A Study on Ordinary Portland Cement Blended with Rice Husk Ash and Metakaolin

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Abstract. This paper tries to investigate the effect of replacing Ordinary Portland cement (OPC) with Metakaolin (MK) and Rice husk ash (RHA) on the physicomechanical properties such as consistency, setting times, soundness and mortar compressive strength of ternary cement up to 40 % cement replacement. The soundness of the blended cement pastes and compressive strength of the blended mortars were conducted using Le Chatelier apparatus and Tonic Technic compression machine while the initial and final setting times were conducted on the blended cement paste using Vicat apparatus.. Nineteen ternary cement mortars were prepared to comprise of OPC, RHA MK at different proportions and tested at 2, 7, 28 and 60 days. Results indicated that as RHA was gradually increased up to 25% at constant MK content, the volume expansion of the ternary cement paste increased gradually. On the other hand, as MK was increased from 5-25% at constant RHA, the volume expansion diminished. The water consistency of ternary cement paste experienced a variation as MK was increased up to 25 wt% at constant RHA up to 10 wt%. However, at 10 wt% constant RHA as MK was increased the water demand gradually increased. Similarly, an increase in RHA at constant MK increased the water demands of the ternary blends. An increase in RHA from 5-25 wt% at 5-25 wt% constant MK resulted in acceleration in the initial and final setting times of cement blends. These accelerations could be attributed to the pozzolanic activity leading in shorter setting time. Whereas a series of accelerations and retardations of both setting times were experienced as the MK was increased from 5-25 wt% at 5-25 wt% constant RHA. It was observed that increment in the MK or RHA up to 10 wt% at constant RHA/MK up to 10 wt% resulted in improved mortar compressive strength of the ternary blend in comparison with control. This improvement was attributed to the high silica/alumina contribution to the matrix by MK inclusion, the C/S ratio in the cement matrix and RHA pozzolanic reactivity despite its unburnt carbon. All mortar compressive strength of the cement blends and control experienced an increase as the curing days were lengthened from 2 to 60 days. The enhanced strength compared with the control especially beyond 28 days could be attributed to the slow pozzolanic reaction resulting from the formation of additional CSH and CAH from the interaction of the residual CH and the silica available in the MK and RHA. The best compressive strength at 60 days was obtained at cement replaced with 15 wt% and 20 wt% at MK 5 wt% RHA producing a mortar compressive strength of 40.5 MPa.

Keywords: Metakaolin; Rice husk ash; Consistency; Setting time; Soundness and Compressive Strength.

INTRODUCTION

In recent times, there has been an excessive excavation of specific natural resources for cement production, thus resulting in scarcity of these resources; on the other hand, the cement production process is very energy-intensive. This negative trend has caused researchers to sort for other alternatives. One of the alternatives involve the use of pozzolanic materials such as metakaolin (MK), rice husk ash (RHA), fly ash (FA) and silica fume(SF). These cementitious materials have been used in recent decades for improving the performance of concrete with improved workability, strength, and durability [1]. Pozzolanic reactions change the microstructure of concrete and chemistry of the hydration products by consuming the released calcium hydroxide (CH) and producing additional calcium silicate hydrates (C-S-H), resulting in increased strength and reduced porosity and therefore improved durability [2]. Rice is the daily staple for more than 3.5 billion people, however, with high demand for rice, its growth is expected to increase [3]. This growth experienced in the agricultural sector has also led to the increase in agricultural waste such as rice husk which can constitute an environment challenge, hence the necessity to convert into value-added materials, thus minimizing environmental problems [4]. RHA is obtained from the combustion of rice hull at controlled temperature; from works of various researchers. RHA has been found to provide several properties ranging from improved workability at low replacement levels and low heat of hydration, lower creep, and shrinkage. Studies by [5, 6, 7, 8] have shown outstanding technical benefits of incorporating RHA in which it significantly improves the durability properties of concrete. Authors [9] also reported that the RHA inclusion up to 15 wt% led to compressive strength increments and above these values led to a decrease in compressive strength. Author [10] reported increased compressive and flexural strengths as a result of cement replacement with RHA. Researcher [11] reported that the RHA replacement level in excess than 30 wt% could lead to a reduction in strength. Authors [12] reported that the cement replacement level was investigated between 10-20 wt% and was discovered to attain an optimal level of 15 wt% RHA replacement.

Metakaolin is a unique pozzolanic material obtained from the calcination of clay materials – kaolinitic clay [13]. Due to its high reactivity with calcium hydroxide and its ability to haste cement hydration [14, 15], the use of MK as an SCM has been intensively investigated. Authors [16] gave the result of an increment in the compressive strength for 28 days up to 10 wt% while [17] reported that after 28 curing days, the concrete compressive strength at various MK replacement levels from 5-30 wt% experienced an increment up to 32 wt%, with an optimum MK level at 20 wt%. Authors [18] reported that cement replacement of 5–10 wt% MK exhibited enhanced strengths at ages up to 365 days. The factors identified contributing to the concrete strength by the inclusion of MK include filler effect, acceleration of Portland cement hydration and pozzolanic reactions [17]. Researchers [19] reported that at 15 wt% RHA replacement and 25 wt% MK replacement, the compressive strength was enhanced by 20.9 % and 17.42% respectively whereas cement blended with 15 wt% RHA and 15 wt% MK enhanced the strength by 24.61 %.

This paper tries to understand and examine the effect of RHA and MK on the physical property of blended cement paste such as water consistency, setting time and soundness as well as the mortar compressive strength of various cement blends and control.

REVIEW OF LITERATURES

According to [20], the effect of cement replacement with RHA at 10–30 wt% at an interval of 10% on concrete properties, observed that the initial and final setting times increased as the RHA content was increased. Similarly, [21] observed that the high silica content of RHA chemical composition contributes to the concrete workability. Other researchers also indicated that owing to the high amorphous silica content present in RHA, it can be considered as an SCM to be employed as a cement replacement [22, 23, 24, 25]. The inclusion of RHA into the cement matrix resulted in an increase in the setting time which could be attributed to the diminution of the clinker content which contributes to the slow exothermic reaction between the diminished cement and water leading to slowness in stiffness of the paste and evaporation of water [21, 26, 27, 28]. Similarly, the trend of increase in both setting time of cement blended with RHA was observed by [11, 29].

Authors [30] observed that no significant difference in the mortar compressive strength of cement blended with 10 wt% RHA of 45 μm sieve size in comparison with control while [31] observed that cement replacement with 25 wt% RHA produced similar concrete compressive and tensile strength while the flexural strength showed slight improvements. Authors [32] also observed that cement blended with 10 wt% RHA, produced better strengths at 28 days i.e. compressive, flexural and tensile compared to the control and their workability diminished as the RHA content was gradually increased from 0–25 wt% due to decrease in the compaction factor by 43.02 %. Authors [33] observed similar trends of decrease in workability as the RHA content was increased. He also investigated the effect of RHA density on the workability and compressive strength of fresh and hardened RHA concrete respectively and concluded that an increase in the RHA content by weight (RHA-W) led to a decrease in its concrete density while an increase in RHA content by volume (RHA-V) led to an increase in its density as the curing days progressed up till 20 % beyond which experienced a decrease in density respectively. This decrease in the density of RHA-W was attributed to the consumption of $Ca(OH)_2$ during pozzolanic reaction which occurs due to secondary hydration to form CSH which is less dense [34, 35, 36], whereas a decrease in workability was observed as the cement replacement was increased for both RHA-W and RHA-V. Authors [37] investigated the effect of RHA on the physicomechanical properties of the aggregate cement bricks and results indicated that the compressive strength increased as curing time progressed and its strength decreased as RHA content was increased. Similarly, the water consistency of the RHA cement blend increased as cement was replaced with 10 wt% RHA. Researchers [38] investigated the effect of partial replacement of cement with RHA on the workability and compressive strength and observed that the strength was enhanced as the RHA content was increased from 10–20 wt% whereas, at 30 wt%, the strength was similar to that of control. The workability of RHA cement blends decreases as the RHA content was increased. Authors [39] investigated the effect of replacing 20 wt% of cement with RHA on the compressive strength and observed that the compressive strength was enhanced by 2.98, 2.76, 3.01 % at 14, 21 and 28 days respectively, whereas at 7 days strength of the cement blend was lower compared to control. Researchers [38, 39] suggested that RHA reactivity was influenced by the silica content, silica crystalline phase and the size and surface area of the ash particle. Author [40] also investigated the effect of RHA on the concrete strength and observed that the 28 days compressive strength increased by 30 % as the RHA was increased from 0–15 % beyond which the compressive strength diminished by 11.57 % of the control strength.

