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Effect of Mixing Method On The Rheology And Hardened Properties of Concrete With Low Water/Binder Ratio

Isaiah Kiburi Achini[1], David Otieno Koteng[2], John Nyiro Mwero[3]

[1]*M.Sc. student and corresponding author. Department of Civil & Construction Engineering, University of Nairobi, P. O. Box 30197-00100 Nairobi, Kenya.*

[2]*Associate Professor, School of Civil & Resource Engineering, The Technical University of Kenya, P.O. Box 52428 - 00200 Nairobi, Kenya.*

[3]*Senior Lecturer, Department of Civil & Construction Engineering, University of Nairobi, P. O. Box 30197-00100 Nairobi, Kenya.*

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Abstract - *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. On the other hand, the effectiveness of the mixing method affects the homogeneity of the mix and can also affect its hardened characteristics such as strength. Loss of moisture and homogeneity of the mix reduces the initial workability increasing plasticizer demand. This paper explores the effects of some common mixing methods on the initial workability and strength of concrete of low water/binder ratio. The effects of a paddle (active) mixer and a rotating drum (passive) mixer are also investigated. Results show that material preparation, the sequence of loading, and the type of mixer all have significant effect on initial workability and strength. In general, lower workability and strength was obtained when a rotating drum mixer was used.*

Keywords - *Mixer type, loading sequence, workability, strength.*

I. INTRODUCTION

The amount of water used in concrete mixing is often reduced to a minimum required to hydrate the cementing paste. The reduction of water/binder ratio increases both the strength and durability of concrete by reducing the porosity of concrete arising from the evaporation of excess water. Addition of a plasticizing admixture then becomes necessary to bring the concrete to a desired level of workability. Under such circumstance, any loss of moisture during mixing can result in incomplete hydration of the paste and loss of strength. On the other hand, the effectiveness of the mixing affects the homogeneity of the mix and can also affect the strength. Loss of moisture and homogeneity of the mix reduces the initial workability of the fresh concrete and increases plasticizer demand. Various methods of mixing concrete have been outlined in existing design codes. In this study, a testing programme was developed so that effects of various mixing methods could be assessed in respect to the properties of low water/binder ratio concrete. Three mixing sequences compiled from suggestions made in existing design codes namely Indian Standard (IS) mixing method [1], American Concrete Institute (ACI) Code [2] and British Standard (BS) Code [3] were used. Additionally, a method involving progressively making paste followed by aggregate also known as Paste-mortar-concrete (PMC) was used. In the IS mixing method, cement and sand were first mixed thoroughly in the mixer followed by fine and coarse aggregates. Water and admixture were added towards the end of mixing. The ACI mixing method recommends initial mixing of part of the coarse aggregate with some of the mixing water, followed by sand and cement. Admixture and remaining coarse aggregate are then added with the remaining mixing water added towards the end of concrete mixing. In the BS method, dry mixing of coarse and fine aggregate for approximately half a minute takes place before adding half of the mixing water. This is followed by the remaining coarse aggregates and cement. The remaining mixing water is added together with chemical admixture and mixing continued for three minutes to ensure uniformity. In all the mixing methods, results obtained using both passive and active mixers were compared.

Proper mixing of materials is particularly of great importance for concrete of low water/binder ratio in order to achieve the durability and workability requirements as well as resistance to various stresses and protection of steel from rust [4]. Rheological properties of concrete include its flowability in fresh state. Since concrete is a complex mixture of materials, its rheology is greatly affected by the characteristics of the constituent's microstructure. Compared to common concrete, low water-binder ratio concrete requires a longer mixing time and, in some cases, high energy to achieve homogeneity. Additionally, rheological properties of low water -binder ratio concrete are influenced by the charging sequence, mixing time, and mixing speed. The type of mixer used affects the dispersion and repartition uniformity of granular substances of a concrete mix [5].

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 [4], [12], [25]. The most preferred method of mixing concrete using large mixers is by adding layers of coarse aggregate, followed by cement and then fine aggregate [10]. Chang [4] suggested that cement, sand and coarse aggregate should be added at the same time into the mixer to improve the uniformity of the concrete and minimize negative impact on concrete's homogeneity. The reason given for this method is to minimize confining of fine aggregates and cement in the corners of mixers. For small scale mixing of concrete especially by hand, Aguwa [12] recommends a minimum of four turns in order to achieve a uniform concrete mix.

