregate since the difference in the behavior is quite significant during mixing. (Adewole & Ajagbe, 2015). Khadiranaikar and Awati (2015) illustrated that the BS method permits usage of fine aggregate composed of almost 50% of relatively small particles (less than 300-micron). This large number of small particles tend to reduce workability of low water/binder ratio concrete during mixing (Meddah, Salim & Belâabes, 2010). For drum mixing using soaked aggregates, BS 1881-125 (1986) specifies the following mixing sequence:

- Addition of about half the coarse aggregate into the mixer
- Addition of all of the fine aggregates follows next,
- Cement and any powder additives such as ground granulated blast furnace slag, pulverized-fuel ash, pigments are added
- Addition of the remaining coarse aggregate followed by all the mixer water
- Mixing continued after all the materials have been added for at least 3 minutes before discharge (BS 1881-125, 1986).

This standard recommends mixing of concrete in ambient temperature of 20 +/- 5°C and relative humidity of not less than 50%. The suggested w/c of 0.35 by the BS method presents a considerable challenge in the production of low water/binder ratio concrete (Ephraim and Ode, 2017). In addition, the standard shows a relationship of water/cement ratio and 28-day compressive strength of up to 58 MPa only. To address these limitations, BS 1881–125, (2013) suggested an improved mixing sequence of concrete as follows for both pan and drum mixers:

- Placement of half of the coarse aggregate followed by fine aggregate into the mixer.
- Addition of the remaining coarse aggregate by spreading it evenly over the pan and then starting the mixer to run for between 15 to 30s.
- Addition of half of the mixing water and mix for a total of 2 to 3 min.
- Mixing is stopped and the contents covered for between 5 to 15 min.
- Spreading cement and any powder admixture in layers over the mixed aggregate for about 30s.
- Addition of the remaining mixing water and additives. Mixing of all the materials continued for 2 min but not exceeding 3 min ensuring proper uniformity.

2.4.4 American Standard for Testing Materials (ASTM) Method

ASTM (1994)-Part A and ASTM (1998)-Part C, have provided guidelines for standardized concrete mixing using the following sequence of charging mixers.

- Part of the mixing water and both fine and coarse aggregates are added into the mixer and mixed first.
- Cement is then added and mixing continued
- The remaining part of the mixing water is added and mixing continued
- Lastly, liquid admixtures are added at this last stage and mixing continued until the color of the entire mix is uniform

2.5 Mixer types

In defining the entire process of concrete mixing, Chang & Peng, (2001) observed that consideration should also be given to the mixer hardware. For instance, when mixing concrete with high quantities of aggregate and low water- binder ratio, the initial shear force may overwhelm the mixer blades making them to stop and manual help will be required to continue operation. On the other hand, mixing the binder before adding aggregate lubricates the coarse aggregates minimizing friction and enhancing mixing efficiency with reduced damages to the mixers. Depending on the design, most concrete mixers can be classified as either forced action mixers which actively use blades to mix concrete contents or free-fall mixers whose blades action is passive. Pan mixers, trough mixers and in some cases continuous mixers, are classified as forced action or active mixers. (Gunther, 1995). Pan mixers are made up of a stationary or rotating low profile cylinder with its blades rotating in the opposite direction. This mixer is suitable for laboratory testing works and has a significant advantage in rapidly mixing of dry concrete (ACI 304, 2000).

Mixer configurations may differ slightly although with common features such as mixing compartments. Pugmill mixers have cylindrical drums with horizontal rotating shafts while truck mixers feature inclined axis compartments which can discharge concrete through the front or rear faces (ACI 304, 2000). The discharge mechanism is different for both active and passive mixers depending on whether the drums are tilting or non-tilting. Blades in mixer drums from different manufacturers also vary with shape. Gunther (1995) reported that active mixers are more vigorous than passive mixers, resulting in more thoroughly mixed concrete within a given time due to enhanced intensity. The resulting concrete had better workability. The effectiveness of mixers is also influenced by the arrangement of blades with the main difference between passive and active mixers being the pattern of blade movement (Amr, 2015).

Incomplete mixing of concrete leads to concrete with poor distribution of materials. Free fall mixers have also been noted to allow a build-up of fine material on mixer walls over successive batches. On the other hand, in a forced action, this problem could be addressed by the opposite movement of blades which would help to discharge the concrete. Another weakness of a free-fall mixer is the likelihood of coarse aggregate segregating within the mixer resulting in an initial discharge of mortar followed by scarcely coated coarse aggregate due to incomplete dispersion of fine particles (Neville. 1994). The selection of a suitable mixer for low water/binder ratio concrete is majorly based on the consistency requirement of the concrete. It is important to consider expected possible variations in concrete workability during the mixing process and also the stage of adding superplasticizers in the mixer. Passive mixers may not generate the force required to sufficiently mix and maintain concrete fluidity (Martinek, 1995). Johansson (1971) indicated that an active mixer had a better homogenizing ability for concrete mixes with a high workability requirement while passive mixers were suitable for mixes with a low workability requirement. A decision should therefore be made on the most economical mixer type for making low water/binder ratio concrete between passive and active mixers to produce a uniform mix without damaging the blades.

2.6 Mixing sequence

Concrete mixing process is influenced by the order of introducing various constituents into the mixer. On the other hand, mixing sequence is often considered to incorporate the time, mixer type, rotation speed of the mixer and loading intervals of charging the mixers (Ferraris, 2001). Chang & Peng (2001) investigated the effect of loading sequences of different materials in preparation of low water/binder ratio concrete and concluded that a mixing process that enables additives to mix sufficiently before adding aggregates resulted into a more consistent mix.

Compared to normal concrete, Sayed-Ahmed, Sennah, & Monsif, (2016) describe low water/binder ratio concrete as a multi-constituent scheme comprising of aggregates, cement, additives, and water whose proper mixing is critical in achieving the desired characteristics either in fresh or hardened state. The method of loading materials into the batching plays a key role in blending the constituents together to achieve a homogeneous concrete mix (Hoy, 1998). Opinion on the optimum charging sequence of concrete materials in the mixer differs. Placing a part of the mixing water into the mixer first, followed by aggregate before adding cement can lower air content in the mix (Kosmatka et al, 2011). He suggested the addition of the remaining mixing water towards the end of mixing once aggregates and cement were thoroughly mixed. Murdock & Brook (1979) suggested the addition of cement, sand and coarse aggregate into the mixer at the same time claiming there is improvement in uniformity of the concrete produced. Neville (1995) differed slightly with this suggestion since macro homogeneity of the concrete solid particles could not be achieved from the start without adequate mixing water. He recommended addition of coarse aggregates with a portion of the mixing water to keep the drum walls clean and scour any concrete residue from previous batch. However, this mixing approach was found to be more suitable for large scale mixing. Most researchers tend to agree that addition of fine materials into the mixer first followed by mixing water and then coarse aggregate produces concrete with better characteristics. (Hoy, 1998), Gaynor and Mullarky, (1975) suggested that charging cement and aggregates should be done simultaneously into the mixer in a continuous flow to avoid packing of material, particularly sand and cement in the head of a truck mixer. This is followed by approximately 1/3 of the water charged to the mixer after all the solids have been added. This charging method was similar to a skip loading sequence proposed by the US Army Engineering Centre and School, (1992. The sequence involved depositing aggregate, cement, and sand into the skip in that order, and then discharging them into a mixer while the mixing water is put into the mixing chamber. Neville

(1995) also hinted that when fine materials were added before the solid particles, there was a chance of confining into corners of the mixer. The main disadvantage of mixing large coarse aggregates on their own is the likelihood of altering the grading structure. To address this problem, Tam et al., (2005) researched the effect of mixing methods on concrete microstructure using recycled aggregates. He suggested a two stage mixing method in which natural and recycled aggregates were mixed for one minute with half of mixing water, followed by cement. Mixing was continued for another 30 seconds, and half of the remaining water required was added and mixed for 2 minutes. The overall effect of this mixing sequence of adding mixing water at two separate times during mixing process produced a concrete labeled "sand enveloped with cement concrete" which had improved features such as reduced bleeding.

On the other hand, Shetty (2005) proposed the following mixing sequence designed for improved efficiency in concrete production while maintaining its properties

- Introduce 25 percent of mixing water into the mixer drum to wet the drum and minimize any possibility of cement sticking on the sides of the drum.
- Place about half of coarse aggregate followed by half the quantity of fine aggregate in the drum.
- The full quantity of cement is then poured followed by the remaining quantity of coarse and fine aggregate strictly in this sequence. This further prevents the spattering of cement or blowing away of cement.
- The remaining 75 percent of water is later added to the drum marking the starting of mixing time. Superplasticizers are also added at this stage and mixing continued for one more minute for the plasticizing effect and proper dispersion to be fully achieved.

In order to prevent balling of cement particles, Irtishad et al., (2002) suggested that water should be added throughout the full period of charging the mixer. Dry materials should be continuously fed into the mixer at the same time. The mixer to be in good working condition, loaded appropriately and with good condition blades. Gaynor (1996) agreed with this mixer loading approach and observed that coarse aggregate and some of the mixing water should be placed prior to sand and cement during mixing to avoid head-packs. The importance of sprinkling water into the mixer before mixing is further emphasized by Neville and Brooks (2010). They suggest that a small amount of water should be fed first, followed by cement and all aggregates, fed uniformly and simultaneously into the mixer. The greater part of water is then fed during the same time as the coarse materials. To ensure the aggregate surface is sufficiently wetted, it is necessary to input the coarse aggregate just after the initial water has been fed. This is mainly applicable in cases of small laboratory pan mixer dealing with stiff mixes. The authors suggest that sand should be fed first, followed by part of the coarse aggregate, water, and cement, and finally the remainder of the coarse aggregate so as to break up any lumps. The question of when to add water and admixtures in the mixing sequence is equally important particularly for low water/binder ratio concrete preparation. There is general concurrence among many authors that the stage of adding water and admixtures plays a key role in ensuring rapid dispersion of concrete constituents. Fulton, (1969) advocated for adding water and admixtures in the last stage of mixing having added dry components first in the mixer. Murdock & Brooke (1979) on the other hand, suggested that water and admixtures should be added at the same time with the other concrete ingredients and mixed simultaneously. Bozarth (1967) differed with this and claimed mixing water should be added before the aggregates. Mass, (1989) agreed in principle that adding water and admixtures into the mixer before other ingredients improved the homogeneity and other rheological factors of the concrete produced

2.7 Literature review summary

Table 2.7 gives a summary of the literature reviewed.

Table 2.7: Literature Review Summary

Study title, author, and year	Study context and outcome	Remarks/ Knowledge gap
Influence of mixing techniques on properties of high-performance concrete, Ping-Kun Chang & Yaw-Nan Peng, 2001	- Explains the effect of admixtures on the flowing characteristics in accordance with the ACI mixing concept by establishing the relationship between superplasticizer concentration and the weight of water to solid ratio (w/s). - Results found that adding all the superplasticizers (SP) in the mixing water in one dose can ensure uniformly mixed low water/binder ratio concrete with good workability performance in both its fresh and hardened states.	The six methods of mixing concrete adopted in this study were all based on ACI concept. The study did not give attention to the effects of adding superplasticizer at various stages of mixing on hardened properties of low water/binder ratio concrete.
Effect of coarse aggregates type on the mechanical properties of high-performance concrete. Ke-Ru, Chen, Yao, and Zhang, 2001	- Investigated the influence of aggregate types, sizes, and shapes on the mechanical properties of concrete. - Concluded that mixing time affects rheological properties of concrete with prolonged mixing weakening the shear thickening of the resulting mix.	Study was limited to rheological properties of self-compacting concrete such as slump-flow and shear thickening behavior.
Advanced concrete technology processes,	- Investigated the 'half-wet system' of mixing concrete which involved	The author emphasized the operation of the mixer with

John and Ban, 2003	premixing cement, sand, and water to form a slurry which was then poured into a drum of already placed aggregate. Results indicated that the 'half-wet system' had significant effect on batching time and reduced wear and tear of mixer blades.	minimal attention to mixing methods used to produce concrete.
Avoiding uniformity problems in truck-mixed concrete, Gaynor, 1996,	- Studied the impact of concrete truck mixers on concrete properties such as uniformity and concluded that non-uniformity in truck-mixed concrete is caused by agglomerations of concrete materials inside the mixer, including head packs and cement balls. To remedy the non-uniformity problems, Gaynor suggested that one-fourth of the mixing water be added as the last ingredient and that the mixer rotate at 20 to 22 rpm from batching to pouring.	Study was limited to truck mixing of normal concrete. Mixing of concrete was not based on any standard mixing procedure.
Concrete Mixing Methods and Concrete Mixers: State of the Art. Journal of Research of the National Institute of Standards and Technology Ferraris, C.F., 2001	- Examined advantages and disadvantages of different mixing methods and various mixer types. Efficiency of the mixer was influenced by the order of introducing constituents into the mixer.	The study did not determine if concrete homogeneity is a direct factor of mixer characterization.

- Influence of mixing procedure and mixer type on fresh and hardened properties of concrete - Dils, De Schutter, Boel 2012	- Examined the use of different concrete mixers, mixing times, mixing speeds, different addition times of the superplasticizer and a different air pressure in the mixing pan to produce concrete. Established that those properties of fresh and hardened concrete can also be affected by the duration of the reduced pressure and that vacuum mixing can lead to improved concrete properties.	The study was limited to normal strength concrete.
Effect of hand mixing on the compressive strength of concrete. Aguwa, J.I., 2010	- The study revealed that compressive strengths of concrete mixed using hands substantially increased with increase in number of turnings but remained almost constant beyond four times of turning for all the ages tested concluding that a minimum of three turnings are required to produce concrete with satisfactory strength.	The study emphasized on compressive strength characteristic of concrete mixed used hand mixing technique.
The influence of mixing on the microstructure of the cement paste aggregate interfacial transition zone and on the strength of mortar. Pope and Jennings, 1992.	- Investigated a two-stage slurry premixing process by first mixing cement and water, then adding to fine aggregate in a large mixer to make mortar. The researchers concluded that the paste-aggregate bond was improved by restraining the amount of direct water contact with the aggregate during mixing since there was a correlation	The study focused on quantitative interfacial microstructure analysis of the cement paste and limestone aggregates bond using only one mixing procedure. The effect of various mixing methods on the distribution of porosity and anhydrous materials along the

	between interfacial microstructure and strength features of concrete.	paste/aggregate interface was not investigated.
Influence of mixing procedure on mechanical properties of high-performance concrete J Fládr, P Bílý, 2017	- Investigated compressive and flexural strength of high-performance concrete mix batches prepared using several mixing procedures. The results showed that the compressive strength of low water/binder ratio concrete made of the same compounds can vary significantly due to amendments of the mixing procedure, while the flexural tensile strength almost remained constant for all the homogenization techniques used.	The study was restricted to physical properties of high-performance concrete. The mixing procedures adopted were not based on any standards.
Investigations of mixing techniques on the rheological properties of self-compacting concrete. Li, Huang, Yi, Wang, Zhang, and Yang, 2020	- Investigated the effects of mixing procedures, including mixing time, mixing speed, and charging sequence. - Established that shear thickening of Self Compacting Concrete is reduced when aggregates and water are mixed before adding other ingredients. In order to achieve proper fluidity and minimize shear thickening behavior of Self Compacting Concrete, the study suggested a mixing time of between four to five minutes and mixing speed of 30–40 revolutions per minute	Study focused on rheological properties of concrete only. It was also restricted to self-compacting concrete with a relatively high water-binder ratio.