According to [41], the water demand increased by 103 and 112 % as the RHA content was increased to 10 and 30 % respectively and this increment was attributed to the RHA fineness and porous surface area. This increment in the water demand agreed with [42, 43]. He also observed that the initial setting time retarded as the RHA content increase while the final setting time accelerated as the RHA content was increased. Similarly, 15 % cement replacement with RHA produced 93.4 % of the strength at 28 days which agreed with [23, 58] with optimal replacement at 15 %. Authors [16, 44] optimal at 10 % and researchers [45] suggested that the optimal cement replacement for compressive, flexural and tensile strengths was at 5 %. RHA inclusion decrease $Ca(OH)_2$ content resulting in excess silica present in RHA which reacts to produce CSH gel which strengthening constituents [46, 47]. Author [25] observed that the RHA cement mortars produce higher strength than the control mix at lower cement replacement but at high cement, replacement experienced a reduction.

MATERIALS AND METHODS

Ternary blends were prepared from replacing Ordinary Portland cement with RHA and MK. The cement replacement was less than or equal to 40 % by weight of the ordinary Portland cement were employed. Nineteen different ternary cement blends were prepared using ordinary Portland cement, RHA and MK in various proportions as summarized in Table 1. A Nigerian commercial ordinary portland cement (OPC) type 32.5 R according to Nigeria Industrial Standard (NIS) was supplied by Ibeto cement company and used as a control. The rice husks were collected in Yelwa, Bauchi metropolis, Bauchi State. RHA was obtained from the combustion of rice husk in a ceramic furnace at a temperature range of 600 °C for 3 hours. The resulting ash was then ground in a ball mill to a particle size less than 65 μm. Raw kaolin was obtained from Alkaleri village which was beneficiated and calcined at a temperature of 700 °C for 2 hours, after which cooled to get MK as reported in our previous work [48]. The chemical and mineralogical composition was determined with an X-ray Fluorescence machine (XRF) and X-ray Diffractometer (XRD). The physical characteristics and chemical composition of OPC, RHA, and MK were tabulated in Table 2 while the X-ray Diffractometer (XRD) of RHA and MK were illustrated in Figures 1 and 2. The Blaine surface of RHA and MK were determined as 298 m^2/kg and 323 m^2/kg via Blaine surface area equipment respectively.

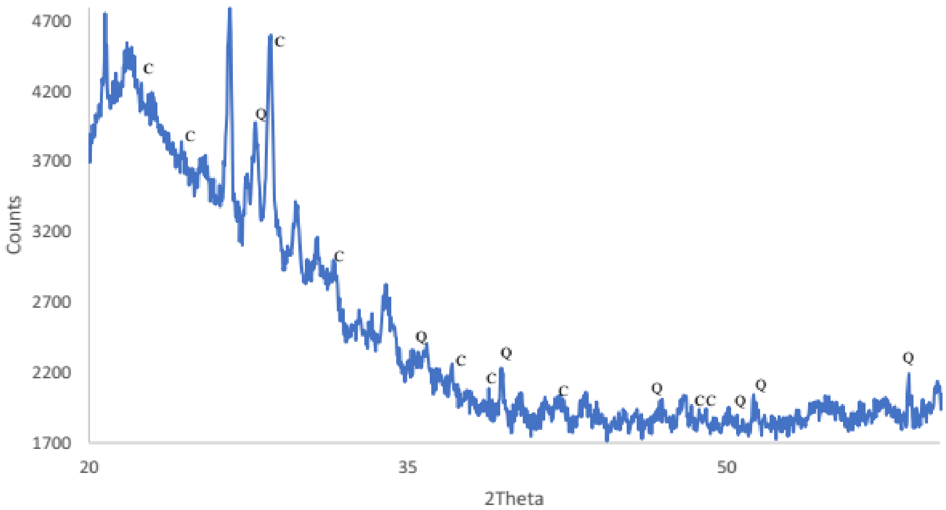

Figure 1 – X-ray Diffraction for RHA

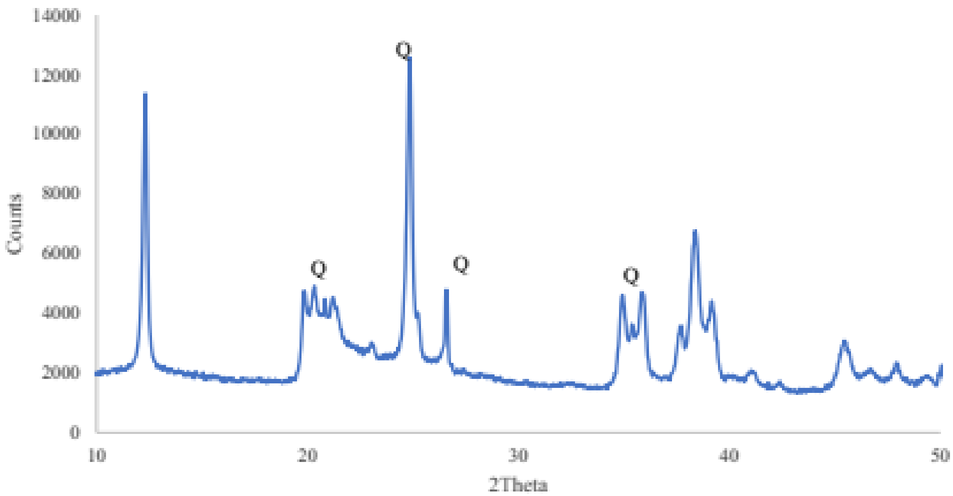

Figure 2 – X-ray diffraction for MK

The required water of standard consistency, initial and final setting time were determined according to [49] through the use of a Vicat apparatus while the soundness was determined with Le Chatelier apparatus according to [50]. The mixing of blended cement pastes was carried out with the standard water of consistency as given in Table 2. The compressive strength test was carried out on mortar samples mixed using water: binder: sand at a ratio of 1:2:5. The mix was then cast in the oiled mold of 50 mm cubes after which were compacted after vibrating with a jolting machine for 2 minutes. The molds were then surface smoothed and covered with an impervious sheet to avoid evaporation, after which were allowed to cure at room temperature for 24 hours. The cubes were demoulded after 24 hours and then placed in a curing tank containing distilled water for testing at the required ages of 2, 7, 28 and 60 days. The samples were removed from the curing tank and tested for mortar compressive strength using the Tonic Technic compression machine.

Table 1 – Chemical Composition of Ordinary Portland cement, RHA and MK

Compound	OPC, %	RHA, %	MK, %
SiO_2	20.25	81.28	53.15
Al_2O_3	5.08	2.42	40.20
Fe_2O_3	3.48	0.71	1.54
CaO	62.35	0.75	0.57
MgO	3.80	1.09	0.14
SO_3	2.61	0.23	0.01
K_2O	0.81	4.02	0.22
Na_2O	0.17	0.18	0.05
TiO_2	0.28	-	2.79
Mn_2O_3	0.16	0.23	-
P_2O_5	0.12	5.73	
Cl	0.05	-	0.00
Cr2O3	0.84	-	-
Sum of Conc.	100.00	100.00	100.00
LSF	96.02	-	-
C_3S	52.30	-	-
C_2S	17.56	-	-
C_3A	7.51	-	-
C_4AF	10.49	-	-
LOI		3.36	1.25
Specific gravity	3.15	2.36	2.60
Blaine fineness, m^2/kg	-	298	323

Table 2 – Mix Proportion and water of consistency and initial and final setting time of blends

No	OPC-RHA-MK	Water cement ratio, w/c	Initial setting time, min	Final setting time, min
1	100-0-0	0.300	50	335
2	90-5-5	0.323	65	325
3	85-5-10	0.333	65	275
4	85-10-5	0.380	45	225
5	80-5-15	0.350	55	245
6	80-15-5	0.433	45	195
7	80-10-10	0.383	55	220
8	75-5-20	0.350	60	205
9	75-20-5	0.493	45	145
10	75-10-15	0.383	50	225
11	75-15-10	0.417	50	205
12	70-5-25	0.350	55	220
13	70-10-20	0.390	55	160
14	70-15-15	0.427	50	150
15	70-20-10	0.457	40	125
16	70-25-5	0.523	35	110
17	65-10-25	0.393	40	140
18	65-15-20	0.433	45	105
19	65-20-15	0.467	35	95
20	60-20-20	0.497	45	110

RESULTS AND DISCUSSION

The chemical composition of RHA indicated oxides like silica, alumina and ferric oxide which were greater than 70 % (84.31 %). Thus, considered a good pozzolan since ASTM C618 for $SiO_2+Al_2O_3+Fe_2O_3$ more than 70 % was satisfied. The silica content of RHA employed in this study was 81.28 % with literature ranging between 77–94 % [25]. The second and third main constituents of RHA are Phosphorus (V) oxide and Potassium of 5.73 % and 4.02 % which fell within the range of 3–7 % and 4–10% respectively [51]. Other major constituents include Al_2O_3 (2.42 %), MgO (1.09 %) as well as the minor constituents such as Fe_2O_3, CaO, SO_3, Na_2O and Mn_2O_3 (less than 1 %). The specific gravity/ density of RHA was found to be 2.31 which was higher than the range of 1.41– 2.23 [24, 25, 52, 53].