Rheological properties are important in successful placement and overall performance of low water-binder ratio concrete. Low water/binder ratio concrete shows significantly higher sensitivity to small changes in the mixing methods used as compared to ordinary concrete. Optimizing the mixing procedure of low water/binder ratio concrete leads to an increase in strength of between 10 to 20% and shows the impact of mixing method on the overall characteristics of such concrete [5], [6].

Johansson [32] investigated concrete mixing time by using different mix classes with separate mixers and concluded that an active mixer produced concrete with better homogeneity than drum mixers. For concrete with low water/binder ratio, there are possible variations in workability during the mixing process using the two types of mixers.

According to Rana, Tiwari, & Srivastava [7], the efficiency of mixing coupled with the type of mixer used also largely influences homogeneity and consistency of concrete. Various constituents of low water/binder concrete can be mixed by either using hands or mechanical methods through machines. Ferraris [8] 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. 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. It is worthwhile to note that research on the effects of mixing methods, including sequences of charging mixers, mixing duration, and mixing speed, on the rheological and hardened properties of low water/binder concrete is regrettably not adequate with no standard mixing method having been established yet. 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 [9],[35]. Neville [10] reported 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 [12], [27]. This further explains the importance of selecting a suitable mixing equipment during concrete preparation. For instance, if water or any liquid constituent of concrete is introduced into the mixer before the solids, the results would be concrete with poorly distributed water irrespective of the duration of mixing. In other mixers, when fine materials are added first, there is likelihood of them confining in the corners of drums or sticking on blades hence affecting concrete uniformity [28]

In this study, the sequences of mixing individual components of concrete i.e. cement, fine and coarse aggregates, water and superplasticizer, were systematically varied in accordance with four methods of mixing outlined in three existing design codes using both an active (forced action) and a passive (free fall) concrete mixer. A fourth method which involves preparation of cementitious materials paste followed by aggregates to make concrete was also included in the study.

II. MATERIALS AND METHODOLOGY.

A. Materials

The binder used was CEM IV/B-P 32.5R manufactured by a local company to KS EAS 18 [11] which is derived from EN 197[15] and having the properties shown in Table I. Fine aggregate was river sand of fineness modulus (FM) 2.76. Coarse aggregate was crushed stone of maximum aggregate size (MAS) 12.7 mm obtained from a quarry in Nairobi area. Ordinary tap water from the city mains was used for concrete mixing, and a polycarboxylate super-plasticizer (SP) marketed locally was used for workability enhancement.

B. Material Preparation and Preliminary Tests

a) Fine aggregate

Fine aggregate was oven dried at 105ºC for 24 hours to minimize the influence of moisture content on the water-cement ratio of concrete. Grading of the aggregate was done according to ASTM C136 [31] requirements using sieves No. 4, 8, 16, 30, 50 and 100. Specific gravity and water absorption of the aggregate were carried out according to BS EN 1097-3 [30] with the results shown in Table II. Figure 1 illustrates particle size distribution of fine aggregates.

b) Coarse aggregate

Coarse aggregates grading was carried out using test sieves of sizes 4.75mm, 9.5mm,12.5mm,19mm and 25mm conforming with ASTM C136 [31]to determine distribution of particle sizes as shown in Figure 2. The Specific gravity, water absorption and bulk density of the aggregates were measured using BS EN 1097-3 [30] with the results summarized in Table III.

Table I: Chemical and physical properties of cement.

Composition	Parameter	CEM IV/B-P 32.5R
Chemical (%)	Loss on ignition (LOI)	4.56
	Insoluble residue (IR)	35.20
	SiO_2	34.23
	Al_2O_3	6.71
	Fe_2O_3	4.69
	CaO	47.15
	MgO	0.41
	SO_3	1.97
	N_2O	1.10
	K_2O	1.52
	Cl^-	< 0.01
Physical	Specific surface (cm^2/g)	48.56
	Initial setting time (min.)	214
	Final setting time (min.)	279
	Soundness (mm)	0.8
	Mortar prism strength at 2 days (N/mm^2)	15.10
	Mortar prism strength at 7 days (N/mm^2)	26.80
	Mortar prism strength at 28 days (N/mm^2)	36.90
	Density (g/cm^2)	2.99