CHAPTER THREE

3. Methodology

3.1 Materials

Cement used in this study was CEM IV/B-P which is a pozzolanic cement manufactured by a local cement company based at Athi-River in Kenya and conforming to KS EAS 18-1:2001 which is derived from EN 197. The Portland cement was manufactured and blended using pozzolanic materials such as volcanic ashes and diatomaceous earth deposits. Fine aggregates used was river sand obtained from suppliers in Nairobi area. Coarse aggregates were crushed stone obtained from a quarry in Nairobi area. The coarse aggregate contained both rounded and angular crushed rock and consisted mainly of sandstone with a variable amount of quartz particles.

A superplasticizer manufactured by Sika (K) Ltd was used. Potable tap water from Nairobi city was used for all concrete works. All the selected materials, except water and superplasticizer, were tested to ascertain their physical, chemical and mechanical properties in accordance with BS EN 12620:2002. Each material was weighed for the required quantities per every mix. Aggregates and cement were weighed on a scale having precision up to 100 grams. Mixing water and plasticizer were weighed on a scale having precision up to 0.1 grams.

3.2 Material Preparation

3.2.1 Fine aggregates

Fine aggregates were oven dried at 105°C for 24 hours to minimize the influence of moisture content on the water-cement ratio of concrete. In accordance with BS 812-2, the aggregates were graded through BS sieve No. 100 to remove particles smaller than 0.15mm such as silt, clay and dust. For proper blending, the particles retained on BS No. 100 sieve were then sieved through BS sieves Nos. 4, 8, 16, 30, 50 & 100. When additional quantities of sand were required, adequate measures were taken to ensure that the grading remained the same.

The sieve analysis results were recorded graphically on a semi-log graph with particle size as abscissa (log scale) and the percentage smaller than the specified diameter of the sieve holes as ordinate as shown in Figure 3.2 (i)

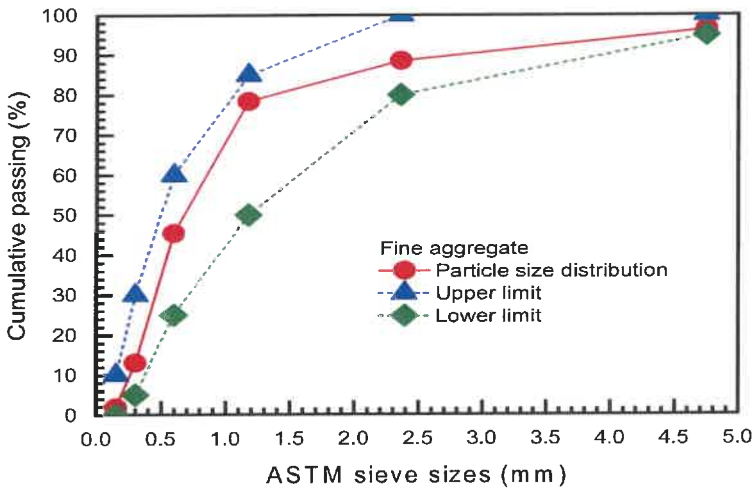

Fig. 3.2 (i): Particle size distribution of fine aggregate.

The fine aggregates were found to be well graded within the overall limits of BS 882-1992. They were made up of a mixture of both smooth well-rounded particles and rougher angular particles.

3.2.2 Coarse aggregates

Coarse aggregates were oven dried at 105°C for 24 hours to minimize moisture content. Sampling was done according to requirements stipulated in BS EN 932-1 (1997) to get suitable representative samples. Aggregates grading was carried out in accordance to the processes of BS EN 933-1 (2012) using test sieves of sizes conforming with BS ISO 3310-2 (2013) to determine distribution of particle sizes. Necessary blending was done to obtain a well graded mix conforming to BS EN 12620:2002 as shown in figure 3.2 (ii)

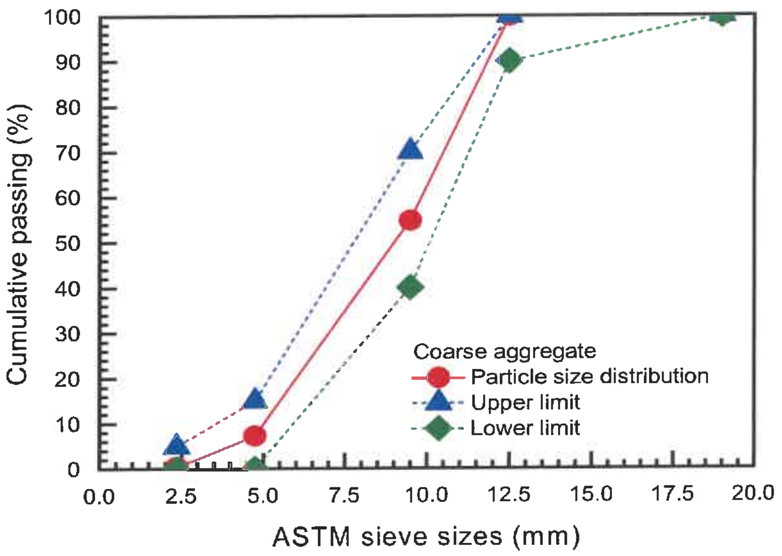

Fig. 3.2 (ii): Particle size distribution of coarse aggregate.

3.3 Material Characterization

Characterization of non-proprietary materials was performed to determine their properties as follows.

Coarse Aggregate

The Specific gravity and water absorption of the aggregates were measured using BS EN 1097-6 and BS 812-2. In each case, representative samples were taken and tested with the average of three values for every property calculated. The maximum and minimum sizes of aggregate were found to be 12.5mm and 5mm respectively. The fineness modulus of crushed stones was 2.77 while the specific gravity obtained was 2.58 which agrees with the recommendations of BS 882:1992 for clean quartz. The values were corresponding to ranges for coarse aggregates reported by Shirley, D.E (1975) that normal-density aggregates generally have specific gravities between 2.5 and 3.0. Table 3.3(i) provides a summary of the properties tested for coarse aggregate.

Table 3.3 (i): Characterization of Coarse aggregates

Property	Coarse Aggregate
Specific gravity	2.58
Water absorption (%)	0.5
Fineness Modulus	2.77
Maximum size (mm)	12.7

Fine aggregate

The fineness modulus (FM) and relative density of the sand were determined in accordance with BS EN 12620:2002. The maximum and minimum sizes of fine aggregates were 4.75mm and 0.15mm respectively. The fineness modulus of sand was 2.76 while the specific gravity obtained was 2.55. The results show that the aggregates were within tolerances specified in BS 812-2. The Specific gravity and water absorption of the aggregates were measured using BS EN 1097-6 and BS 812-2. Table 3.3(ii) provides some of the properties tested for fine aggregates.

Table 3.3(ii): Characterization of fine aggregates

Property	Fine Aggregate
Specific gravity	2.55
Water absorption (%)	0.7
Fineness Modulus	2.76
Maximum size (mm)	4.75

3.4 Concrete Mix Design

Since concrete with low water/binder ratio is synonymous with high-to-ultra high strength, a mix design targeting a 28-day average strength of 60 MPa was carried out to ACI 211.4R-08 in order to proportion concrete constituent materials based on desired properties such as strength and workability. ACI recommends a relationship between compressive strength and w/c ratio with the primary requirement of mix design being workable concrete which is easy to place. On this basis, the design targeted a concrete slump range of between 40 and 55 mm and water/cement ratio below 0.35. The following parameters were therefore considered:

Specified strength	60 MPa
Required Slump	50 mm
Maximum size of aggregate	12.7 mm
Fineness modulus of fine aggregate	2.76
Absorption Capacity of coarse aggregate	0.5 %
Absorption Capacity of fine aggregate	0.7%
Moisture Content of fine and coarse aggregate	Zero
Exposure Conditions	Normal
Water Cement Ratio	0.3

The design quantities required for each laboratory batch of approximately 14 liters were computed as shown in same Table 3.4.

Table 3.4: Physical and mechanical properties of materials used

Material	Quantities (kg/ m^3)	Quantity per batch (kg)
Aggregates		
Coarse	1088	14.53
Fine	780	5.63
Cement	616	8.84
Super Plasticizer (3.75% cement)	23.1	0.33
Water	196	2.65

3.5 Mixing methodology

Four different mixing methods namely British Standard (BS) method, American Concrete Institute (ACI) method, Indian Standard (IS) method, and a method involving progressively making paste followed by aggregate referred to as Paste-Mortar-Concrete (PMC) method were used. In the PMC method, a paste made up of cement mixed with the superplasticizer and water was prepared, followed by fine aggregates to make a mortar and then aggregates came last.

For every mixing method, the sequence and stages of loading various concrete constituents varied as follows:

a. British Standard Method

- Half of the coarse aggregates placed into the mixer followed by fine aggregates
- Remaining coarse aggregates added and mixer allowed to run for between 15 to 30s.
- Half of the mixing water was added, and mixing continued for a total of 2 to 3 min.
- The mixer was stopped, and the contents covered for between 5 to 15 min.
- Cement was spread in a layer over the mixed aggregate
- Remaining mixing water with liquid chemical admixture was added the mixing continued for 3 min ensuring proper uniformity.

b. Indian Standard Method

- Cement and sand were thoroughly mixed first in the mixer
- Coarse aggregates then added.
- Water and admixtures then added mixed together
- Mixing continued until a uniform color was obtained throughout the mix.

c. American Concrete Institute Method

- Approximately 10% of coarse aggregate placed in the drum followed by 1/3 of the mixing water.
- Sand and cement were then added
- 1/3 of the water mixed with liquid chemical admixtures and the remaining coarse aggregate were added.
- Mixing was continued and the remaining 1/3 of the water added just before discharge

d. Paste Mortar Concrete Method

- Mixing water and liquid chemical admixture added into the mixer
- Cement was added and mixed thoroughly to make a paste
- Fine aggregates were added and mixed to make mortar
- Coarse aggregates were added, and mixing continued until the mix was homogeneous

3.6 Investigation of mixer charging sequence

In order to study the effects of mixing methods on strength and durability characteristics of low water/binder ratio concrete, a minimum of three samples from each batch were taken for testing for all the mixing methods in accordance with BS EN 12350-1. Sampling was appropriately done throughout the pour to ensure best and uniform representation of each batch.

The molds used for preparing cubes for compression and water absorption tests were 100mm x 100mm x 100mm while molds used for tensile strength cylinders were 150 mm diameter by 300 mm height in accordance with BS 1881-116:1983 and BS EN 12390-1. The molds were oiled to prevent sticking of concrete and ensure a smooth surface.

As per the guidelines outlined in BS EN 12390-2, concrete samples were scooped into the mold in three equal layers and compacted by hand using a compacting rod. Proper tampering and tapping were done to eliminate trapped air and allow further compaction. Once complete the concrete was levelled off using a concrete float for a smooth surface flash, labeled, covered with a moist cloth, and left standing for 24 hours. The specimens were then demolded and cured in saturated lime water bath in accordance with BS EN 12390-2 until the time of test. Square cubes specimens with parallel opposite faces and edge length of 71mm were prepared for abrasion testing.

Table 3.6: Number of samples prepared for all the tests

Mixing Method	**Mixer Type**	**Compressive Strength (Testing days: 3,7,14,28,56,90)**	**Tensile Strength (Testing day: 28)**	**Durability Tests (Testing days 28, 56, 90)**
BS	Passive	18	3	9
	Active	18	3	9
IS	Passive	18	3	9
	Active	18	3	9
ACI	Passive	18	3	9
	Active	18	3	9
PMC	Passive	18	3	9
	Active	18	3	9
Total		**144**	**24**	**72**

3.6.1 Tests on workability

Tests on fresh concrete included slump and slump flow diameter which were noted at the end of each mixing sequence. This test was used to check the consistency of fresh concrete by assessing amount of water added into the mix and was done in accordance with BS EN 12350.

Slump tests were carried out before cubes were cast. The workability of the mix was determined using slump testing apparatus consisting of a standard cone of 100mm upper diameter, 200mm lower diameter, and of height 300mm. Each cone was filled with concrete samples in three stage with each stage tamped 25 times with a standard tamping rod in accordance with BS EN 12350-2. The mold was then carefully lifted upwards and the difference in height between the top of the cone and top of highest point of concrete recorded as slump. The shape of concrete was also observed to categorize the slump as either true, shear or collapse in accordance with BS EN 206-1:2000. The spread of the concrete was measured and recorded.

3.6.2 Tests on compressive strength

Tests on hardened concrete included compressive strength, split tensile strength, water absorption, abrasion resistance and density using test procedures for hardened concrete outlined in BS EN 12390. The dimensions and the weights of all the samples were taken using a meter rule and a weighing balance respectively before crushing. The cubes were removed from the curing tank, dried and grit removed. The cubes were tested using a calibrated compression machine in the laboratory.

Testing of the cubes was done by exerting progressive force on the face perpendicular to the casting face till they fail. For every three specimens tested per sample, the average force at failure was recorded in Newtons as the maximum compressive force of the concrete in accordance with BS EN 12390-3. The mode of failure for all specimens was also noted and an image record was kept.