The high density could be attributed to the particle size of the RHA i.e. the higher the density the higher the particle size and vice visas [42]. The carbon content is determined as LOI was 3.36 % which satisfies the ASTM requirement for LOI which should not exceed 12 %. MK contains major components like silica, alumina and while minor components like ferric oxide which were greater than 70 % (95.92 %). Thus, considered a good pozzolan since ASTM C618 for $SiO_2+Al_2O_3+Fe_2O_3$ more than 70 % was satisfied. The specific gravity of MK was found to be 2.60 which agreed with ranges from the literature [54]. The LOI of MK was 1.25 % which satisfies the ASTM requirement for LOI which should not exceed 12 %.

Figure 1 depicts the diffractogram for RHA indicated by silica peaks at value observed at respectively and comprised of about 95.4% silica with other minor constituents while the mineralogical composition of MK is indicated from the XRD pattern illustrated in Figure 2. The diffraction spectra indicated the presence of quartz and amorphous aluminum silicate phases which agree with [54].

Figure 1 illustrates XRD patterns for RHA calcined at 600 °C for 2 hours. The results indicated that Cristobalite is the main crystal phase of RHA at 2 Theta of 22, 25.3, 28.5, 31.5, 36, 36.25, 38.5, 43.1, 45, 47, and 48.5 °C while Quartz was detected at 2 Theta of 21, 27.5, 36.5, 39.5, 45, 50.3, 50.8, 55, 55.2, and 60 °C respectively. The amorphous silica present in RHA is essential in determining the pozzolanic reactivity when combined with lime and water and this degree can be estimated via XRD.

From the mineralogical composition of MK, the diffraction spectra indicated the presence of quartz and amorphous aluminum silicate phases. The results indicated that Quartz is one of the main crystal phase of MK at 2 Theta of 20.8, 24.8, 26.6, 34.9. The reactivity of MK is dependent on the Penta coordinated Aluminum ions formed during the dehydroxylation process according to [55].

Water requirement for consistency of the ternary blends

Effect of MK content on the water requirement for consistency at constant RHA content. Figure 3 illustrates the effect of MK at constant RHA content on the consistency of the ternary cement blend. A gradual increase in the consistency was observed as the MK content was increased from 5–25 wt% cement replacement at constant RHA of 5 wt% and 10 wt% respectively.

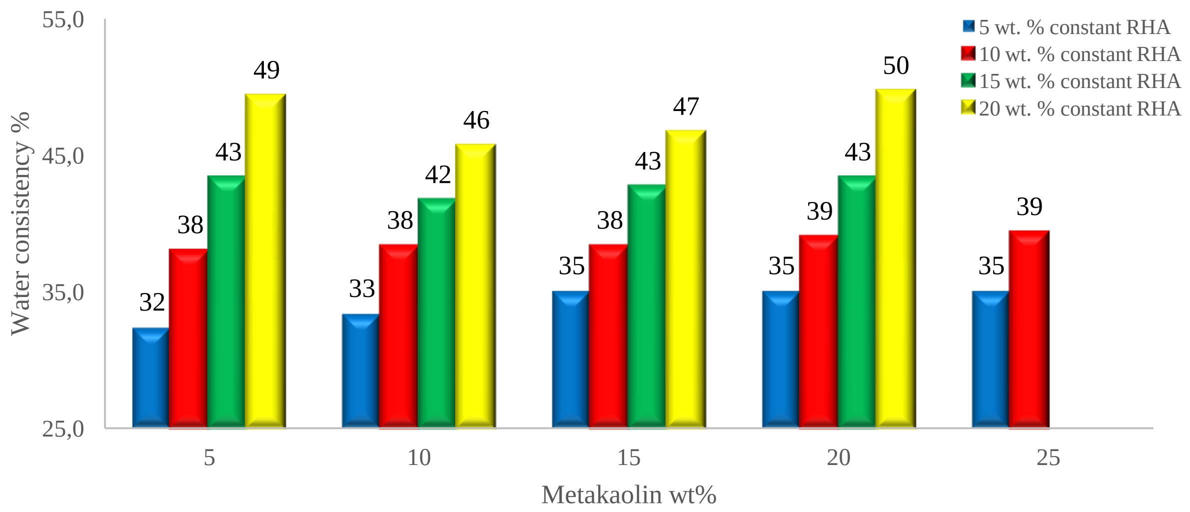

Figure 3 – Effect of MK at constant RHA on the consistency of ternary blend

The reason for the increased consistency as the MK content increased could be attributed to the high reactivity of the MK stemming from the high specific surface area and amorphous structure [54, 56] coupled with the presence of RHA which contains unburnt carbon resulting in more water requirement. This trend is also in agreement with [54, 56, 57]. Whereas, at 15 and 20 wt% constant RHA content, an increase in the MK content led to an initial decrease followed by an increase in the consistency of the ternary cement blend. The initial decrease in the consistency could be attributed to the diminution of the clinker content but experienced an increase in the water consistency as the MK content was increased due to its reactivity.

Effect of RHA content on the water requirement for consistency at constant MK content. Figure 4 illustrates the effect of RHA at constant MK on the consistency of the ternary cement blend. The water requirement for normal consistency at constant MK from 5–20 wt% indicates an increase as the RHA content increased. This increment in water requirement can be attributed to the high surface area due to the amorphous nature and the unburnt carbon particle present in the RHA [27, 28], a similar trend was observed according to [5]. A similar trend of an increase in the RHA content at constant MK content resulted in a decrease in the workability of the cement paste blended with RHA which was in agreement with works by [37, 59, 60]. It could be observed that RHA significantly contributed to the water demand of the cement blend compared to the MK. The water required for normal consistency ranged from 0.323–0.523 for RHA increment at constant MK content from 5–20 wt%. According to [41], the water demand increased by 103 % and 112 % when RHA was increased from 10–30 % whereas resulted from increasing RHA at constant MK from 5–25 wt% led to increasing in the water demand by 107.7 to 174.3 %.