Table II: Physical properties of fine aggregate

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

Table III: Physical properties of coarse aggregate

Property	Value
Specific gravity	2.58
Water absorption (%)	0.5
Bulk density (kg/m^3)	1,527
Maximum size (mm)	12.7

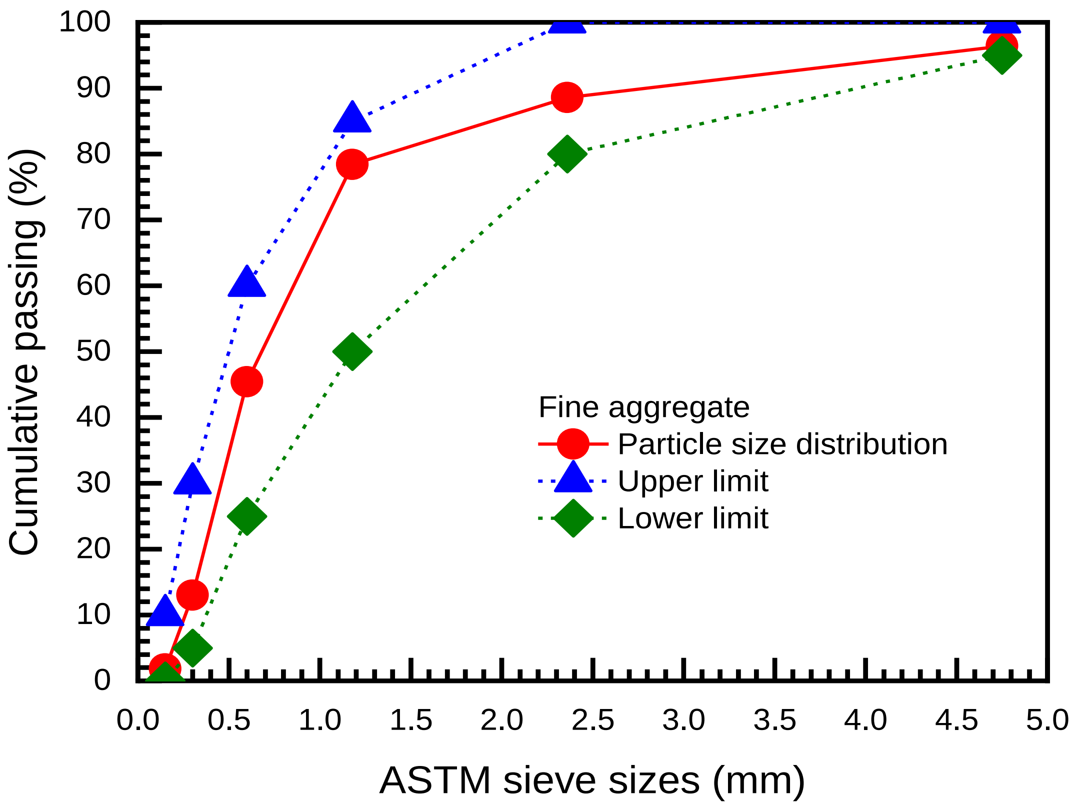


Fig. 1: Particle size distribution of fine aggregate

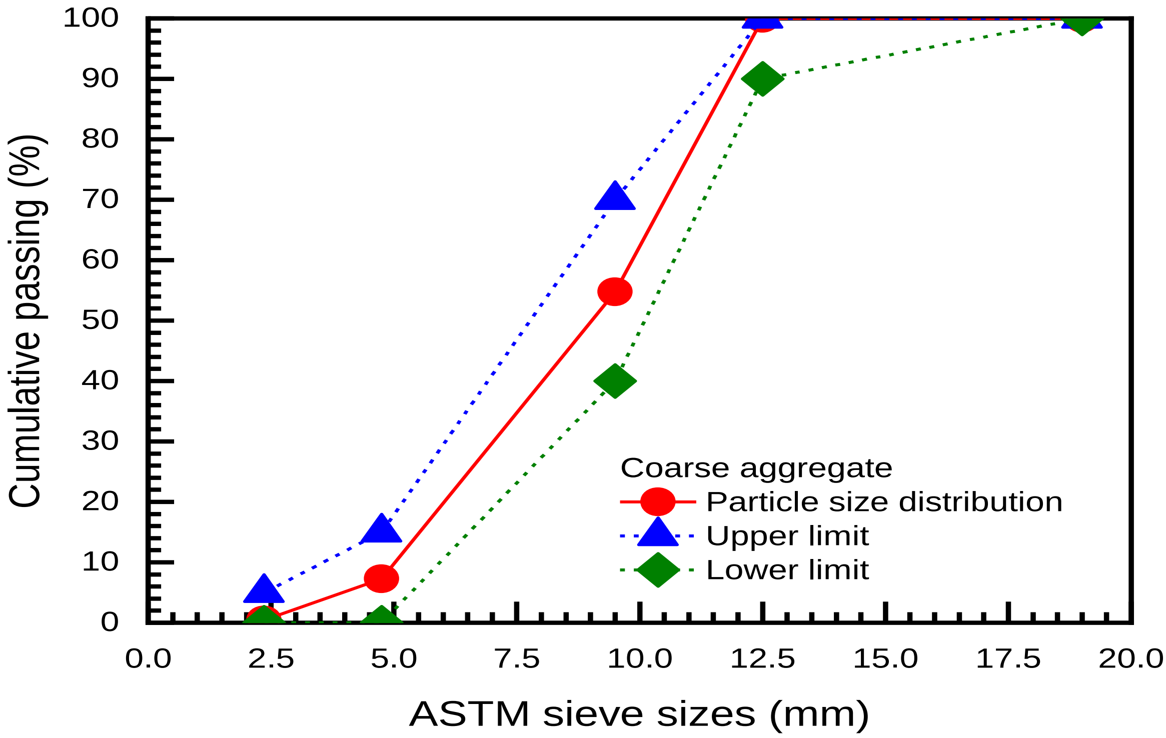


Fig. 2: Particle size distribution of coarse aggregate.

C. Concrete Mix Design

Concrete mix design targeting a 28-day average strength of 60 MPa was carried out to ACI 211.4R-08 [16] 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. Under normal exposure conditions, the quantities of materials indicated in Table 4 were obtained.

Table IV: Material proportions (kg/m^3)

Coarse aggregate	Fine aggregate	Cement	Water	Super-plasticizer
1,088	780	616	196	23

D. Mixer Loading Sequence and Mixing

Different mixing methods based on standard design codes namely British Standard (BS) method, American Concrete Institute (ACI) method, Indian Standard (IS) method were used. Additionally, a method involving progressively making paste followed by aggregate also known as Paste-mortar-concrete (PMC) was used. During mixing, the speed of the mixers, both active (forced action) and passive (free fall), 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 [31] and British Cement Association (BCA). This was to avoid lengthy mixing time which would significantly affect concrete properties. For every mixing method, the sequence of loading various materials into the mixer was varied as follows:

a) Method 1 – (ACI Method)

Approximately 10% of coarse aggregate and 1/4 to 1/3 of the mixing water were placed in the mixer drum to prevent materials such as sand and cement from packing in the drumhead. Sand and cement were then added followed by 2/3 to 3/4 of mixing water mixed with liquid chemical admixtures and mixing was started. The remaining coarse aggregates were added and mixing was continued. The remaining 1/4 to 1/3 of the water was added just before discharge.

b) Method 2 – (BS Method)

Dry mixing with half of the coarse aggregates and fine aggregates was started for approximately half a minute. The remaining coarse aggregates were added and mixer allowed to run for between 15 to 30s. Half of the mixing water was then 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 and the remaining mixing water with liquid chemical admixture were added. Mixing was continued for 30 seconds to ensure proper uniformity.

c) Method 3 – (IS Method)

In this method, cement and sand were thoroughly mixed first in the mixer followed by fine and coarse aggregates. Mixing water mixed with admixtures were added and mixing was continued until a uniform color was obtained throughout the mix.

d) Method 4 – (PMC Method)

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

(a). Forced action (active) mixer. **(b). Passive mixer.**

Fig. 3: Forced action and passive mixers.