In total, seventy-two specimens were tested for abrasion at the ages of 28, 56 and 90 days of curing. The specimens were loaded at the center with 294 Newtons load while firmly fixed in the holding device with the surface to be abraded facing the grinding disc. The path of the machine's grinding disc was evenly sprinkled with 20 grams of the abrasive powder. The grinding disc was put in motion at a speed of 32 revolutions per minute while the abrasive powder was continuously fed to the grinding path so that it remained uniformly distributed in a track corresponding to the width of the test specimen. Abrasion resistance was calculated based on depth measurements recorded throughout the test as the percentage scraped. The volume decrease was measured in cubic centimeters per 50 square centimeters due to wear. Abrasive dust used in this test was corundum crystalline Al^2O^3

Fig 3.6: Abrasion Testing Machine

3.7 Investigation of effect of mixer type

Two types of mixers, passive and active were used for this experiment. The speed of the drum mixer was controlled by an electric mortar. The speed of the drum mixer was limited to between 20 and 25 rpm (Hoy, 1998). This was also to ensure uniformity in estimating mixing time for all batches. The speed of the blades was adjusted according to the manufacturer's specification based on the size of the mix to produce concrete with homogeneous distribution.

The two types of mixers used are illustrated in Figure 2. During mixing, the speed of the mixers was kept constant while the mixing time was adjusted according to the requirements of each method. However, where mixing time was not entirely indicated, a minimum of one minute and a maximum of three minutes was adopted in accordance with recommendations of ACI-

304 (1985) and BCA, (1992). This was to avoid lengthy mixing time which would significantly affect concrete properties.

a. Forced action (active) mixer

b. Free fall (passive) mixer

Fig 3.7: Mixers used to make concrete specimen

3.8 Presentation of results

The data obtained was analyzed using statistical tools and presented in tables and graphs. Charts showing the effect of mixing methods on plastic and hardened characteristics of concrete with low water-binder ratio have been included in the main body of this report while tables with detailed findings and raw-data sheets have included as annexures to the main report.

CHAPTER FOUR

4. Results & Discussion

4.1 Investigation of mixer charging sequence

4.1.1 Workability

Figure 4.1(i) presents slump results for both active and passive mixers obtained using various mixing methods.

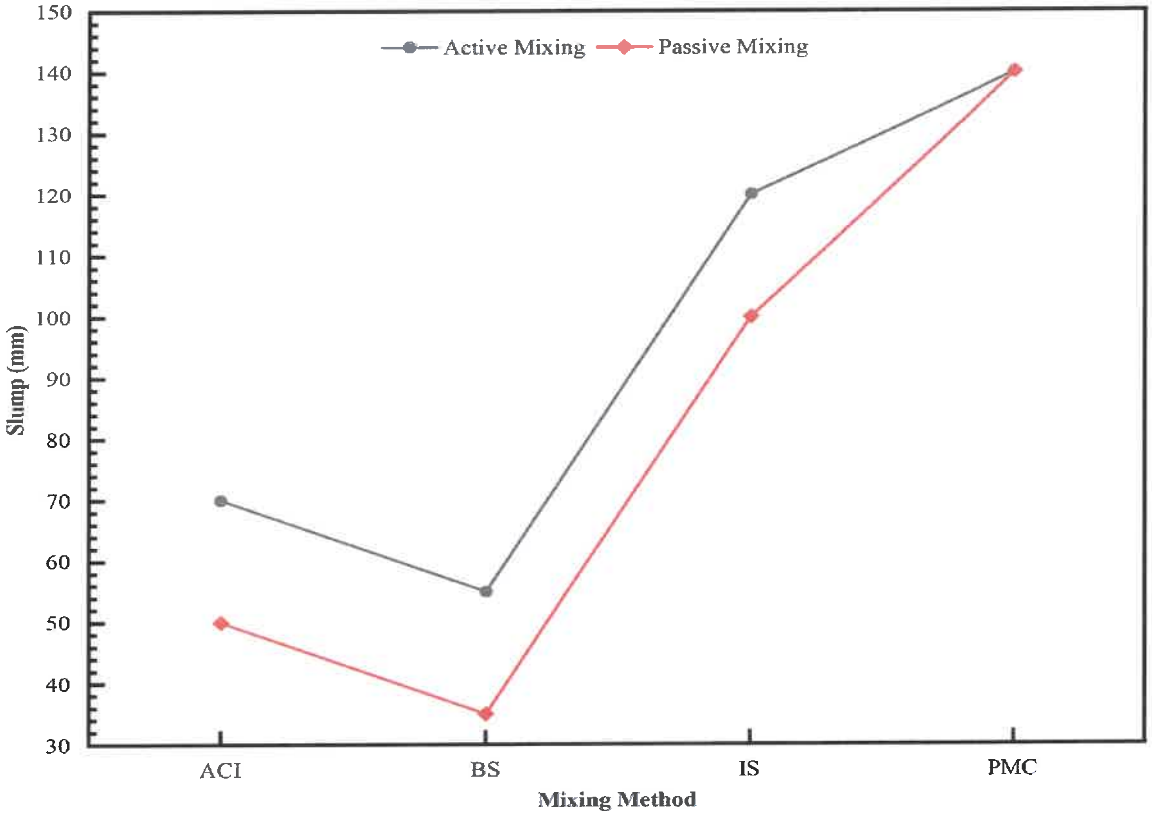

Fig 4.1(i): Slump results for various mixing methods

The slump obtained for all samples ranged from 35mm to 140mm. PMC ACI and IS methods gave improved results of workability exceeding the design workability of 50mm while concrete prepared using BS mixing method exhibited poorer workability characteristics with a workability below the design target. PMC method gave the best workability results with a concrete slump of 140 mm using an active mixer. On the other hand, the BS method gave a slump of 35mm clearly showing a wide variation in workability between the two mixing procedures. The same trends were echoed in the results of flow table test as shown in Figure 4.1(ii).

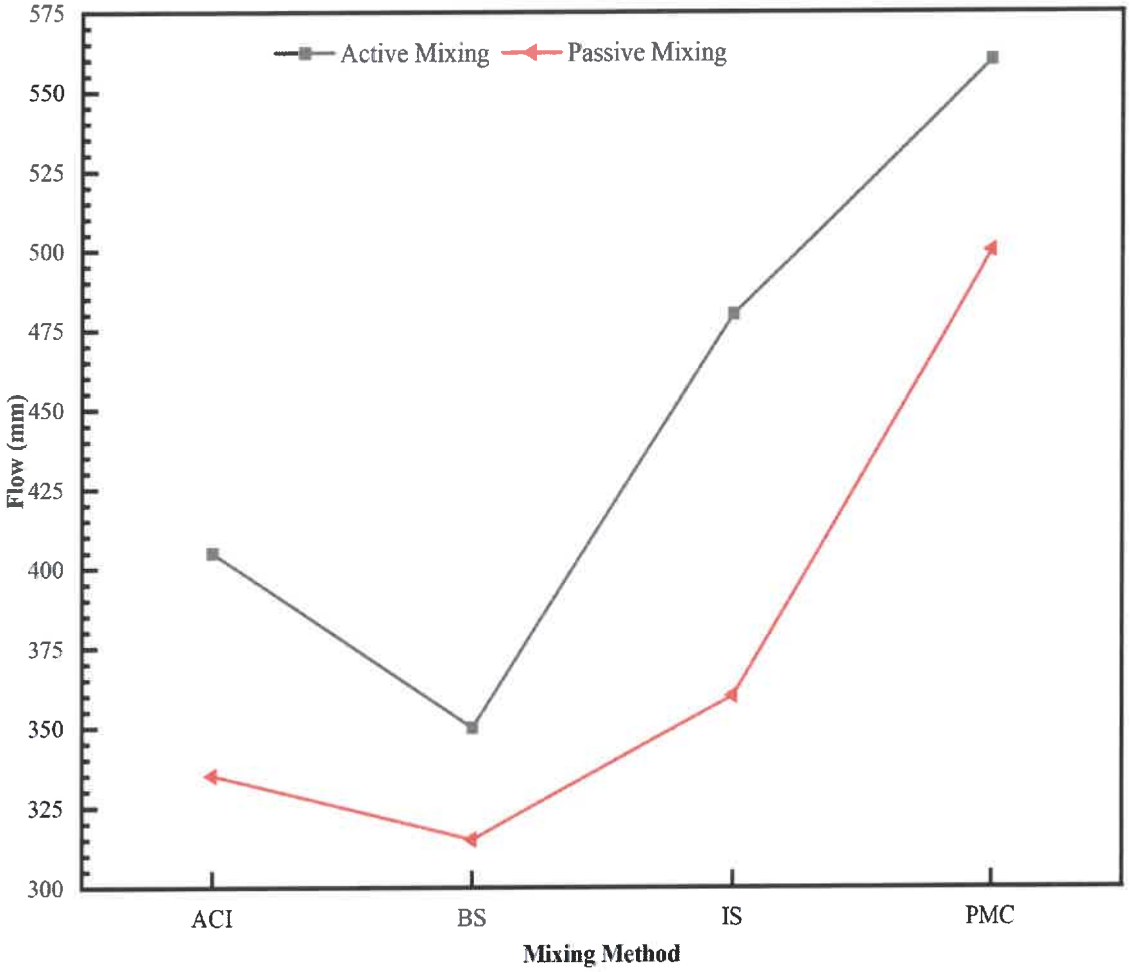

Fig 4.1(ii): Flow table results for various mixing methods

When BS and ACI methods were used, the resulting mix was slightly thick with sticky consistency. The PMC method resulted into concrete with a runnier consistency by the time mixing was complete.

4.1.2 Concrete compressive strength

Figure 4.1(iii) shows results of concrete compressive strength tests for samples mixed using various mixing procedures with an active mixer.

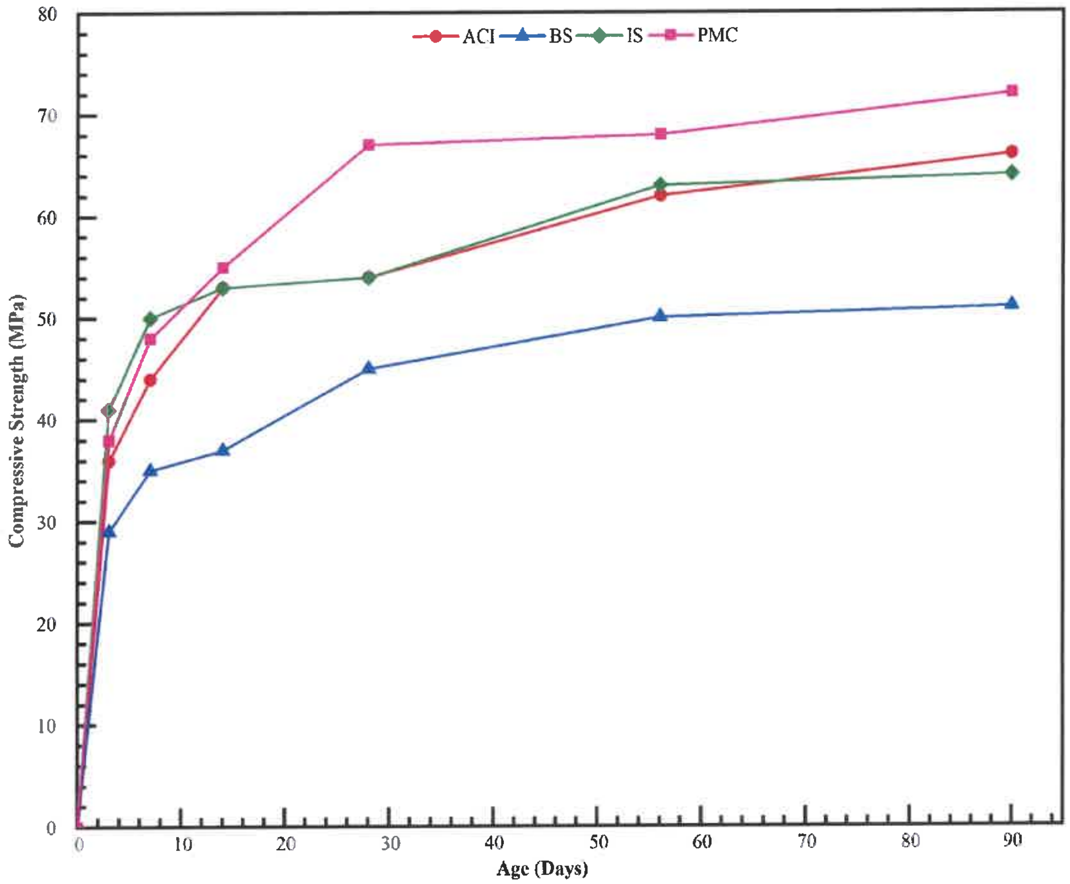

Fig 4.1(iii): Compressive strength of concrete mixed with an active mixer for various mixing methods

Progressively, the BS mixing method gave the lowest values of compressive strength throughout the testing period recording a change of only 31% between day 3 and day 90. On the other hand, the PMC method recorded a change in strength of 45% within the same period. IS and PMC methods produced concrete with higher strengths at early ages, while ACI method gave relatively higher strengths at later ages. The PMC method recorded highest compressive strength of 69.7 MPa at 90 days while BS mixing method recorded the lowest compressive strength of 51 MPa. In the early age of testing up to day 7, the results for ACI method very closely followed the results for BS method. In the same manner, the results for PMC and IS were very similar. This shows that the mixing method of concrete influences the overall compressive strength with time. Concrete mixed using BS and ACI methods gained strength at a higher rate in the early age but slowed down after day 7 and 14 respectively. However, compressive strength increased for the two methods, albeit slowly, up to day 90. The surge in strength for PMC method and fall in strength for IS method on day 28 and 90 respectively were outlying results attributed to suspected errors caused by experimental variations. Ordinarily, it was expected that the concrete samples would exhibit a continuous strength increase.

Figure 4.1(iv) summarizes compressive strengths for concrete mixed using various methods with a passive mixer.