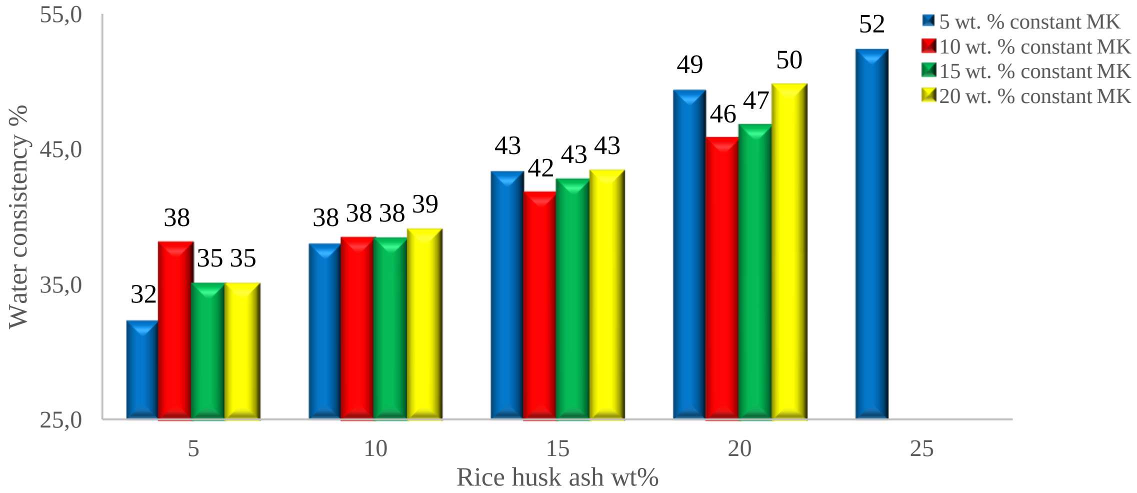

Figure 4 – Effect of RHA at constant MK on consistency of ternary blend

Setting time of ternary cement blends

Effect of RHA content at constant MK content on the setting time. Figures 5 and 6 indicate the effect of RHA at constant MK content on the initial and final setting time of ternary cement blends respectively. Contrary to [20, 37, 59, 60], an elongation of the initial and final setting time of RHA cement blend as the RHA content increases, It was observed that as the RHA content was gradually increased at constant MK content there was an acceleration in the initial setting time (shorter time). An increase in the RHA content from 5–25 wt% at 5 wt% constant MK content resulted in acceleration from 65 to 35 minutes for initial setting time. Similar trends were observed for 10, 15 and 20 wt% constant MK content as the RHA was gradually increased. This acceleration in the setting times could be attributed to the presence of MK as well as the high RHA reactivity due to the high siliceous content which reacts with $Ca(OH)_2$ during hydration to form calcium silicate hydrate, thus, resulting in shorter setting time. Other researchers also indicated that owing to RHA high amorphous silica content and its fineness could be contributory factor to the reduction of setting time as a result of rapid solubility of the siliceous content in the RHA, thus, leading to quicker pozzolanic reaction since RHA reactivity is influenced by the silica content, silica crystalline phase, and the size and surface area of the ash particle [38, 39].

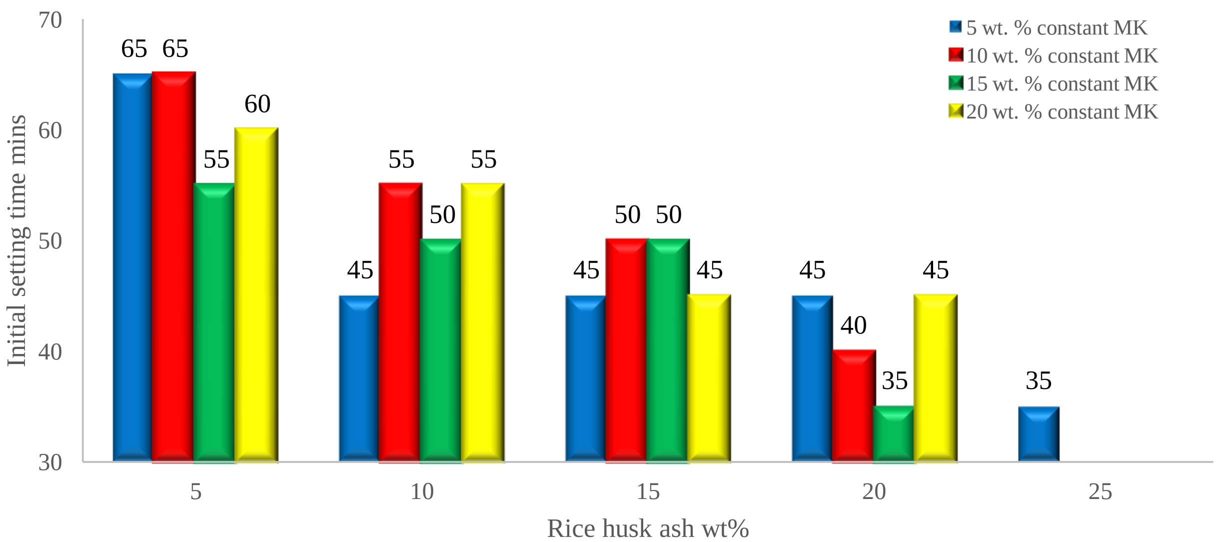

Figure 5 – Effect of RHA content at constant MK content on initial setting time of ternary blends

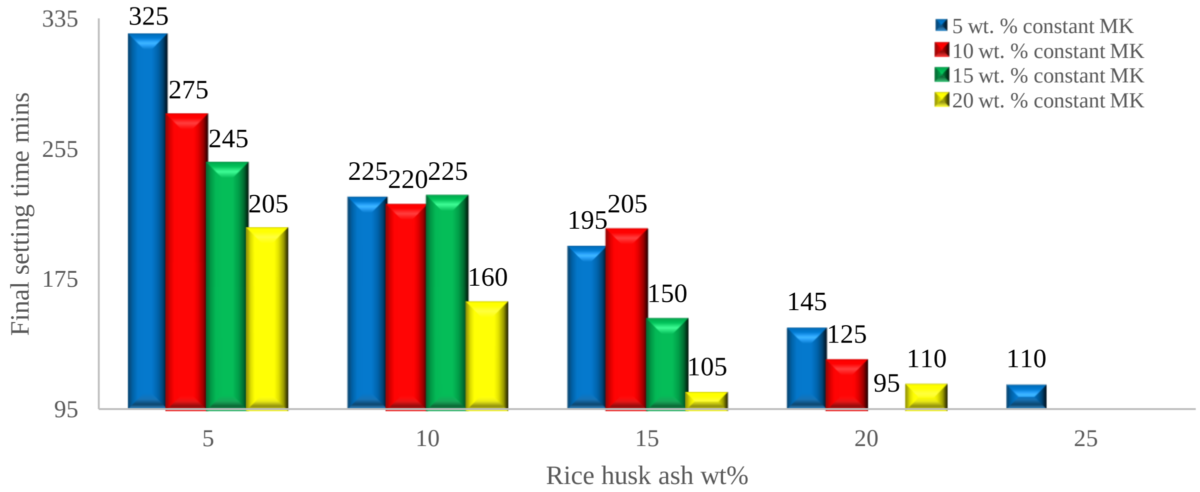

Figure 6 – Effect of RHA content at constant MK content on final setting time of ternary blends

Similarly, the final setting time diminished (accelerated setting time) was observed as RHA was gradually increasing at constant MK content. This can be attributed to the solubility of the RHA which was enhanced by improved surface area at the expenses of the gypsum and enter into reaction with calcium hydroxide during hydration, thus, the function of gypsum to regulate the setting time is interrupted resulting in acceleration of the final setting time.

Effect of MK content at constant RHA content on the setting time. Figures 7 and 8 illustrate the effect of MK content at various constant RHA content on the initial and final setting time at standard consistency of ternary cement respectively. As the MK content was increased from 5 -10 wt% at 5% constant RHA, the initial setting time of the ternary cement blend experienced no significant change, whereas, any further increment in the MK content beyond 10 wt% resulted from a series of acceleration and elongation in the initial setting time.

In general, a series of increases and decreases in the setting times as the MK content increases at constant RHA content was in agreement by [54] for binary blends. According to [54, 61] indicated no consistent change in the setting time produced as MK content increased up to 25 wt% at constant RHA content which was similar to results obtained as MK content was increased at constant RHA content.

A prolonged initial and final setting times could be attributed to the coating effect of MK particles on the cement matrix coupled with the ettringite formation as well as dilution of OPC as the MK content was increased. Whereas, the acceleration of the setting times could be due to a slight decrease in water consistency as the MK content was increased. Thus, it was observed that the cement replacement was independent of the MK content.