E. Preparation and Curing of Test Specimens

A minimum of three samples from each batch were taken for testing for all the mixing methods in accordance with BS EN 12350-1 [33]. In total, 144 samples for compressive strength testing were prepared using both passive and active mixers. The molds used for preparing cubes for compression tests were 100mm x 100mm x 100mm. The molds were oiled to prevent sticking of concrete and ensure a smooth surface. As per the guidelines outlined in BS EN 12390-2 [34], concrete sample was 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 to BS EN 12350 [33] until the time of test.

a) Initial Workability

Tests on fresh concrete included slump and slump flow diameter for each mixing sequence which was noted in the beginning. This test was used to determine the rheological characteristics and check the consistency of fresh concrete by assessing amount of water added into the mix in accordance with BS EN 12350-2 [33]. 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. The shape of concrete was also observed to categorize the slump as either true, shear or collapse in accordance with BS EN 206-1:2013 [26]. The spread of the concrete was measured and recorded.

b) Compressive Strength Test

Compressive strength of concrete was determined at 3, 7, 14, 28, 56, and 90 days according to procedures outlined in BS EN 12390-3 [34]. The consideration to test concrete strength beyond the 'standard' 28 days was based on recommendations by Tamimi & Ridgway [17]. Although he did not test concrete beyond 28 days, his findings led to the conclusion that concrete continues to gain with age. The mode of failure for all specimen was also noted and an image record was kept.

Fig. 4: Testing of compressive strength

III. RESULTS AND DISCUSSION

A. Effect of Mixing Method on Initial Workability

The slump obtained for all samples ranged from 35mm to 180mm as shown in Table V. Paste-mortar-concrete (PMC) and IS methods gave improved results of workability over concrete prepared using ACI and BS mixing methods which exhibited poorer workability characteristics. The Paste-mortar-concrete (PMC) method gave the best workability results with a concrete slump of 180 mm. On the other hand, the BS method gave a slump of 35mm which was lower than 55 mm obtained by the ACI method. The same trends were echoed in the results of flow table test. 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. 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 deflocculate 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.

Table V: Initial workability

Method	**Forced action mixer**		**Passive mixer**	
	Slump (mm)	**Flow Table diameter** (mm)	**Slump** (mm)	**Flow Table diameter** (mm)
ACI	70	475	50	335
BS	55	350	35	320
IS	120	580	100	380
Paste-mortar-concrete (PMC)	180	700	140	420

The low results could also be related to the possibility of agglomeration of concrete materials inside the mixer during mixing using the procedures outlined in the two methods [13], [17], [36]. The results further show that PMC method produced by far the largest flow values. In this mixing method, aggregates were added after cement and superplasticizer paste 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 et al [18] and Tarek [25]. 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.

Tamimi [17] and Abdelgader [19] 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. 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 did not mix with the aggregates when they were added. Besides this, there seemed to be lumps of cement in the concrete mix indicating incomplete mixing. From the results, it is apparent that the procedure of charging the mixer also plays a key role in developing a homogenous low water/binder ratio. 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 [9] An efficient and effective mixing procedure leads to a homogeneous mix, which is the prerequisite for increased flowability of concrete [18].

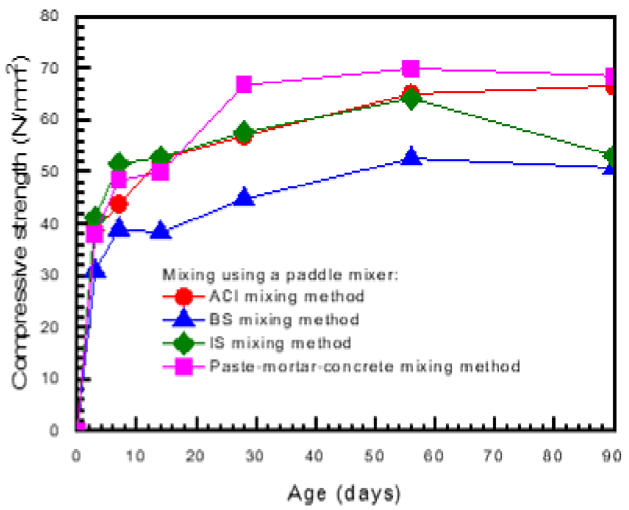
B. Effect of Mixing Method on Compressive Strength

The Paste-mortar-concrete (PMC) method recorded highest compressive strength of 69.7 MPa at 90 days while BS mixing method recorded the lowest compressive strength of 53 MPa on the same day. In the early age of testing up to day 7, the results for ACI method very closely followed a similar format with the results for BS method. In the same manner, the trend of results for PMC and IS were 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 as shown in Figure 5 (a) & (b).