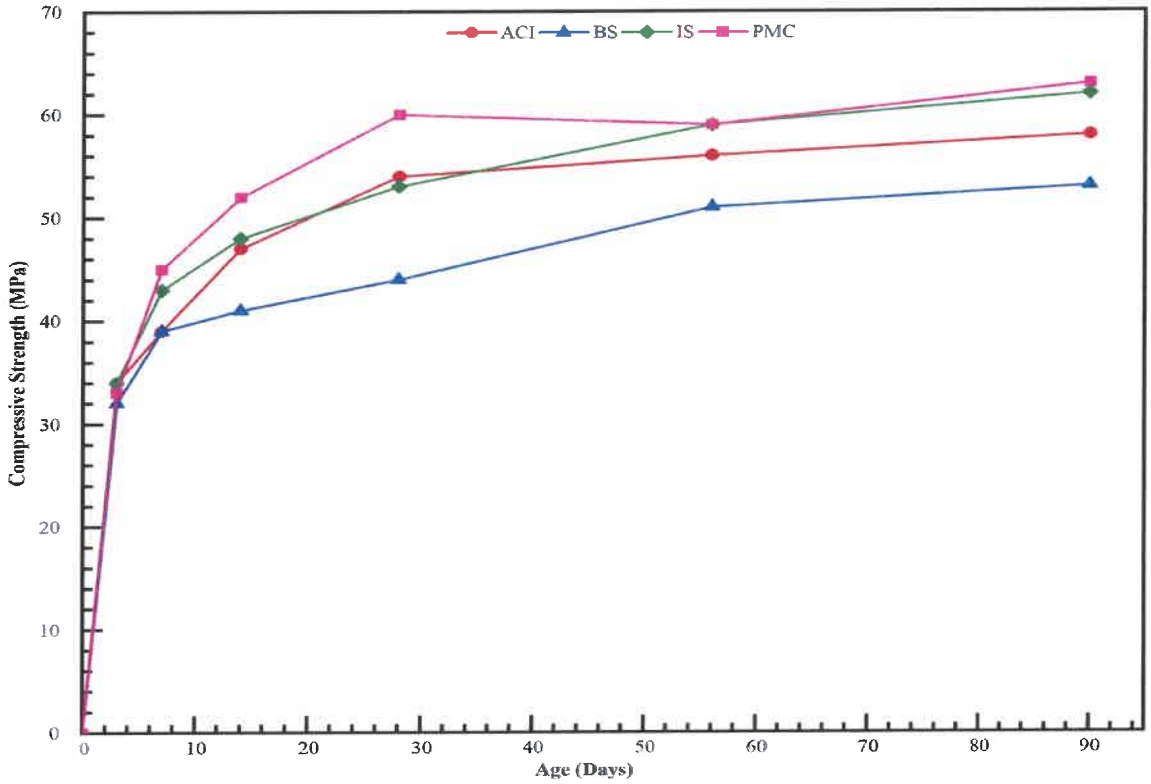

Fig 4.1(iv): Compressive strength of concrete mixed with a passive mixer for various mixing methods

At the initial stages of curing, concrete prepared using all the methods developed strength at a uniform rate with differences in strength appearing from day 14. Between day 3 and day 14 the strength variations of concrete was almost unaffected by the mixing method. Similar concrete strength development behavior was reported by A. Rasheed et al, (2018). British Standard method had slightly lower strength values than the remaining methods, but the variance of strength for all the mixes was minor at less than 10 MPa from the average readings. On day 28, a strength development pattern similar to the active mixing specimen was observed. The PMC and IS methods recorded better results of strength than the other two methods between day 28 and day 56. Unlike active mixer results, there was minimal change in strength for IS and ACI methods beyond day 56. The other two methods had a slight decline in strength in the same period. On average, PMC and IS mixing method, recorded better strengths than BS and ACI methods. These results were found to be consistent with active mixing results although the value of strengths obtained were relatively lower for passive mixing.

4.1.3 Split Tensile strength.

Figure 4.1 (v) presents split tensile strength results for concrete produced using various mixing methods.

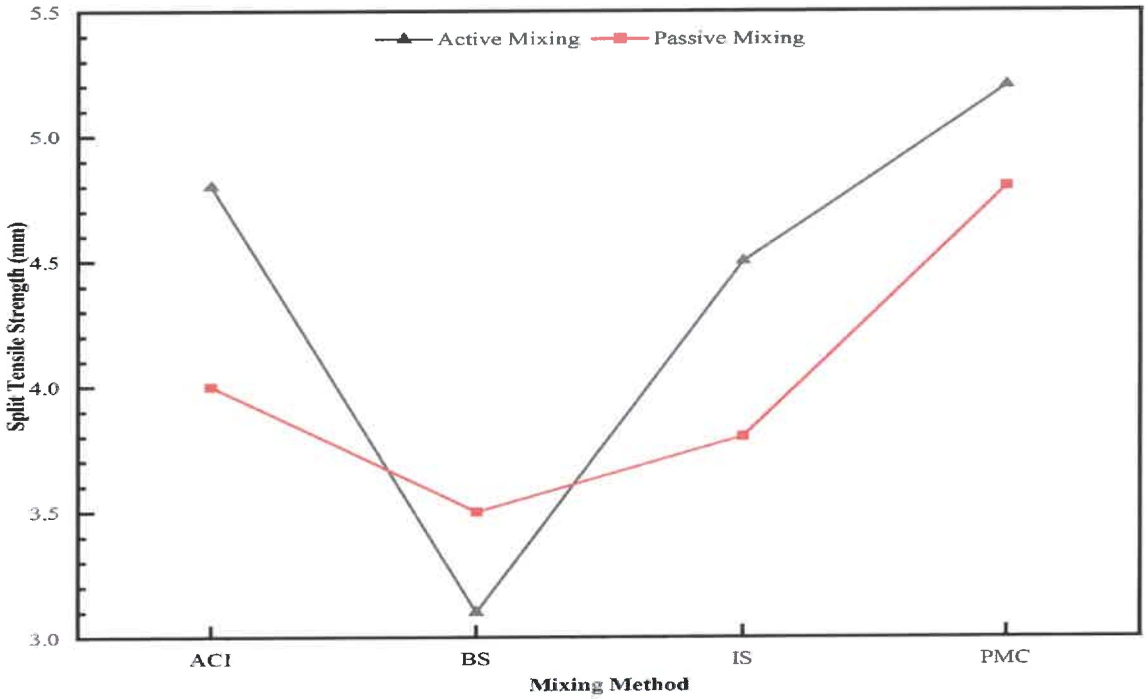

Fig 4.1(v): Concrete split tensile strength using various mixing methods

From the findings, at day 28, tensile strength of concrete produced using PMC mixing method was the highest with values of 5.2 MPa and 4.7 MPa using active and passive mixers respectively. Comparing all mixing methods, the lowest tensile strength value was obtained using BS method using an active mixer. Results of tensile strength for IS and ACI methods using passive mixing were relatively similar. On average, concrete samples produced using active mixer were 8 to 10% stronger than passively mixed concrete except for the BS mixing method.

4.1.4 Concrete density

Concrete density results for samples prepared using various mixing methods are presented in Figures 4.1(vi) and 4.1(vii).

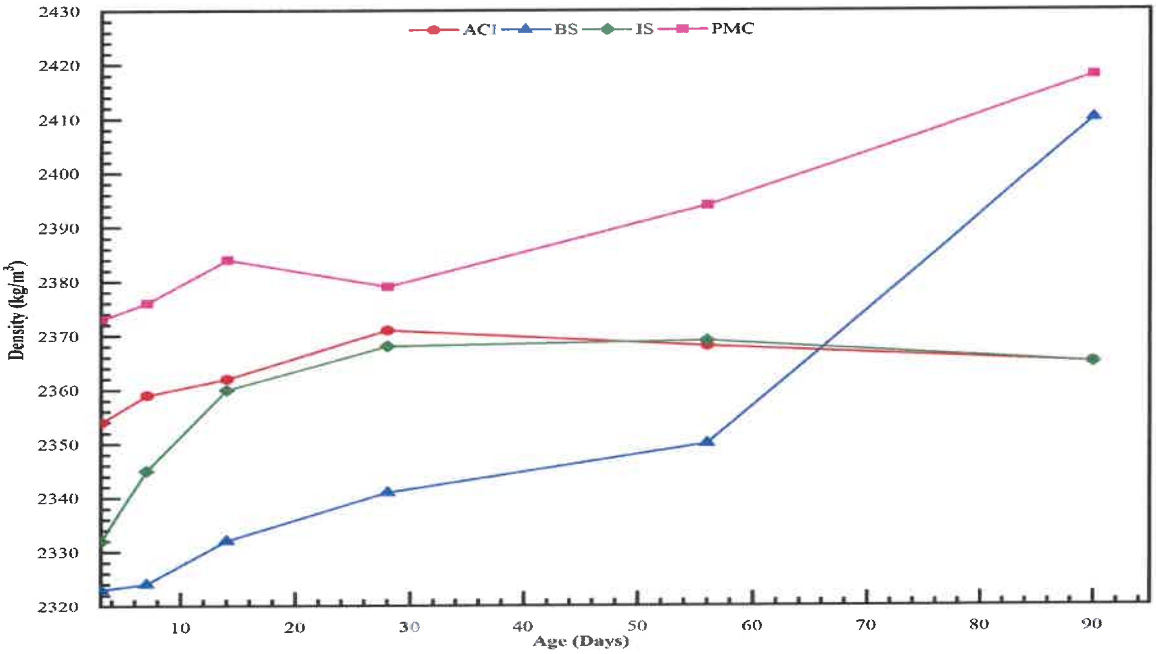

Fig 4.1(vi): Density results obtained using passive mixing

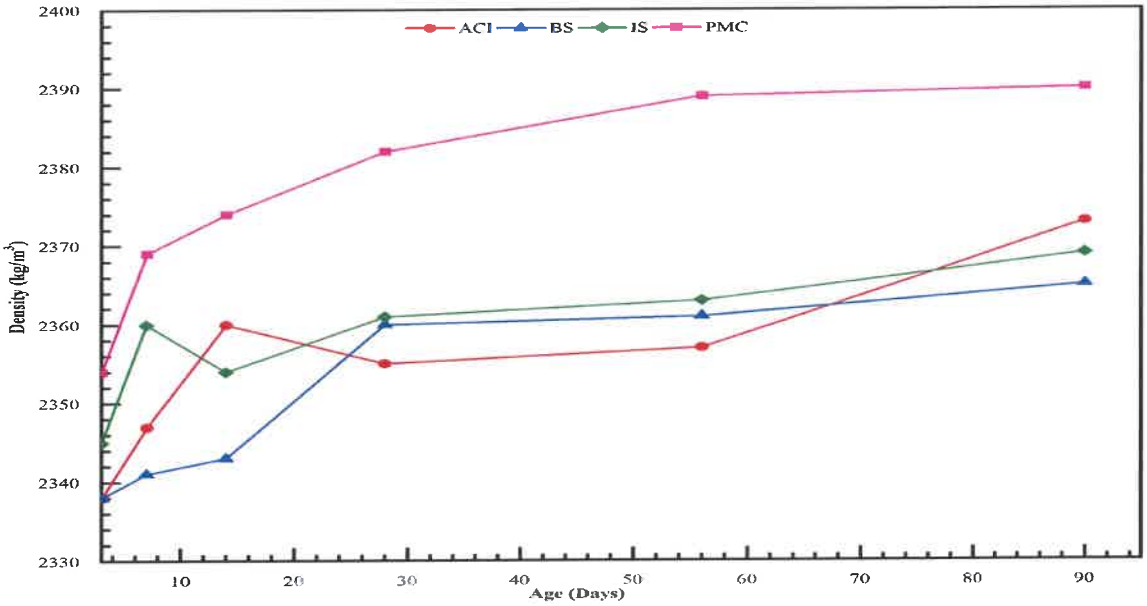

Fig 4.1(vii): Density results obtained using active mixing

PMC and IS mixing methods recorded highest densities of 2378 Kg/ m^3 and 2371 Kg/ m^3 on day 90 respectively. BS and ACI mixing methods had approximately the same value of density on day 90. There was similarity in the trend of densities for samples prepared using PMC and IS method throughout the testing phase. Equally, the ACI and BS mixing methods gave results exhibiting a similar trend except day 28. However, the rate of density change with time for all the mixing methods was low at 1.2%. This agreed with findings by Shohana, (2015). The slight reduction in densities for the PMC mixing method on day 7 was rather erratic and could be an outlier error caused by experimental variations.

4.1.5 Water absorption

Figures 4.1 (viii) and 4.1 (ix) show results of water absorption for concrete samples prepared using active and passive mixers respectively. The PMC and ACI mixing methods gave smaller water absorption results than the BS and IS methods across all ages. The results demonstrate higher rates of water absorption for specimens prepared using passive mixing in all days of testing. On day 90, results for active mixer were 30% higher than those of passive mixer for all mixing methods.

The variations in water-absorption results were minimal for IS mixing method between day 56 and 90 using an active mixer. The same trend was observed for the BS method using a passive mixer. Variation in absorption across all ages for the IS, PMC and ACI mixing methods was almost linear using passive mixing.