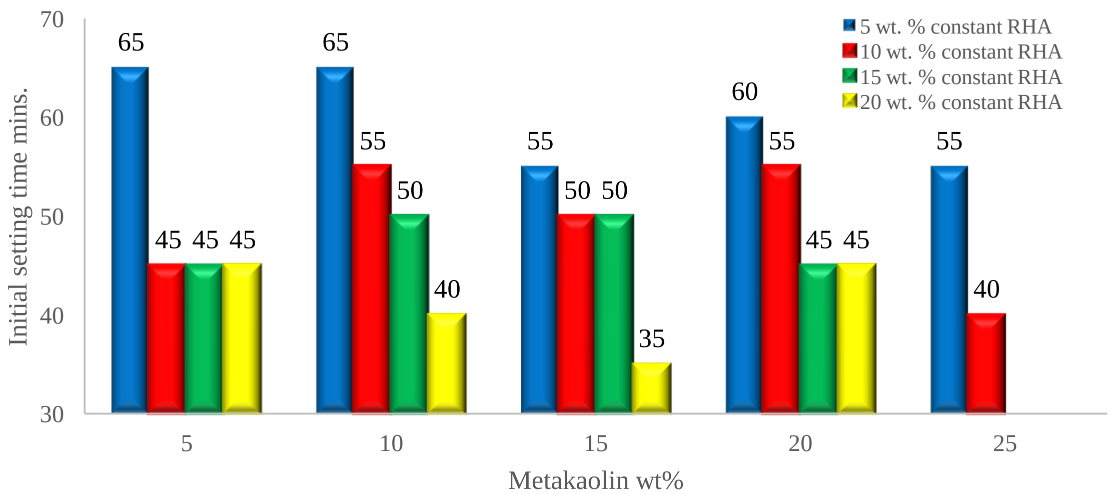

Figure 7 – Effect of MK content at constant RHA content on initial setting time of ternary blends

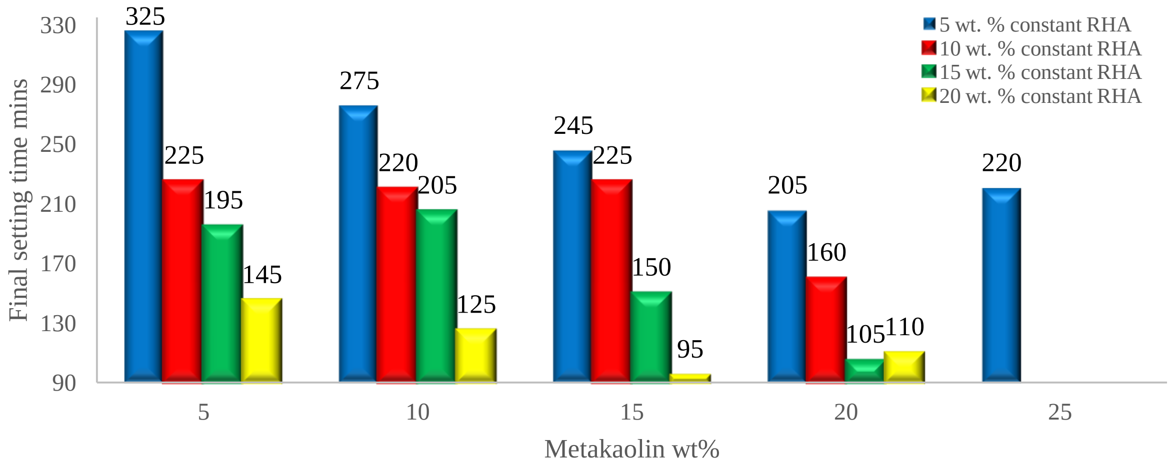

Figure 8 – Effect of MK content at constant RHA content on final setting time of ternary blends

Volume expansion/soundness of the ternary blends

Effect of RHA content on the soundness of Ternary Cement pastes at constant MK content. Figure 9 illustrates the effect of RHA content on the volume expansion (reduction in volume stability) of ternary cement paste at 5–20 wt% constant MK content. An increase in the RHA content at 5 wt% constant MK content resulted in an increase in the volume expansion from 1.0 mm to 2.5 mm. A similar trend of an increase in the volume expansion (reduction of volume stability) was experienced as the RHA content increased at constant MK content of 10, 15 and 20 wt% respectively. This volume instability can be attributed to the presence of CaO and MgO evident in the RHA.

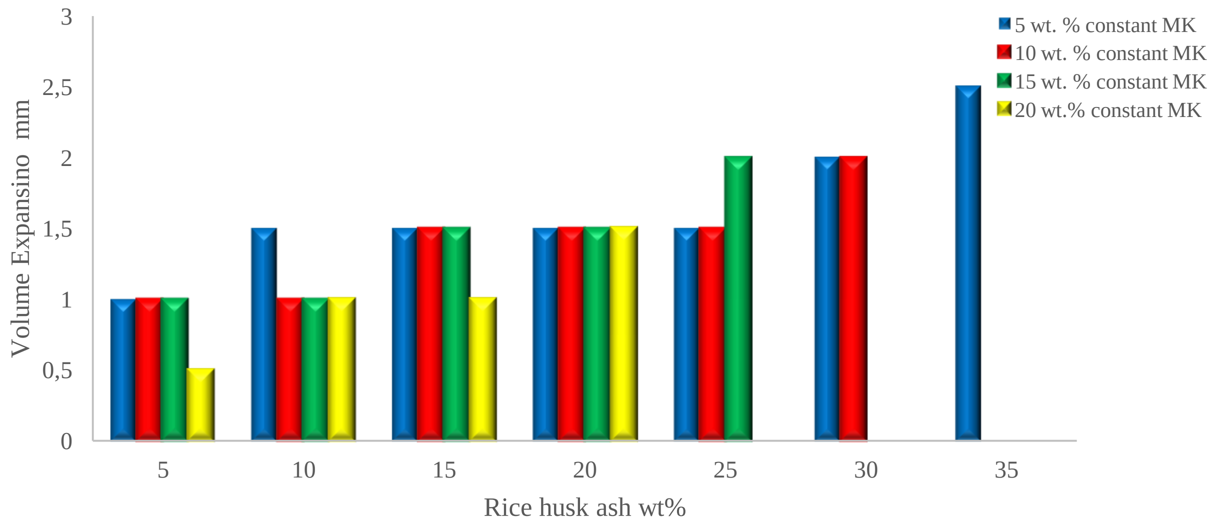

Figure 9 – Effect of RHA content at constant MK content on volume expansion of ternary blends

No significant change in the volume expansion was observed for the ternary cement blends between 10-25 wt% at 5 wt% constant MK content. This could be attributed to the pozzolanic reaction resulting in a reduction of the free lime. A similar trend was observed for between 5–10 wt% and 15-25 wt% RHA at 10 wt% constant MK content respectively. Ternary cement blends between 5-10 wt% and 15-20 wt% at 15 wt% constant MK also experienced no significant changes in the volume expansion possibly due to consumption of the available free lime that is responsible for unsoundness.

Effect of MK content on the soundness of ternary cement paste at constant RHA content. Figure 10 indicates a stepwise decrease of 0.5 mm in the volume expansion from 1.0 to 0.5 mm at 5 wt% constant RHA content whereas the volume expansion diminished from 1.5–0.5 mm as the MK content increases at 10 and 15 wt% constant RHA content respectively. This observed reduction in the volume expansion may be attributed to the diminution of OPC which contains a significant CaO/ MgO constant responsible for unsoundness. Authors [62] indicated that the main factor responsible for the volume expansion is free CaO and MgO content in the cement matrix. They concluded that the expansion is due to delayed hydration of CaO and MgO to form $Mg(OH)_2$ and $Ca(OH)_2$.

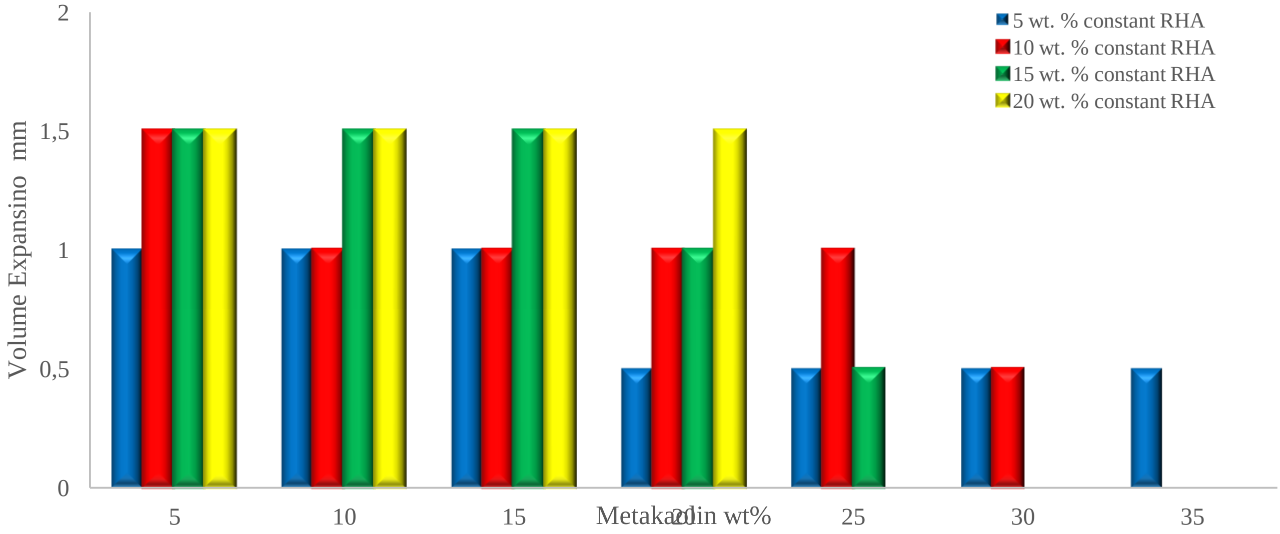

Figure 10 – Effect of MK content constant RHA content on volume expansion of ternary blends

It could be concluded that the RHA retarded the volume stability of the ternary blend, MK enhanced its stability owing to the presence of limited CaO/MgO content in its matrix. The OPC had a volume expansion of 3.0 mm in comparison with those of ternary cement blend which were relatively lower. This confirms the fact that the CaO and MgO contents present in OPC were significantly high compared to that of RHA and MK respectively.