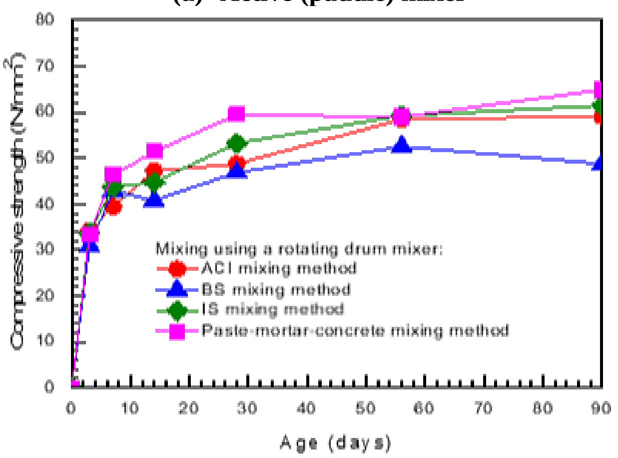
Comparing results obtained using all the mixing methods, there was a close relationship between the sequence of loading concrete constituents and compressive strength development. In particular, there was improved early age compressive strength development for the PMC and IS mixing methods which involved 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 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 gave better overall strength results. The results obtained agreed with observations made by Aitcin and Neville [17] that various pozzolanic materials in blended cements participate in different ways though at different rates in the hydration process and in creating 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 [18], [19].



(a) Active (paddle) mixer



(b) Passive (rotating drum) mixer

Fig. 5 (a) & (b): Compressive strength results for various mixing methods

C. Effect of mixer type on rheological and hardened properties of concrete

Whereas the overall mixing time for all the methods remained constant, the main reason for the higher strengths using the PMC method was the ability of the mixer to effectively pre-mix the cement paste before adding aggregates creating a more intimate contact between the cement grains and water, resulting in more efficient hydration. Differences in strength results were noted between concrete mixed using active and passive mixers. The same trend was noted in the workability results with samples prepared using active mixer giving better results.

This could explain the suitability of active mixing in producing more homogeneous and consistent concrete than passive mixing. Concrete failure mode, which is a measure of its toughness properties relates to the ability of the concrete to absorb energy during cracking, while various concrete particles hold together [29]. Specimens prepared using BS and ACI methods reached complete failure through crushing at a shorter time than specimens prepared using PMC and IS methods at the same loading rates. From the geometry of the samples at failure, the PMC and IS methods produced quadrangular pyramids from the top and bottom almost intersecting at the center. For the BS and ACI method specimens, cracking along several failure planes was observed just before failure implying that the mixing was not homogeneous.

Unlike an active mixer, blades of the passive mixer used in the laboratory were fixed while the drum rotated 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 especially where aggregates were first charged in the mixer as in the case of BS method, caused difficulties during the mixing process, occasionally requiring temporary stoppage of mixing to dislodge mix particles from the fixed blades. The blades were also positioned relatively close to each other making some concrete constituents to be easily trapped during mixing [17]. The quality of the concrete produced through a given mixing method can be an intrinsic measure of the efficiency of the mixer [26].

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 with no formation of lumps. This agreed with Ping-Kun Chang and Yaw-Nan Peng, [27] who established that active mixers are more efficient in distributing concrete constituents uniformly to produce homogenous mixes.

IV. CONCLUSION

- Based on the results of the study it can be concluded that mixing methods affects compressive strength of low water/binder ratio concrete.
- Mixing methods significantly affected the workability and the overall rheological behavior of freshly mixed low water/binder ratio concrete. PMC method produced low water/binder ratio concrete which was homogeneous and having enhanced flowability. Concrete strengths correlated well with other

parameters such as workability for all mixing methods.

- Influence of mixer type on strength characteristics of low water/binder ratio concrete was also noticeable in this study. From the results, it can be safely stated that the best mixer for workability and strength of low water/binder ratio concrete was the active mixer.
- The stage of adding various concrete constituents into the mixer, particularly water and admixture, was found to influence concrete properties. The clearest indication from the results obtained in this research was that incorporating additives at the start of the mixing process and later adding aggregates was beneficial in achieving concrete with good strength characteristics.
- There is need for more thorough investigation to quantify effects of parameters such as mixing time, mixer power, size of the batch during mixing on the overall characteristics of low water/binder ratio concrete.

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