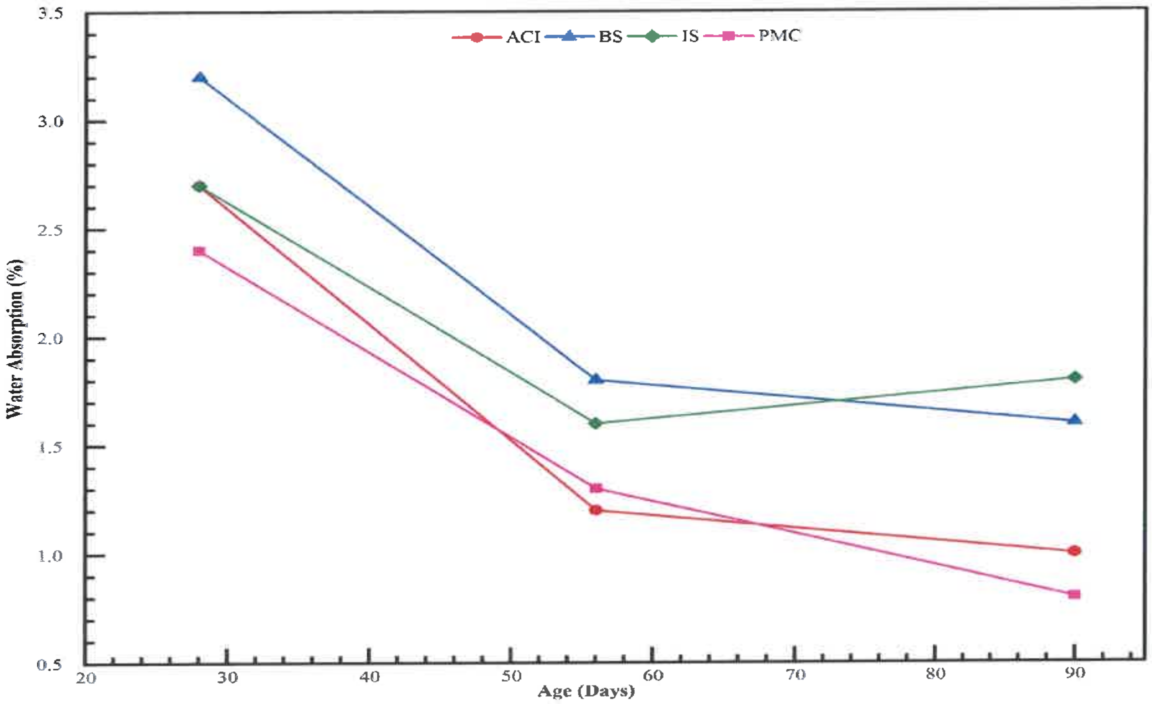

Fig 4.1 (viii): Water Absorption rate for concrete prepared using active mixer

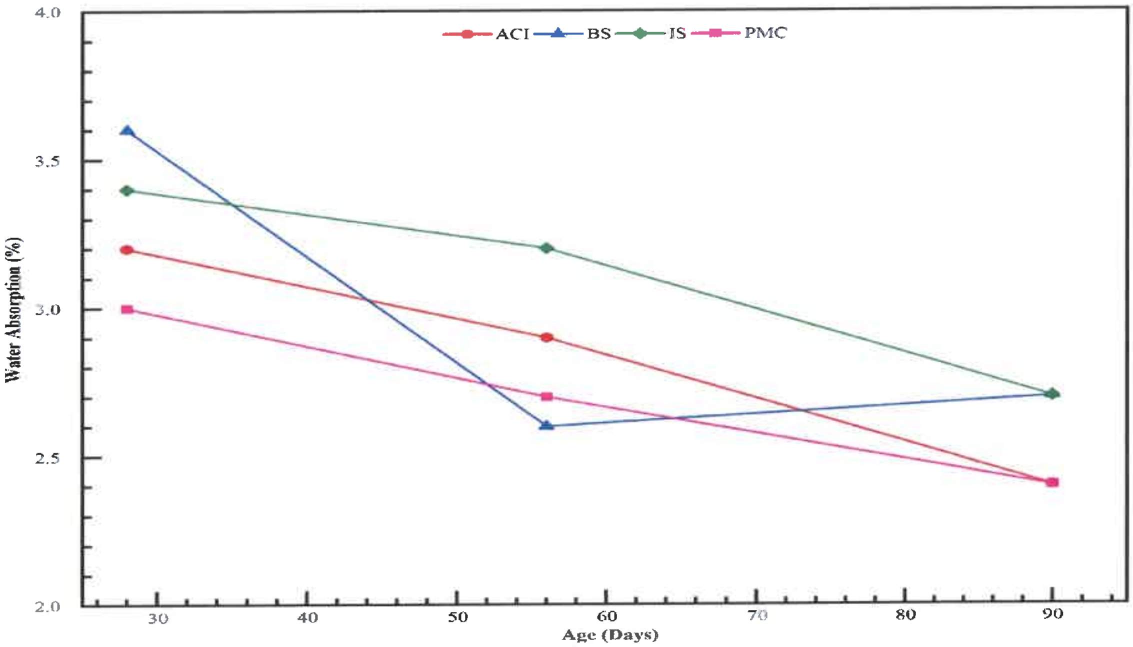

Fig 4.1 (ix): Water Absorption rate for concrete prepared using passive mixer

4.1.6 Abrasion resistance

Figure 4.1 (x) presents results of abrasion resistance for concrete samples prepared using various mixing sequences. The abrasion resistance results did not vary much with mixer types, hence the average values for each method are presented. The cube samples mixed using PMC and ACI mixing sequence had higher abrasion wear resistance compared to those mixed using IS and BS mixing methods. Generally, the results exhibited very similar trend to those of strength described earlier.

The largest deviations were from concrete produced using BS method, closely followed by that from PMC method. BS method gave the lowest abrasion resistance while PMC recorded the highest. Both the BS and IS methods had almost similar results at day 90. BS mixing method gave the best improvement in abrasion resistance of 15.6% between age 28 and 56 days. However, specimens prepared by this method performed poorly in abrasion resistance in all days. At day 90, PMC mixing method gave the best improvement in abrasion wear resistance of 22.7% compared to other mixing methods. ACI and IS methods had minimal improvements of 20.3 and 20.5 respectively on day 90. Overall, the change in abrasion resistance for all methods was fairly moderate between day 56 and 90.

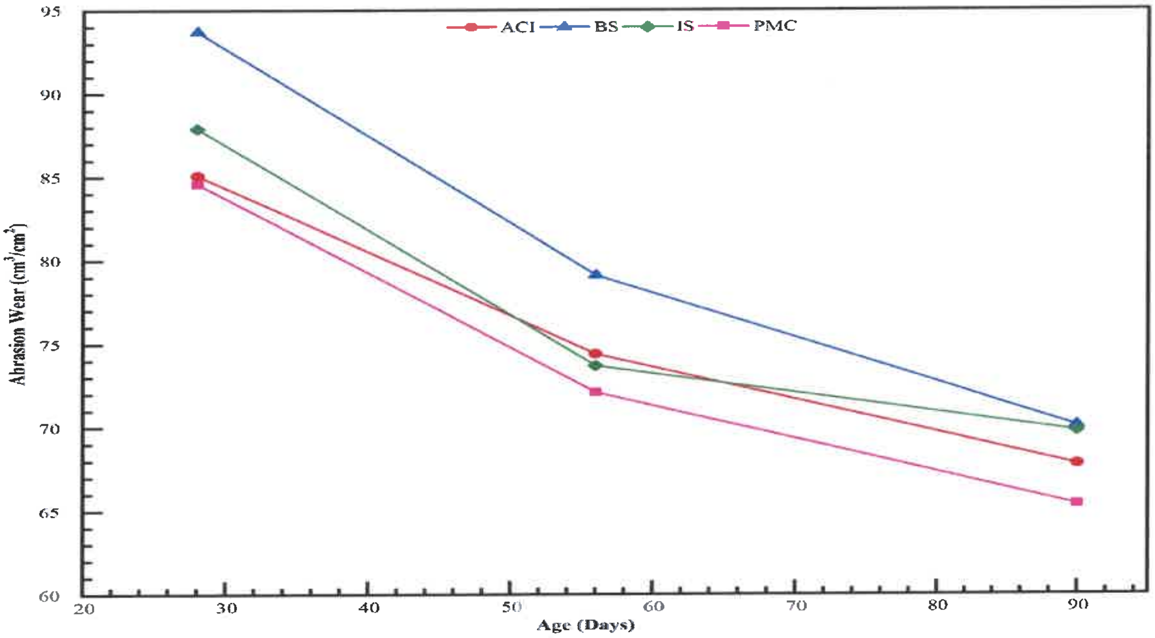

Fig 4.1(x): Abrasion resistance results for various mixing methods

4.2 Investigation of Mixer Type

4.2.1 Workability using various mixers

The results of slump and flow table tests for concrete obtained using the active mixer were found to be higher than passive mixer. As shown in figures 3 and 4, PMC and IS methods gave improved results of workability with an active mixer over concrete prepared using ACI and BS mixing methods which exhibited poorer workability characteristics using a passive mixer. The passive mixer was not ideally suited to mix low water binder ratio concrete since a high proportion of the binder particles got stuck to the side of the rotating drum and failed to mix properly with the aggregates. Besides, there seemed to be lumps of cement in the concrete mix indicating incomplete mixing.

4.2.2 Compressive strength

The average compressive strengths of concrete mixed using active mixers were greater than concrete mixed using passive mixers in all days as shown in figures 5 and 6. In particular, IS and PMC mixing methods gave highest values of compressive strength using an active mixer at the end of the testing phase on day 90. Progressively, compressive strength values obtained using BS mixing method were noted to be low when the passive mixer was employed. The results were in close similarity with earlier results of workability for this method.

4.2.3 Split tensile strength.

From the findings shown in figure 7, tensile strength of concrete produced using PMC mixing method recorded the highest values of 5.2 MPa and 4.7 MPa using active and passive mixers respectively at day 28. Comparing all mixing methods, the lowest tensile strength value was obtained using BS method with an active mixer. IS and ACI methods recorded similar tensile strength results obtained using passive mixing. On average, concrete samples produced using active mixer were 8 to 10% stronger than passively mixed concrete except for the BS mixing method.

4.2.4 Concrete density

In When comparing concrete density obtained using both mixers, the highest value was obtained using the PMC method on day 90. As shown in figures 8 and 9, all other mixing methods recorded relatively lower values of density with the BS and ACI mixing methods giving the lowest readings on the same day. These results drew a close similarity with trends of earlier results for other concrete parameters investigated. Generally, densities of concrete prepared using active mixing for various methods were found to be higher than similar results for passive mixing. Progressively, density results obtained using BS mixing method were noted to be low when both passive and active mixers were employed.

4.2.5 Water absorption

Figures 10 and 11 show results of water absorption for concrete samples prepared using active and passive mixers respectively. The PMC and ACI mixing methods gave lower water absorption results than the BS and IS methods across all ages using both mixing methods. The results demonstrate higher rates of water absorption for specimens prepared using passive mixing in all days of testing. On day 90, results for active mixer were almost 30% higher than those of passive mixer for all mixing methods. (check also the same for the abstract)

The variations in water-absorption results were minimal for IS mixing method between day 56 and 90 using an active mixer. The same trend was observed for the BS method using a passive mixer. Variation in absorption across all ages for the IS, PMC and ACI mixing methods was almost linear using passive mixing.

4.3 Discussion

4.3.1 Workability

The PMC method involved initial preparation of a homogeneous cement paste before adding aggregates. In this method, the mix was wet enough to allow the superplasticizer to act effectively and deflocculated the cement grains prior to addition of the aggregate. However, when BS and ACI methods were used, the mix consistency was much stiffer implying that the deflocculating effect of the superplasticizer may have been inhibited leading to the low workability results. The low results could also be related to the possibility of poor interlocking between binder particles and coarse aggregate during mixing using the procedures outlined in the two methods (Tamimi & Ridgway, 1996). The results further show that IS and PMC methods produced by far the largest flow values. In the two methods, aggregates were added after cement and superplasticizer pastes hence minimizing loss of free water which enhances concrete fluidity.

The tests also demonstrated that adding superplasticizer in the early stages of mixing ensued in adequate flow values agreeing with Abibasheer (2015). The improved workability exhibited by PMC method could also be explained by dispersion of concrete constituents with fine cement particles absorbing mixing water during the initial stages of mixing and later forming a lubrication zone around the aggregates in the later stages of mixing resulting in a more workable mix. Hoy (1998) referred to this mixing approach as a two-stage mixing process where a cohesive binder of fine particles is first mixed followed by aggregate in the later stages of mixing leading to improved workability.

From the results, it is apparent that the procedure of charging the mixer plays a key role in developing a homogenous concrete. A small change in mix procedure may affect the rheological behavior of freshly mixed concrete. BS method required all the aggregates to be added at the beginning of the process. Dry aggregates have the capacity to absorb mixing water during the initial stages of loading materials in the mixer. This could have led to lower workability since less quantity of mixing water was available for providing lubrication per unit surface area of aggregate and hence restraining mobility of particles (Ahmed, 2002).

4.3.2 Compressive Strength

Comparing compressive strength results obtained using all the mixing methods, there was a close relationship between the sequence of loading concrete constituents and compressive strength development. In particular, there was improved early age compressive strength development for the PMC and IS mixing methods which involved addition of aggregates in the later stages of mixing after binder preparation. The two methods were somewhat similar as far as coarse aggregate charging into the mixer was concerned. This implies that compressive strengths were very much influenced by changes to the binder aggregate interface.

In the case of PMC method, a very rich paste of mixing water, admixture and cement promoted a more intimate mixing of all the particles with an improved efficiency of hydration. This resulted in more rapid strength development at early ages using the active mixer and eventually giving better overall strength results. The results obtained agreed with observations made by Aitcin and Neville (1993), that various pozzolanic materials in blended cements participate in different ways though at different rates in the hydration process and in creating the bonds that determine the final strength of the concrete. A homogeneous paste therefore creates a good environment for this blending to take place. In the case of BS method, aggregates were first added into the mixer followed by cement then mixing water and admixtures. This could explain the low strength results obtained since the interface between aggregates and cement paste was not strong enough. The weak bond formed between cement paste and aggregate resulted in lower values of compressive strength for the hardened concrete (Mehta, 1986).

4.3.3 Tensile Strength

It is likely that two occurrences during mixing led to the differences in tensile strength particularly when comparing results for PMC and BS mixing methods. With BS method, the coarse aggregate was in the mixer from the start while PMC method started with a cement paste followed by aggregates. This difference in charging the mixers may have interfered with interfacial transition zone formed between aggregates and cement paste which plays a key role in confining concrete constituents together during mixing (Hoy, 1998). With the concrete mixing having been done using a layer of low water/cement ratio paste, ACI and BS mixing methods slowed down the aggregate coating process leading to poor interfacial zone and consequently low tensile strengths (Chengqing et al, 2018).

The order of adding ingredients into the mixer and particularly water and admixture greatly influenced tensile strength of the concrete. According to BS EN 206 (2013), enough blending of all concrete components is necessary to produce a homogeneous mix. As observed in PMC method, superplasticizer was thoroughly mixed with water and cement to make a paste before adding aggregate. This method resulted in better split tensile strengths than all other methods.

The effectiveness of superplasticizers is considered to be highly influenced by the rate of dissolution of the sulfates and their reactivity with the C_3A to form a layer of ettringite during the initial mixing stage. When the sulfate ions are released, superplasticizers are believed to become fixed by adsorption onto the C_3A therefore enhancing cement particles dispersion by availing molecules at the cement-liquid interface (Fládr & Bílý, 2017). This explains the relationship between high workability for the PMC method and the corresponding high tensile strengths. The method followed a wet mixing approach where a paste of cement, additives and mixing water was prepared before adding fine aggregates followed by coarse aggregates. (Mass. 1989).

4.3.4 Concrete density

PMC and IS mixing methods were considered suitable for mixing concrete with low water-binder ratio with high density since paste was prepared before adding aggregates. Generally, properly mixed concrete has better density due to ability of smaller particles fitting within the larger particles and bridging the voids during mixing process. This could be explained by proper condensation of cement and sand which were thoroughly mixed before adding coarse aggregate in the case of IS and PMC mixing methods. In contrast, coarse aggregates were mixed with water before adding sand and cement in the case of ACI mixing method leading to poor movement of sand and cement grains relative to each other during mixing hence low values of density (Chiara, 1999). Effective concrete mixing also enhances the pozzolanic reactions of nanoparticles from chemical admixtures further improving the filling effect and reducing pores for a dense concrete. (Chengqing et al, 2018).