Compressive strength of the ternary blends

The effect of MK content on the mortar compressive strength of cement blend and control at 5-20 wt% constant RHA and the effect of RHA content on the mortar compressive strength of cement blends at constant 5-20 wt% MK content are presented in Figures 11–14 and Figures 15–18 respectively.

Effect of MK content on the Compressive Strength of blended cement mortars at constant RHA content. Figures 11–14 illustrate the effect of MK content on the compressive strength at constant RHA content of 5, 10, 15 and 20 wt% respectively. It could be observed generally that as the curing days lengthened from 2–60 days, all cement blends and OPC experienced an increase in their mortar compressive strengths despite diminution of the clinker content.

Figure 11 indicated that as the MK content increased from 0–25 wt% at 5 wt% constant RHA, the cement blends produced improved mortar strengths at the various curing days. There was a significant strength gain as the curing days progressed at 28 days and beyond in comparison with control. According to [1], this strength development could be attributed to the high levels of silica and alumina in MK, and an increase in the C/S ratio due to CAH and CSH produced from interaction with CH, thus providing significant strength gain. Cement blends containing 20 wt% MK content produced the best mortar compressive strength of 40.5 MPa at curing time beyond 28 days (36 % strength gain compared with OPC control). This improvement was in agreement with [14, 15, 17] which showed similar trend after 28 days.

It could be observed from Figure 12 that for cement replacement of 5–10 wt% MK at 10 wt% RHA resulted in an enhanced mortar compressive strength compared with control especially after 28 days. Cement blended with 5 wt% MK content at 10 wt% constant RHA produced the best-improved mortar compressive strength beyond 2 days in comparison with OPC. This enhanced strength could be attributed to the high silica content present in the RHA coupled with MK rich in alumina and silica content which produces additional CSH and CAH with the residual CH present in the matrix. Authors [54] indicated a similar trend of improved strength as MK content increased at the replacement of 10–15 wt%.

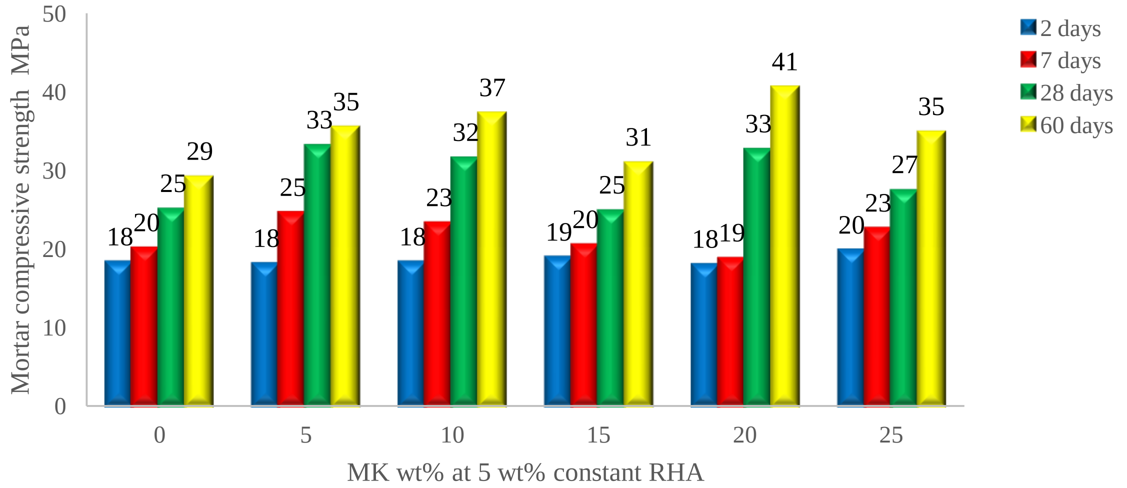

Figure 11 – Effect of MK content on Strength of blends and OPC mortars at 5 wt% constant RHA

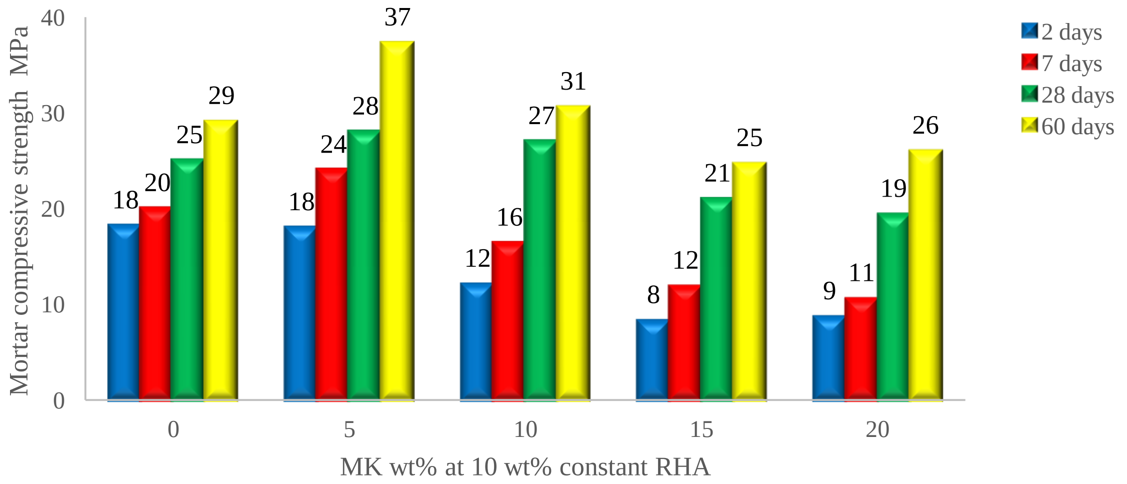

Figure 12 – Effect of MK content on mortar strength of blends at constant 10 wt% RHA and OPC

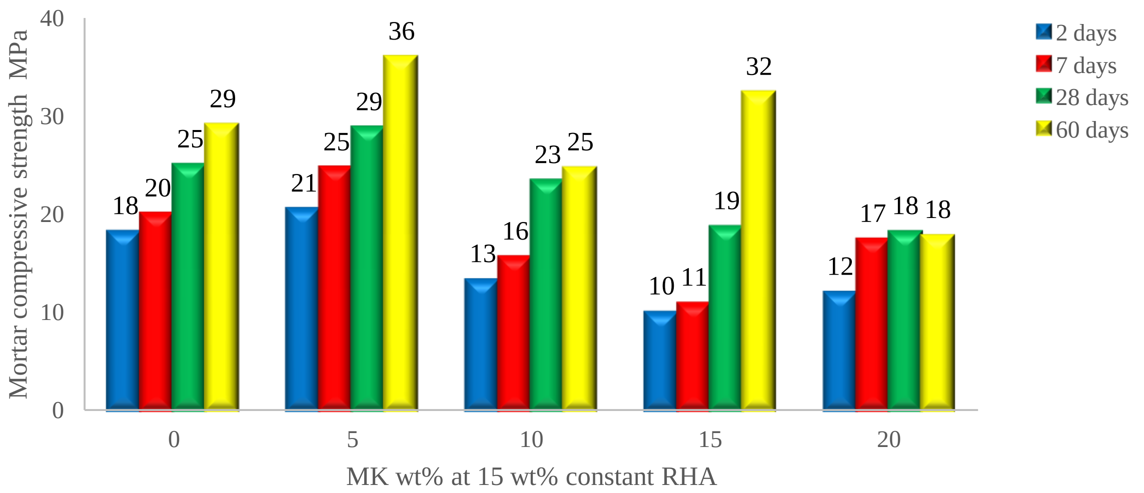

Figure 13 – Effect of MK content on mortar strength of blends at constant 15 wt% RHA and OPC

At 15 wt% RHA content, an increase in the MK content beyond 5 wt% produced lower strength in comparison with OPC. As the MK content was gradually increased from 5–20 wt% at 15 wt% constant RHA, it could also be observed that after 28 days, most of the blended cement mortar had either attained or exceeded the compressive strength of the control at 60 days expect at 20 wt% MK. This improved compressive strength of the ternary cement blends could be attributed to the formation of more nucleation sites, resulting in improved reactivity and packing which agrees with [54]. Similar trends of increase in the mortar compressive strength of OPC-MK at constant RHA increased as the curing time progressed up to 60 days and was observed for 10 wt%, 15 wt% and 20 wt% constant RHA content as illustrated in Figures 11, 12 and 14 respectively. Cement blended with 5 wt% MK produced the highest compressive strength due to MK acting as a nucleation site resulting in the acceleration of OPC hydration. The decrease in the mortar compressive strength as the cement replacement increased could be due to the diminution of the clinker content which agrees with [63] which also indicated a diminution indicated a diminution in the compressive strength as MK content was increased up to 20 wt%.