Another important consideration regarding density is entrapped air which has been shown to affect concrete density (Mohamed, 2017). Unlike entrained air, which is deliberately considered in concrete design, entrapped air forms large pores in concrete reducing the bond between various concrete constituents. Whereas measurement of entrapped air was outside the scope of this study, there is likelihood that it contributed to the low-density values for ACI and BS mixing methods whose sequence of charging materials in the mixer started with coarse aggregates. These methods produce stiff concrete mixes due to low water/cement ratio of the concrete implying that more air bubbles attached in the coarse aggregates during mixing. On the other hand, PMC and IS mixing methods were considered suitable for mixing concrete with low water-binder ratio with high density since paste was prepared before adding aggregates, hence minimizing entrapped air. Additionally, adding admixtures at the beginning of concrete mixing as in the case of PMC, extended the bonding phase of cementitious particles through hydration thus improving the mechanical properties of concrete (Sahmaran et al, 2007). Since concrete density indirectly measures the durability of concrete due to porosity and ease of water absorption, PMC and IS methods are more suitable for production of concrete with low water-binder ratio with high strength and durability.

4.3.5 Water absorption

Water absorption results corresponded with the earlier results of workability and strength. The results of PMC and ACI mixing methods indicated that water absorption was affected by the microstructure of the hardened concrete. Both methods produced concrete with better microstructure compared to that of BS and IS methods, due to improved mixing (A.S, Adithya & Palanisamy, Magudeaswaran. 2016). During mixing, when aggregates and water were mixed first in the BS and IS methods, there was loss of concrete workability which was eliminated when paste was prepared prior to adding aggregates in the PMC and ACI mixing methods.

High water absorption results for the BS mixing method may have been influenced by its porosity. The mixing method generated concrete with weak aggregate-cement paste bonds allowing water molecules to easily break and flow within the interfacial transition zone (Mathias et al, 2017) In addition, the BS mixing method resulted in concrete with poorly parked particles and much more porous hence the higher rate of absorption. The test results suggested that proper mixing of low water binder ratio concrete influences the quality of hardened concrete by reducing air entrapment making the rate of absorption in concrete slower. The dispersing of cementitious materials within the paste increased the effectiveness of the additives resulting to better bonding and ultimately higher strength.

Plasticizer used in preparation of low water/binder ratio concrete for this test had an effect of densification of the transition zone (Scrivener et al. 1988). The improved water absorption results for PMC mixing method could be attributed to the introduction of superplasticizer in the initial stage of mixing to make a paste which in effect improved the densification of the transition zone and ultimately reduced the ‘filler effect’ ultimately reducing the concrete porosity.

4.3.6 Abrasion Resistance

Abrasion wear means that some concrete particles fractured from the specimens due to friction force produced by abrasive material in the rolling action. The more the wear damage, the weaker the strength of the material subjected to abrasion (Sonebi and Khayat, 2001). From the results, it was observed that a strong correlation exists between abrasion and strength of concrete. It was likely that the PMC mixing method sequence of loading materials in the mixer contributed to the high results of abrasion resistance. Deriving from the close correlation of the abrasion results with split tensile trend, the coating of coarse aggregates with a premixed cementitious paste enhanced the interfacial zone in the concrete which in turn improved the confining effect of the aggregates and the other constituents.

From the results, the wear depth over time for each mixing method gave an indication of concrete quality with a higher wear depth indicating lower abrasion resistance. The statistical difference in the wear depth of the specimen between day 28 and day 90 corresponded more with the trend of split tensile strength than compressive strength, following what was expected in literature.

From the results, the PMC method had a significant improvement in abrasion resistance by day 90 of about 20% compared to other methods. As it was noted in other tests such as strength and water absorption, the densified concrete produced by PMC method had shown significantly improved performance compared to other mixing methods.

Previous research has shown that aggregates play a key role in abrasion resistance (Cengiz et al, 2009). The coarse aggregate used in all the mixing methods was of the same hardness and therefore it was assumed that there was no concern that the abrasion of the aggregate could influence variations of the test results. The variations in results therefore could only be an effect of mixing process which influences the parking of the aggregate particles and the overall bonding with the cement/binder content. This explains the low results of abrasion resistance for samples prepared using BS method whose uniformity was noted to be relatively poor compared to other methods. In the BS mixing method, aggregates were introduced in the mixer before adding the binder and superplasticizer and it is possible that this sequence caused points of relative weakness especially at the aggregate interface, which led to weaker concrete in the early age. The differences in abrasion resistance for PMC and ACI mixing methods observed on day 90 was slight and their concrete was considerably strong, showing a correlation with earlier results of strength and workability.

4.3.7 Mixer types

The quality of the concrete produced through a given mixing method can be an intrinsic measure of the efficiency of the mixer (BS EN 206, 2013). Active mixer used in this study was able to produce concrete with uniform distribution of the constituents and better consistency than passive mixer. Mixing time was not included in the scope of this study, but it was observed that operating the active mixers at recommended speeds and power within the specified time produced concrete with minimal segregation and formation of lumps. The findings agreed with Chang & Peng, (2001) who established that active mixers are more efficient in distributing concrete constituents uniformly to produce homogenous mixes. An efficient and effective mixing resulted in a homogeneous mix, which is the prerequisite for increased flowability of concrete (Abibasheer et al. 2015). This influenced the overall strength and durability of concrete.

Unlike an active mixer, blades of a passive mixer or rotating drum are fixed while the drum rotates to give the particles a centrifugal force. This led to several problems including sticking of particles on the drum walls hence reducing mixer efficiency. Some of the drier mixes caused difficulties during the mixing especially when aggregates were first charged in the mixer as in the case of BS mixing method. On several occasions the mixer became blocked requiring temporary stoppage of mixing to dislodge the blockages from the fixed mixing blades. The positioning of blades relatively close to each other made some concrete constituents to be easily trapped during mixing (Tamimi & Ridgway, 1996).

CHAPTER FIVE

5. Conclusions & Recommendations

5.1 Conclusions

The objective of this study was to investigate effects of mixing methods on plastic and hardened characteristics of concrete with low water-binder ratio. Specifically, the study aimed at analyzing strength and durability characteristics of concrete mixed using various sequences of mixing as suggested by IS, BS, ACI and PMC methods. Based on the results it can be concluded that:

i. The difference in workability results for concrete prepared using various mixing methods was attributable to the sequence of adding concrete constituents in the mixer.

ii. Compressive and tensile strength of concrete with low water binder-ratio were lowest for BS mixing method and highest for concrete prepared using PMC method with both active and passive mixers.

iii. Concrete produced using IS and PMC mixing methods gave higher density results than BS and ACI mixing methods. This difference was also attributable to the sequence of mixing various concrete constituents.

iv. The best mixing method for durability characteristics of concrete with low water-binder ratio was the PMC method involved preparation of cement paste followed by aggregate.

v. The stage of adding various concrete constituents into the mixer, particularly water and admixture, was found to influence durability properties of concrete with low water-binder ratio.

vi. Active mixing significantly affected the workability and the overall rheological behavior of freshly mixed concrete with low water-binder ratio. Results of strength and durability for concrete with low water-binder ratio correlated well with other parameters such as workability for both the active and passive mixers.

vii. A passive free-fall mixer was found to have considerably low workability and strength results.

viii. Improper mixing of concrete has a direct influence on hardness and abrasion resistance of concrete.

5.2 Recommendations

5.2.1 Recommendations from this study

i. The results of this research have indicated the effects of three conventional mixing methods on concrete with low water-binder ratio. However, other concrete mix design methods exist. It is recommended that further studies be carried out to compare a wider range of mixing methods recommended by other design codes. This will enable concrete users to adopt the most knowledgeable and assertive mixing method for effective project implementation.

ii. From the findings of this study, use of PMC method in preparation of concrete with low water/binder ratio is recommended to the industry. With proper design, close monitoring and supervision of projects, insistence on proper mixing method using the PMC approach will enhance quality control in construction projects and significantly reduce structural component failures attributed to poorly mixed concrete.

5.2.2 Recommendation for further study

i. During mixing, effort was made to keep factors such as mixing time, mixer power, size of the batch, size and grading of the aggregate constant for each mixing method to ensure consistency for all specimens. The same was however not quantified and factored in the analysis of the results obtained. There is need for more thorough investigation of the effects of varying such parameters during mixing on the overall characteristics of low water.

ii. Depending on project scopes, manufacturers are now producing high capacity mixers. There is need to investigate the possibility of transferring findings of this study to other types and sizes of concrete mixers. Similar findings of this study did not include other concrete additives such as steel or carbon fibers which may also influence concrete parameters depending on mixing method employed. Further studies on mixing concrete with such additives are recommended.

iii. Regarding mixers, there are variations in power consumed during mixing of concrete. This also has a direct relationship with the efficiency of the mixer which ultimately influences the quality of concrete produced. Investigation into the effects of mixer power on concrete characteristics would be of interest.

iv. Discussion of this study's findings were primarily based on available literature. Use of latest technology to investigate the micro-structure characteristics of concrete produced using various mixing methods is recommended considering the overall cost/benefit analysis for each method.

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APPENDICES

Appendix A: Concrete Mix Design

Effect of Mixing Method on the Rheology and Hardened Properties of Concrete With Low Water-Binder Ratio

The concrete used in this study was proportioned to attain strength of 60 MPa. ACI committee recommendation (ACI 211.4R) was used for design.

Design Requirements

Target Strength = 60 MPa

Water binder-cement ratio (w/c) = 0.30

Assumed Slump = 50 mm

Material Properties

Maximum Aggregate size used = 12.7mm (passing and retained on 10mm sieve)

Specific gravity of cement = 3.14

Specific gravity of sand = 2.65

Specific gravity of coarse aggregate = 2.67

Bulk density of fine aggregate (Dry rodded) = 1700 kg/ m^3

Bulk density of coarse aggregate (Dry rodded) = 1692 kg/ m^3

Recommended Superplasticizer quantity = 0.8% of water

Step 1: Calculation of Weight of Coarse Aggregate (ACI 211.4R, Table 4.3.3)

Weight of coarse aggregate = Bulk density × fractional volume of coarse aggregate

= 1692 × 0.70

=1184.40 kg/ m^3

Step 2: Calculation of Water content (ACI 211.4R, Table 4.3.4)

Consider as no-air entrained concrete, Using W/C ratio chart, for 60MPa, W/C ratio = 0.30. W/B ratio = 0.30.

Assume slump value as 25mm to 50mm, Coarse aggregate as 12.7mm

Mixing Water = 169 liters

Void content of Fine Aggregate for this mixing water = 35%

Void content = (1- ((bulk density of C.A)/ (specific gravity of F.A)) ×1000) ×100

Void content V = 35.54%

Mixing water adjustment = (V- 35) ×4.74 = 2.56 liters

Total water content = 171.55 liters (169+2.47)

Step 3: Calculation of cement content (ACI 211.4R, Table 4.3.5(b))

Weight of cement = (total water content /water binder ratio)
= (171.55/ 0.30)
= 571.86 kg/ m^3

Step 4: Volume of Ingredients

Total volume of material = $1.000m^3$
Volume of cement = 571.86 / (3.15 x 1000)
= 0.182 m^3
Volume of water = 171.55 / (1 x 1000)
= 0.172 m^3
Volume of coarse aggregate = 1184.40 / (2.77 x 1000)
= 0.427 m^3
Volume of void = 0.0015 m3 (1.5%)
Total volume of material except F.A = 0.782 m^3
Volume of fine aggregate = 0.218 m^3
Weight of fine aggregate = (volume of F.A × specific gravity of F.A)
= (2.65 x 1000) x 0.218
= 576.375 kg/ m^3

Step 5: Superplasticizer

For 0.8% = (0.18/100) x 743.41
= 5.9 liters

Step 6: Correction for water

Weight of water (for 0.8% plasticizer) = 171.55 – 5.9
= 165.65 liters

Step 5: Summary of Mix Ratio

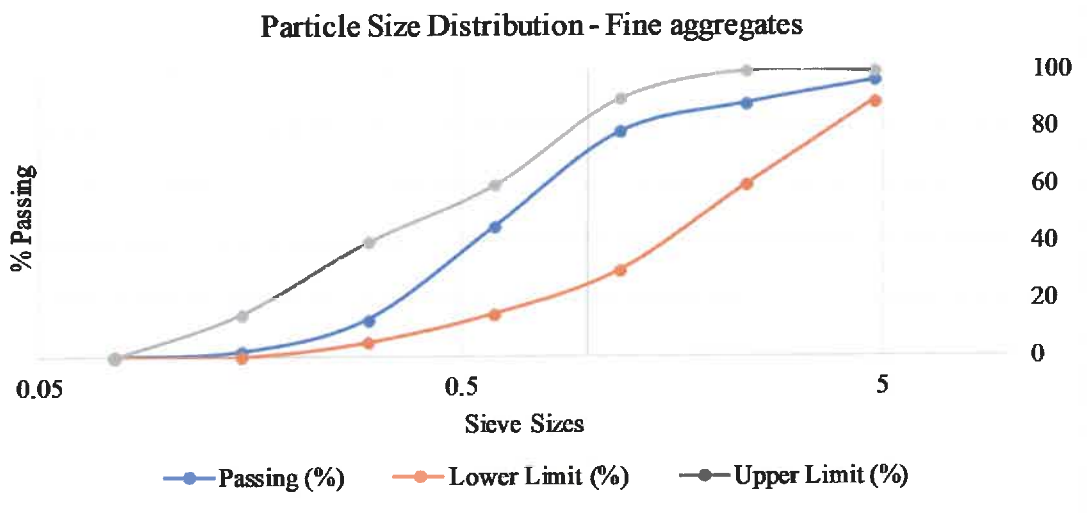
Weight of cement = 571.86 kg/m3
Weight of fine aggregate = 576.375 kg/m3
Weight of coarse aggregate =1184.40 kg/m3
Water content = 165.65 Kg/m^3
Superplasticizer = 5.9 liters/m^3

Cement	Fine Aggregates	Coarse Aggregates	Water Content	Superplasticizer
1	1.01	2.07	0.29	0.01