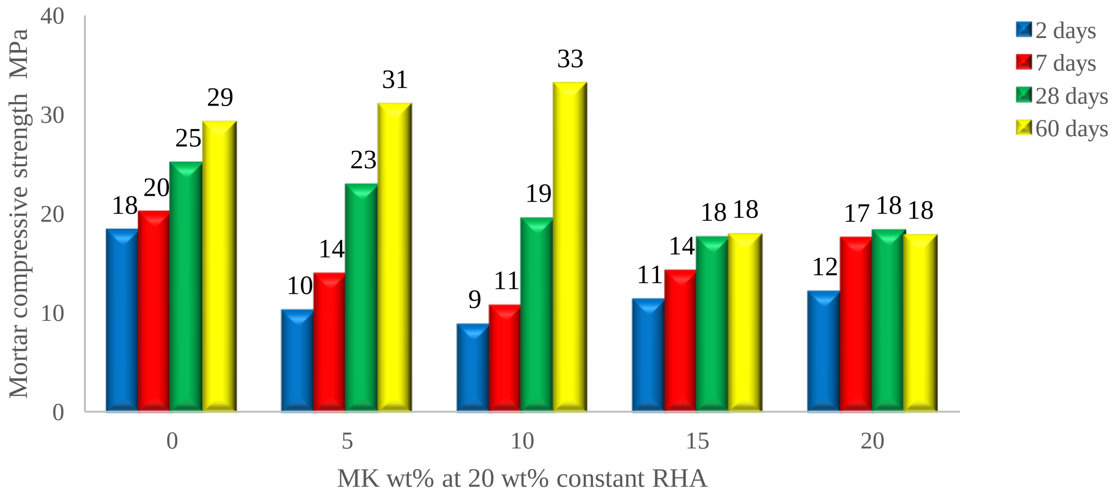

Figure 14 – Effect of MK content on mortar strength of blends at constant 20 wt% RHA and OPC

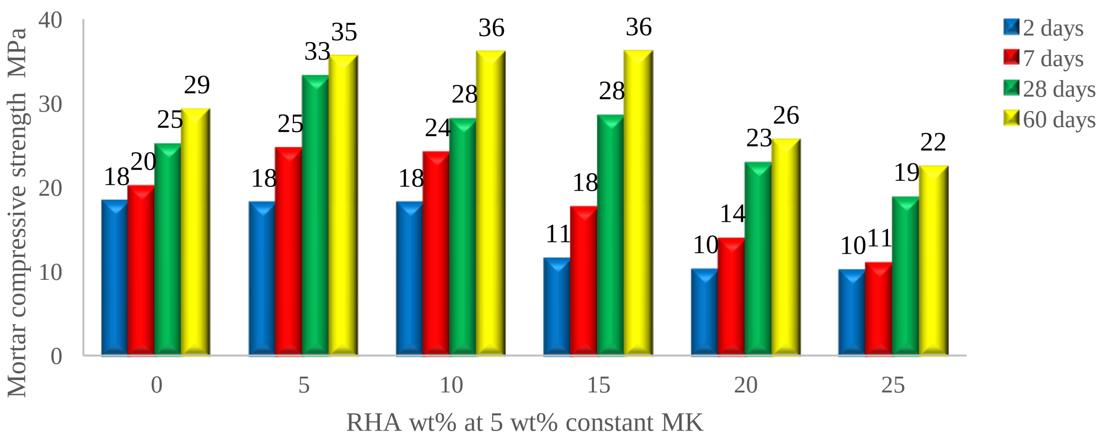

Figure 15 – Effect of RHA content at constant 5 wt% MK on compressive strength of blends and OPC mortars

It could be seen from Figure 14 that at the early age up to 28 days, that all blends produced mortar compressive strengths lower than the control which could be related to the dilution of OPC with MK and RHA. Whereas beyond 28 days, the compressive strengths of ternary cement blends with 5 wt% and 10 wt% MK at 20 wt% constant RHA were better than OPC control. The production of more hydration products like CSH, CAH & CASH which reduces the available pores resulting in a higher strength according to [64].

Effect of RHA at constant MK on the compressive strength of blended cement mortar. Figures 15–18 illustrate the effect of replacing cement with RHA content at 5, 10, 15 and 20 wt% constant MK content on the mortar compressive strength of ternary cement blends respectively. A significant reduction in the mortar compressive strength of the blended mortar was observed as RHA increased beyond 10 wt% at 5 wt% constant MK at 2 days, the mortar compressive strength began to diminish significantly in comparison with control. The reduction in blended cement mortar strengths could be attributed to the high unburnt carbon of the RHA (LOI of 3.36 wt%), owing to more water demand. The lower compressive strengths were experienced due to higher water requirements and dilution of Portland cement which agrees with [66]. A reduction in the compressive strength of the blended mortar was experienced when the RHA content was increased beyond 15 wt% after 7 days in comparison with OPC. The increase in compressive strength up to 15 wt% despite OPC dilution could be attributed to the pozzolanic activity resulting in enhanced strength. These results agree with the works of [9, 65] that RHA inclusion up to 15 wt% resulted in an enhanced mortar compressive strength beyond which resulted in a decrease in compressive strength. Results indicated a maximum compressive strength of 36 MPa for a ternary blend with 15 wt% RHA at 5 wt% constant MK content.

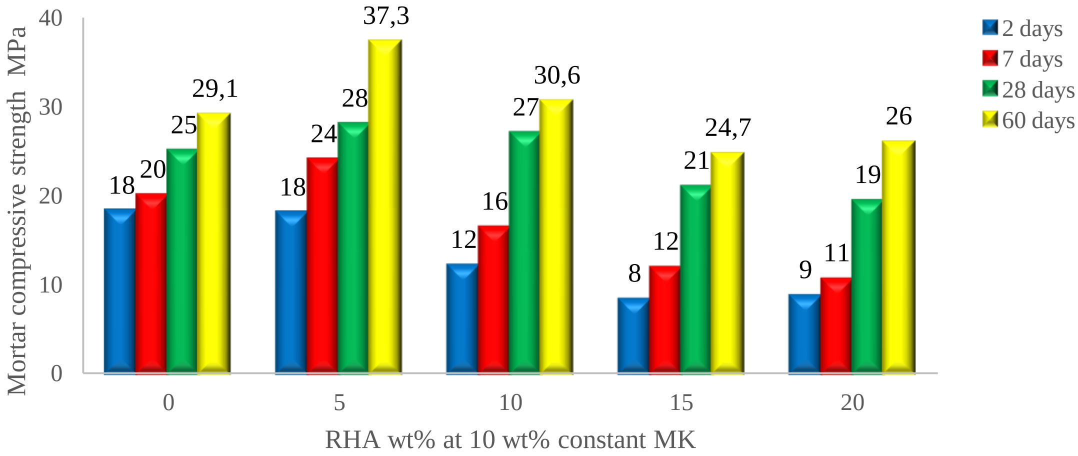

Figure 16 – Effect of RHA content at constant 10 wt% MK on compressive strength of blends and OPC mortars