Appendix B: Particle size distribution for aggregates

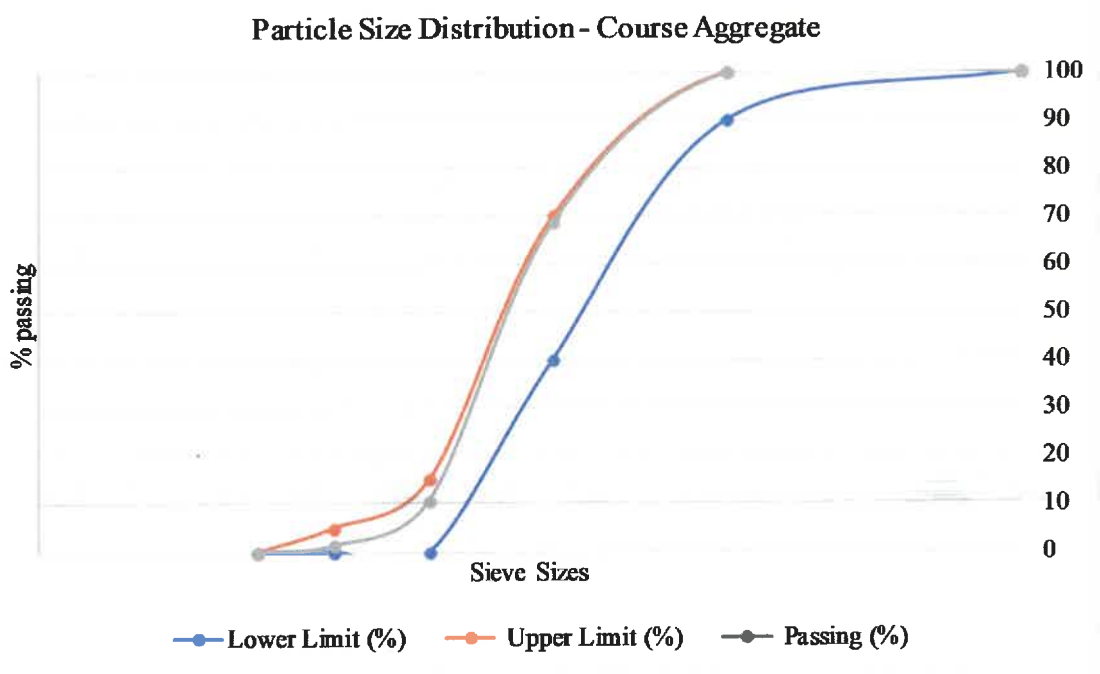
Particle Size distribution

a. Fine aggregates



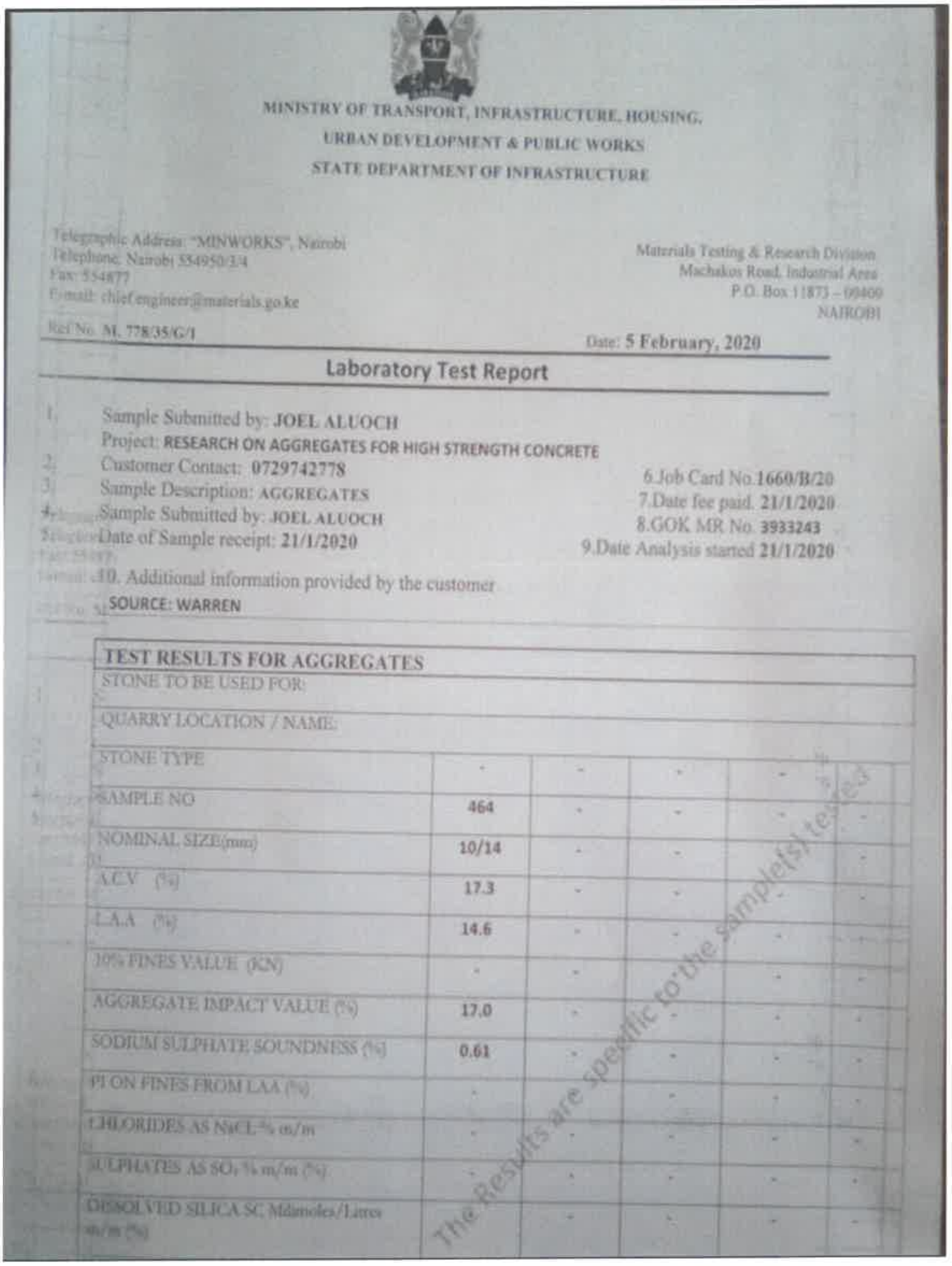
Particle size Distribution Curve for Sand

a. Course aggregates



Particle size Distribution Curve for Course Aggregate

Appendix C: Materials analysis results



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Ref No. **M. 778/35/G/1**

Date: **5 February, 2020**

Laboratory Test Report

1. Sample Submitted by: **JOEL ALUOCH**
   Project: **RESEARCH ON AGGREGATES FOR HIGH STRENGTH CONCRETE**
2. Customer Contact: **0729742778**
3. Sample Description: **AGGREGATES**
4. Sample Submitted by: **JOEL ALUOCH**
5. Date of Sample receipt: **21/1/2020**

6.Job Card No.**1660/B/20**
7.Date fee paid. **21/1/2020**
8.GOK MR No. **3933243**
9.Date Analysis started **21/1/2020**

10. Additional information provided by the customer
SOURCE: WARREN

TEST RESULTS FOR AGGREGATES

STONE TO BE USED FOR:

QUARRY LOCATION / NAME:

STONE TYPE	-	-	-	-	
SAMPLE NO	**464**	-	-	-	-
NOMINAL SIZE(mm)	**10/14**	-	-		-
A.C.V (%)	**17.3**	-	-	-	-
L.A.A (%)	**14.6**	-	-	-	-
10% FINES VALUE (KN)	-	-		-	-
AGGREGATE IMPACT VALUE (%)	**17.0**	-	-	-	-
SODIUM SULPHATE SOUNDNESS (%)	**0.61**	-	-	-	-
PI ON FINES FROM LAA (%)	-		-	-	-
CHLORIDES AS NaCL % m/m	-	-	-	-	-
SULPHATES AS SO₃ % m/m (%)	-	-	-	-	-
DISSOLVED SILICA SC Mdamoles/Litres m/m (%)		-	-	-	-

Appendix D1: Compressive Strength Results using Indian Standard mixing method

NAME:	ACTIVE MIXING USING INDIAN STANDARD			PASSIVE MIXING USING INDIAN STANDARD		
TEST: COMPRESSIVE STRENGTH / DENSITY						
AGE (DAYS)	3	**DATE**	27-May-19	3	**DATE:**	03-Jun-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2508	2482	2542	2346	2349	2300
DENSITY (Kg/m3)	2508	2482	2542	2346	2349	2300
AVERAGE DENSITY (Kg/m3)	2510.667			2331.667		
CRUSHING LOAD						
GAUGE 1 (KN)	405.00	395.00	400.00	340.00	325.00	315.00
GAUGE 2 (KN)	425.00	415.00	425.00	365.00	350.00	330.00
AVERAGE LOAD	415	405	412.5	352.5	337.5	322.5
CRUSHING STRESS (Mpa)	41.5	40.5	41.25	35.25	33.75	32.25
AVERAGE STRESS (Mpa)	41.083			33.750		
AGE (DAYS)	7	**DATE**	31-May-19	7	**DATE:**	07-Jun-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2604	2436	2476	2342	2338	2355
DENSITY (Kg/m3)	2604	2436	2476	2342	2338	2355
AVERAGE DENSITY (Kg/m3)	2505.333			2345.000		
CRUSHING LOAD						
GAUGE 1 (KN)	440.00	500.00	515.00	420.00	425.00	435.00
GAUGE 2 (KN)	465.00	515.00	535.00	440.00	450.00	455.00
AVERAGE LOAD	452.5	507.5	525	430	437.5	445
CRUSHING STRESS (Mpa)	45.25	50.75	52.5	43	43.75	44.5
AVERAGE STRESS (Mpa)	49.500			43.750		
AGE (DAYS)	14	**DATE**	07-Jun-19	14	**DATE:**	14-Jun-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2417	2300	2376	2361	2353	2396
DENSITY (Kg/m3)	2417	2300	2376	2361	2353	2396
AVERAGE DENSITY (Kg/m3)	2364.333			2370.000		
CRUSHING LOAD						
GAUGE 1 (KN)	520.00	550.00	475.00	445.00	375.00	435.00
GAUGE 2 (KN)	540.00	580.00	500.00	455.00	400.00	455.00
AVERAGE LOAD	530	565	487.5	450	387.5	445
CRUSHING STRESS (Mpa)	53	56.5	48.75	45	38.75	44.5
AVERAGE CRUSHING STRESS (Mpa)	52.750			42.750		
AGE (DAYS)	28	**DATE**	21-Jun-19	28	**DATE:**	28-Jun-19

SPECIMEN SPECIFICATIONS	SAMPLE			SAMPLE		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2360	2406	2347	2354	2346	2403
DENSITY (Kg/m3)	2360	2406	2347	2354	2346	2403
AVERAGE DENSITY (Kg/m3)	2371.000			2367.667		
CRUSHING LOAD						
GAUGE 1 (KN)	460.00	585.00	545.00	520.00	505.00	545.00
GAUGE 2 (KN)	480.00	605.00	570.00	540.00	525.00	560.00
AVERAGE LOAD	470	595	557.5	530	515	552.5
CRUSHING STRESS (Mpa)	47	59.5	55.75	53	51.5	55.25
AVERAGE CRUSHING STRESS (Mpa)	54.083			53.250		
AGE (DAYS)	56	**DATE**	19-Jul-19	56	**DATE:**	26-Jul-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2357	2361	2310	2324	2365	2355
DENSITY (Kg/m3)	2357	2361	2310	2324	2365	2355
AVERAGE DENSITY (Kg/m3)	2342.667			2348.000		
CRUSHING LOAD						
GAUGE 1 (KN)	620.00	625.00	645.00	580.00	600.00	575.00
GAUGE 2 (KN)	640.00	650.00	670.00	600.00	615.00	590.00
AVERAGE LOAD	630	637.5	657.5	590	607.5	582.5
CRUSHING STRESS (Mpa)	63	63.75	65.75	59	60.75	58.25
AVERAGE CRUSHING STRESS (Mpa)	64.167			59.333		
AGE (DAYS)	90	**DATE**	22-Aug-19	90	**DATE:**	29-Aug-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2395	2328	2385	2368	2345	2353
DENSITY (Kg/m3)	2395	2328	2385	2368	2345	2353
AVERAGE DENSITY (Kg/m3)	2369.333			2355.333		
CRUSHING LOAD						
GAUGE 1 (KN)	505.00	595.00	460.00	615.00	605.00	595.00
GAUGE 2 (KN)	520.00	620.00	485.00	630.00	630.00	615.00
AVERAGE LOAD	512.5	607.5	472.5	622.5	617.5	605
CRUSHING STRESS (Mpa)	51.25	60.75	47.25	62.25	61.75	60.5
AVERAGE CRUSHING STRESS (Mpa)	53.083			61.500		

Appendix D2: Compressive Strength Results using British Standard mixing method

NAME:	ACTIVE MIXING USING BRITISH STANDARD			PASSIVE MIXING USING BRITISH STANDARD		
TEST: COMPRESSIVE STRENGTH / DENSITY						
AGE (DAYS)	3	**DATE**	27-May-19	3	**DATE:**	03-Jun-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2370	2310	2334	2559	2316	2244
DENSITY (Kg/m3)	2370	2310	2334	2559	2316	2244
AVERAGE DENSITY (Kg/m3)	2338.000			2373.000		
CRUSHING LOAD						
GAUGE 1 (KN)	250.00	305.00	295.00	330.00	300.00	315.00
GAUGE 2 (KN)	270.00	320.00	315.00	350.00	320.00	330.00
AVERAGE LOAD	260	312.5	305	340	310	322.5
CRUSHING STRESS (Mpa)	26	31.25	30.5	34	31	32.25
AVERAGE STRESS (Mpa)	29.250			32.417		
AGE (DAYS)	7	**DATE**	31-May-19	7	**DATE:**	07-Jun-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2358	2315	2350	2282	2451	2538
DENSITY (Kg/m3)	2358	2315	2350	2282	2451	2538
AVERAGE DENSITY (Kg/m3)	2341.000			2423.667		
CRUSHING LOAD						
GAUGE 1 (KN)	240.00	395.00	380.00	400.00	440.00	415.00
GAUGE 2 (KN)	260.00	410.00	400.00	425.00	460.00	435.00
AVERAGE LOAD	250	402.5	390	412.5	450	425
CRUSHING STRESS (Mpa)	25	40.25	39	41.25	45	42.5
AVERAGE STRESS (Mpa)	34.750			42.917		
AGE (DAYS)	14	**DATE**	07-Jun-19	14	**DATE:**	14-Jun-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2355	2326	2318	2307	2312	2318
DENSITY (Kg/m3)	2355	2326	2318	2307	2312	2318
AVERAGE DENSITY (Kg/m3)	2333.000			2312.333		
CRUSHING LOAD						
GAUGE 1 (KN)	350.00	345.00	375.00	350.00	460.00	385.00
GAUGE 2 (KN)	370.00	360.00	400.00	365.00	480.00	410.00
AVERAGE LOAD	360	352.5	387.5	357.5	470	397.5
CRUSHING STRESS (Mpa)	36	35.25	38.75	35.75	47	39.75
AVERAGE CRUSHING STRESS (Mpa)	36.667			40.833		
AGE (DAYS)	28	**DATE**	21-Jun-19	28	**DATE:**	28-Jun-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**

LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2347	2353	2410	2307	2319	2337
DENSITY (Kg/m3)	2347	2353	2410	2307	2319	2337
AVERAGE DENSITY (Kg/m3)	2370.000			2321.000		
CRUSHING LOAD						
GAUGE 1 (KN)	425.00	465.00	425.00	370.00	490.00	425.00
GAUGE 2 (KN)	440.00	485.00	440.00	385.00	515.00	445.00
AVERAGE LOAD	432.5	475	432.5	377.5	502.5	435
CRUSHING STRESS (Mpa)	43.25	47.5	43.25	37.75	50.25	43.5
AVERAGE CRUSHING STRESS (Mpa)	44.667			43.833		
AGE (DAYS)	56	**DATE**	19-Jul-19	56	**DATE:**	26-Jul-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2346	2329	2407	2377	2358	2346
DENSITY (Kg/m3)	2346	2329	2407	2377	2358	2346
AVERAGE DENSITY (Kg/m3)	2360.667			2360.333		
CRUSHING LOAD						
GAUGE 1 (KN)	510.00	510.00	430.00	595.00	530.00	505.00
GAUGE 2 (KN)	530.00	555.00	450.00	620.00	545.00	525.00
AVERAGE LOAD	520	532.5	440	607.5	537.5	515
CRUSHING STRESS (Mpa)	52	53.25	44	60.75	53.75	51.5
AVERAGE CRUSHING STRESS (Mpa)	49.750			55.333		
AGE (DAYS)	90	**DATE**	22-Aug-19	90	**DATE:**	29-Aug-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2282	2368	2386	2363	2510	2345
DENSITY (Kg/m3)	2282	2368	2386	2363	2510	2345
AVERAGE DENSITY (Kg/m3)	2345.333			2436.500		
CRUSHING LOAD						
GAUGE 1 (KN)	490.00	545.00	470.00	545.00	415.00	470.00
GAUGE 2 (KN)	500.00	565.00	480.00	560.00	430.00	470.00
AVERAGE LOAD	495	555	475	552.5	422.5	470.00
CRUSHING STRESS (Mpa)	49.5	55.5	47.5	55.25	42.25	47.00
AVERAGE CRUSHING STRESS (Mpa)	50.833			48.750		

Appendix D3: Compressive Strength Results using ACI mixing method

NAME:	ACTIVE MIXING USING ACI			PASSIVE MIXING USING ACI		
TEST: COMPRESSIVE STRENGTH / DENSITY						
AGE (DAYS)	3	**DATE**	27-May-19	3	**DATE:**	03-Jun-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2323	2338	2363	2384	2334	2344
DENSITY (Kg/m3)	2323	2338	2363	2384	2334	2344
AVERAGE DENSITY (Kg/m3)	2341.333			2354.000		
CRUSHING LOAD						
GAUGE 1 (KN)	345.00	380.00	335.00	355.00	335.00	300.00
GAUGE 2 (KN)	365.00	400.00	355.00	375.00	355.00	325.00
AVERAGE LOAD	355	390	345	365	345	312.5
CRUSHING STRESS (Mpa)	35.5	39	34.5	36.5	34.5	31.25
AVERAGE STRESS (Mpa)	36.333			34.083		
AGE (DAYS)	7	**DATE**	31-May-19	7	**DATE:**	07-Jun-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2328	2349	2334	2337	2358	2352
DENSITY (Kg/m3)	2328	2349	2334	2337	2358	2352
AVERAGE DENSITY (Kg/m3)	2337.000			2349.000		
CRUSHING LOAD						
GAUGE 1 (KN)	400.00	430.00	450.00	380.00	420.00	350.00
GAUGE 2 (KN)	425.00	450.00	470.00	400.00	440.00	370.00
AVERAGE LOAD	412.5	440	460	390	430	360
CRUSHING STRESS (Mpa)	41.25	44	46	39	43	36
AVERAGE STRESS (Mpa)	43.750			39.333		
AGE (DAYS)	14	**DATE**	07-Jun-19	14	**DATE:**	14-Jun-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2350	2326	2313	2359	2323	2343
DENSITY (Kg/m3)	2350	2326	2313	2359	2323	2343
AVERAGE DENSITY (Kg/m3)	2329.667			2341.667		
CRUSHING LOAD						
GAUGE 1 (KN)	510.00	525.00	510.00	485.00	445.00	455.00
GAUGE 2 (KN)	530.00	545.00	530.00	500.00	465.00	485.00
AVERAGE LOAD	520	535	520	492.5	455	470
CRUSHING STRESS (Mpa)	52	53.5	52	49.25	45.5	47
AVERAGE CRUSHING STRESS (Mpa)	52.500			47.250		
AGE (DAYS)	28	**DATE**	21-Jun-19	28	**DATE:**	28-Jun-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100

WEIGHT (g)	2338	2363	2305	2329	2356	2339
DENSITY (Kg/m3)	2338	2363	2305	2329	2356	2339
AVERAGE DENSITY (Kg/m3)	2335.333			2341.333		
CRUSHING LOAD						
GAUGE 1 (KN)	460.00	540.00	575.00	330.00	475.00	480.00
GAUGE 2 (KN)	480.00	560.00	600.00	350.00	495.00	500.00
AVERAGE LOAD	470	550	587.5	340	485	490
CRUSHING STRESS (Mpa)	47	55	58.75	34	48.5	49
AVERAGE CRUSHING STRESS (Mpa)	53.583			43.833		
AGE (DAYS)	56	**DATE**	19-Jul-19	56	**DATE:**	26-Jul-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2369	2322	2345	2362	2319	2364
DENSITY (Kg/m3)	2369	2322	2345	2362	2319	2364
AVERAGE DENSITY (Kg/m3)	2345.333			2348.333		
CRUSHING LOAD						
GAUGE 1 (KN)	625.00	520.00	690.00	585.00	515.00	565.00
GAUGE 2 (KN)	640.00	530.00	715.00	610.00	535.00	580.00
AVERAGE LOAD	632.5	525	702.5	597.5	525	572.5
CRUSHING STRESS (Mpa)	63.25	52.5	70.25	59.75	52.5	57.25
AVERAGE CRUSHING STRESS (Mpa)	62.000			56.500		
AGE (DAYS)	90	**DATE**	22-Aug-19	90	**DATE:**	29-Aug-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2319	2341	2369	2295	2390	2348
DENSITY (Kg/m3)	2319	2341	2369	2295	2390	2348
AVERAGE DENSITY (Kg/m3)	2343.000			2344.333		
CRUSHING LOAD						
GAUGE 1 (KN)	675.00	535.00	645.00	505.00	595.00	570.00
GAUGE 2 (KN)	695.00	550.00	650.00	520.00	610.00	590.00
AVERAGE LOAD	685	542.5	647.5	512.5	602.5	580
CRUSHING STRESS (Mpa)	68.5	54.25	64.75	51.25	60.25	58
AVERAGE CRUSHING STRESS (Mpa)	62.500			56.500		

Appendix D4: Compressive Strength Results using Paste, Mortar Concrete mixing method

NAME:	ACTIVE MIXING USING PASTE, MORTAR, CONCRETE (PMC)			PASSIVE MIXING USING PASTE, MORTAR, CONCRETE (PMC)		
TEST: COMPRESSIVE STRENGTH / DENSITY						
AGE (DAYS)	3	**DATE**	27-May-19	3	**DATE:**	03-Jun-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2325	2402	2334	2333	2367	2418
DENSITY (Kg/m3)	2325	2402	2334	2333	2367	2418
AVERAGE DENSITY (Kg/m3)	2353.667			2372.667		
CRUSHING LOAD						
GAUGE 1 (KN)	350.00	390.00	370.00	310.00	310.00	350.00
GAUGE 2 (KN)	370.00	410.00	390.00	330.00	335.00	370.00
AVERAGE LOAD	360	400	380	320	322.5	360
CRUSHING STRESS (Mpa)	36	40	38	32	32.25	36
AVERAGE STRESS (Mpa)	38.000			33.417		
AGE (DAYS)	7	**DATE**	31-May-19	7	**DATE:**	07-Jun-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2372	2343	2813	2279	2391	2333
DENSITY (Kg/m3)	2372	2343	2813	2279	2391	2333
AVERAGE DENSITY (Kg/m3)	2509.333			2334.333		
CRUSHING LOAD						
GAUGE 1 (KN)	505.00	465.00	455.00	450.00	310.00	460.00
GAUGE 2 (KN)	525.00	485.00	470.00	465.00	330.00	480.00
AVERAGE LOAD	515	475	462.5	457.5	320	470
CRUSHING STRESS (Mpa)	51.5	47.5	46.25	45.75	32	47
AVERAGE STRESS (Mpa)	48.417			41.583		
AGE (DAYS)	14	**DATE**	07-Jun-19	14	**DATE:**	14-Jun-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2342	2383	2341	2380	2355	2382
DENSITY (Kg/m3)	2342	2383	2341	2380	2355	2382
AVERAGE DENSITY (Kg/m3)	2355.333			2372.333		
CRUSHING LOAD						
GAUGE 1 (KN)	480.00	490.00	495.00	510.00	500.00	500.00
GAUGE 2 (KN)	500.00	510.00	520.00	535.00	520.00	520.00
AVERAGE LOAD	490	500	507.5	522.5	510	510
CRUSHING STRESS (Mpa)	49	50	50.75	52.25	51	51
AVERAGE CRUSHING STRESS (Mpa)	49.917			51.417		
AGE (DAYS)	28	**DATE**	21-Jun-19	28	**DATE:**	28-Jun-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100

WEIGHT (g)	2334	2346	2345	2372	2381	2377
DENSITY (Kg/m3)	2334	2346	2345	2372	2381	2377
AVERAGE DENSITY (Kg/m3)	2341.667			2376.667		
CRUSHING LOAD						
GAUGE 1 (KN)	690.00	640.00	655.00	580.00	575.00	595.00
GAUGE 2 (KN)	715.00	655.00	650.00	595.00	600.00	625.00
AVERAGE LOAD	702.5	647.5	652.5	587.5	587.5	610
CRUSHING STRESS (Mpa)	70.25	64.75	65.25	58.75	58.75	61
AVERAGE CRUSHING STRESS (Mpa)	66.750			59.500		

AGE (DAYS)	56	**DATE**	19-Jul-19	56	**DATE:**	26-Jul-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2361	2295	2332	2352	2389	2389
DENSITY (Kg/m3)	2361	2295	2332	2352	2389	2389
AVERAGE DENSITY (Kg/m3)	2329.333			3565.000		
CRUSHING LOAD						
GAUGE 1 (KN)	405.00	535.00	690.00	565.00	595.00	595.00
GAUGE 2 (KN)	420.00	550.00	710.00	585.00	615.00	615.00
AVERAGE LOAD	412.5	542.5	700	575	605	605
CRUSHING STRESS (Mpa)	41.25	54.25	70	59.75	52.5	57.25
AVERAGE CRUSHING STRESS (Mpa)	55.167			89.250		

AGE (DAYS)	90	**DATE**	22-Aug-19	90	**DATE:**	29-Aug-19
SPECIMEN SPECIFICATIONS	**SAMPLE**			**SAMPLE**		
	1	**2**	**3**	**1**	**2**	**3**
LENGTH,L (mm)	100	100	100	100	100	100
BREADTH,B (mm)	100	100	100	100	100	100
THICKNESS,H (mm)	100	100	100	100	100	100
WEIGHT (g)	2373	2389	2372	2401	2435	2435
DENSITY (Kg/m3)	2373	2389	2372	2401	2435	2435
AVERAGE DENSITY (Kg/m3)	2378.000			2418.000		
CRUSHING LOAD						
GAUGE 1 (KN)	690.00	645.00	750.00	620.00	390.00	390.00
GAUGE 2 (KN)	695.00	650.00	750.00	670.00	440.00	440.00
AVERAGE LOAD	692.5	647.5	750	645	415	415
CRUSHING STRESS (Mpa)	69.25	64.75	75	64.5	41.5	41.5
AVERAGE CRUSHING STRESS (Mpa)	69.667			53.000		

Appendix E: Water Absorption Test Results

WATER ABSORPTION TEST RESULTS

ACTIVE (PADDLE) MIXER

Sample ID	Date casted	28 Days Date	Date soaked	Dry weight (g)	Weight (g), after soaking for						Water Absorption 24hrs(%)
					0 mins	10 mins	30 mins	60 mins	120 mins	24 hrs	
Indian Standard	11/06/2021	09/07/2021	13/07/21	7995	7995	8039	8063	8084	8110	8210	2.69
American Concrete Institute	15/06/2021	13/07/21	17/07/21	8047	8047	8085	8107	8128	8151	8262	2.67
Paste Mortar Aggregate	15/06/2021	13/07/21	17/07/21	8013	8013	8051	8071	8089	8113	8222	2.61

PASSIVE (ROTATING DRUM) MIXER

						0 mins	10 mins	30 mins	60 mins	120 mins	24 hrs		
Sample ID	No	Date Casted	28 days Date	Date Soaked	Dry Weight (g)							Water absorption (24hrs)	Average Wat absorption (%
						0 Min	10 Min	30 Min	60 Min	120 Min	24 hrs		
American Concrete Institute	1	19/06/21	17/07/21	21/07/21	7999	7999	8046	8067	8086	8110	8188	2.36	2.35
	2				8085	8085	8127	8149	8170	8194	8274	2.34	
	3				8238	8238	8286	8311	8334	8360	8432	2.35	
Indian Standard	1	22/06/21	20/05/21	24/07/21	8052	8052	8107	8134	8156	8180	8252	2.48	2.44
	2				8169	8169	8222	8244	8265	8287	8359	2.33	
	3				8111	8111	8166	8194	8216	8241	8315	2.52	
Paste Mortar Aggregate	1	18/06/21	16/07/21	20/07/21	8145	8145	8187	8207	8222	8239	8309	2.01	2.07
	2				8240	8240	8284	8305	8319	8338	8412	2.09	
	3				8194	8194	8241	8260	8275	8293	8368	2.12	
British Standard	1	21/06/21	19/07/21	23/07/21	7867	7867	7929	7953	7977	8004	8084	2.78	2.65
	2				8050	8050	8124	8154	8179	8209	8275	2.80	
	3				7971	7971	8025	8050	8070	8092	8160	2.37	