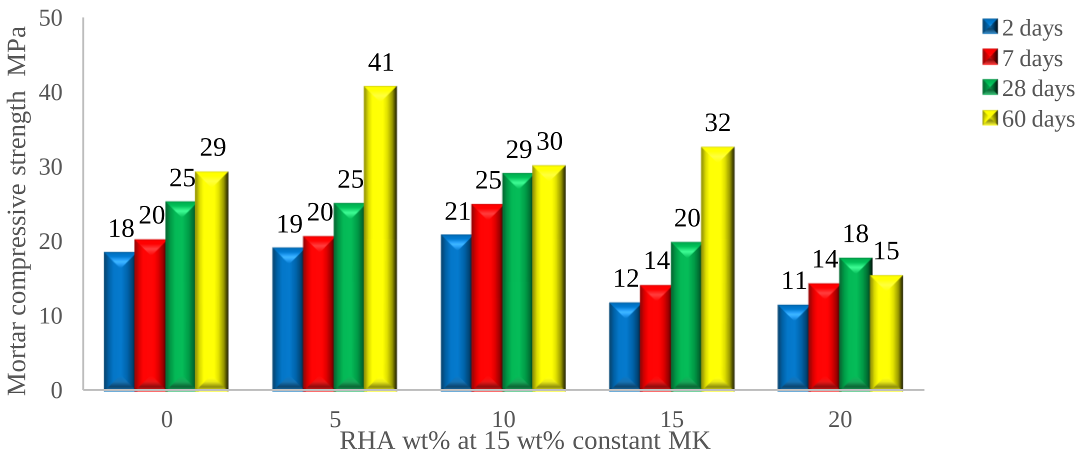

Figure 17 – Effect of RHA content at constant 15 wt% MK on compressive strength of blends and OPC mortars

From Figure 16, a reduction in the mortar compressive strength beyond 10 wt% RHA at constant 10 wt% MK was observed beyond 7 days whereas beyond 5 wt% RHA at 10 wt% constant MK led to a reduction in its strength up to 7 days. Cement replacement with 5 wt% RHA at 10 wt% constant MK produced the best mortar compressive strength of 37.3 MPa at 60 days which could be attributed to the pozzolanic activity leading to the formation of more CSH despite clinker diminution [47].

Similarly, the mortar compressive strength of up to 15 wt% RHA at 15 wt% constant MK and up to 10 wt% RHA at 20 wt% constant MK were higher than OPC control as observed in Figures 17 and 18 respectively. The initial increase in strength may be partially due to the pozzolanic reaction and the presence of reactive silica in RHA according to [23, 66]. Furthermore, the strength development of RHA above 15 wt% cement replacement resulted in a reduction in the compressive strength in comparison to OPC. This is an indication that the optimal cement replacement with RHA should not exceed 20 wt%. This decrease in the mortar compressive strength could either be attributed to the diminution of the clinker (reduction in the CaO / SiO_2) content coupled with the presence of unburnt carbon from the high loss of ignition (LOI) content of RHA [28].

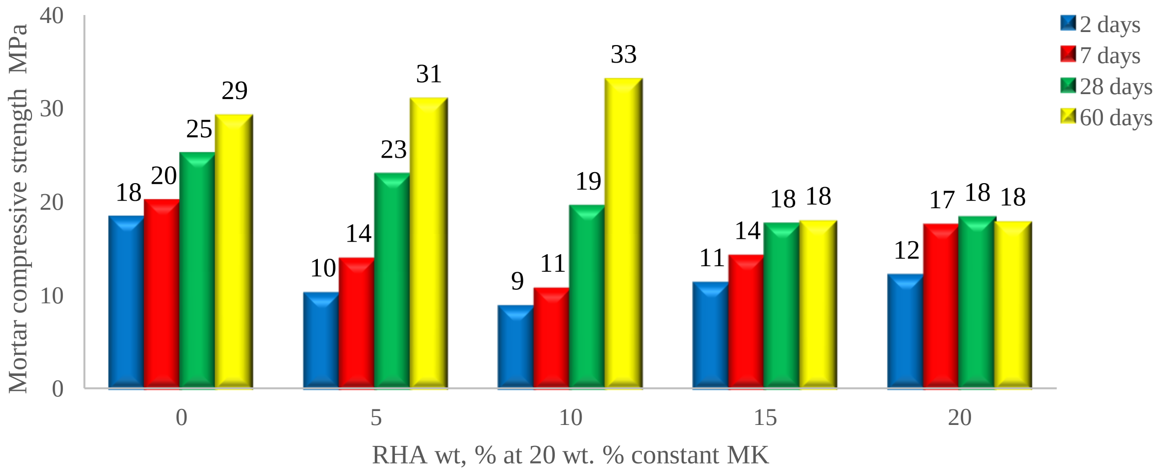

Figure 18 – Effect of RHA content at constant 20 wt% MK content on Strength of blends and OPC mortars

It was observed that any further increase in the RHA content beyond 10 wt% at constant 20 wt% MK resulted in a diminution of the compressive strength at 60 days. In general, MK produced a significant positive effect on the mortar compressive strength compared with RHA since RHA had a high unburnt carbon of 3.36 wt% which increases the water demand, thereby lowering the compressive strength [28].

CONCLUSION

The water consistency of ternary cement paste increased with an increase in OPC replacement with MK content up to 25 wt% at constant RHA content up to 10 wt%. However, beyond 10 wt%, constant RHA content with an increase in MK content results in no significant change (variation) in the water consistency. An increase in RHA content at constant MK content increased the water demands of the ternary blend. This increase could mainly be due to the unburnt carbon present in the RHA matrix.

The initial and final setting times experienced acceleration as the RHA was increased at constant MK content due to the high reactivity and the rapid solubility of the siliceous content in the RHA thus, leading to quicker pozzolanic reactions. Whereas a series of retardations and accelerations of both setting times were experienced as the MK content was increased at constant RHA content.

The volume expansion of the ternary cement paste gradually increases as RHA content increases up to 25 wt% at constant MK content due to CaO and MgO present in RHA. On the other hand, as the MK content increases up to 25 % at constant RHA content, the volume expansion diminished. The increase in volume expansion (volume instability) could be due to CaO and MgO present in the RHA. The decrease in volume expansion can be attributed to the diminution of ordinary Portland cement which contains significant content of CaO/MgO responsible for unsoundness. The ternary blends produced better and lower volume expansion results in comparison with the control.

The mortar compressive strength of the cement increased as the curing days were lengthened for both OPC and the ternary cement blends. The compressive strengths of the various blended cements showed significant improvement in comparison with OPC control which can be attributed to the formation of CSH and CAH from the reaction of the CH available after cement hydration and the silica and alumina present in MK and RHA, thus providing significant strength gain. A direct relationship exists between the MK content at constant RHA content and the compressive strength improvement. This can either be attributed to the high silica/ alumina contribution to the matrix or the C/S ratio in the cement matrix.

The mortar compressive strengths of MK-RHA-OPC blends were generally lower than control mixtures at pre 28 days, whereas, beyond 28 days compressive strengths of MK-RHA-OPC mixture were higher compared to OPC control. Since MK and RHA being highly pozzolanic, they both form additional calcium silicate hydrate and calcium aluminate hydrates by reaction with calcium hydroxide formed upon cement hydration, resulting in increased strength of the blended cement. During the initial stage of cement hydration, a sufficient amount of calcium hydroxide is not available, thus the early strength of blended cement is lower than that of ordinary cement.

Cement replacement of 5 wt% RHA and up to 25 wt% MK produced the best strength for the various ternary cement blends. The optimal ternary cement blend for the best mortar compressive strength was between 15–20 wt% MK and 5 wt% RHA. Similarly, ternary cement comprising of up to 10 wt% MK and up to 10 wt% RHA content produced a better strength gain compared to OPC control. This favorable behavior of blended cement at different ages was related to the high pozzolanic rate of MK and RHA, transforming the portlandite generated during the OPC hydration into CSH gels.

A decline in the mortar compressive strength of MK-RHA-OPC at 15 wt% RHA inclusion at constant MK content due to an increase in the water requirement coupled with clinker diminution. On the other hand, the strength gain diminished beyond 28 days was experienced as MK content was gradually increased up to 20 wt% while RHA was held constant beyond 15 wt%. The mortar compressive strength of cement replacement up to 20% RHA content at constant MK content experienced an increase followed by a decrease. This variation in the mortar compressive strength could be attributed to RHA's reactivity as well as the unburnt carbon present in the RHA matrix.

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CONFLICT OF INTEREST

The authors declared that they have no conflict of interest.

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