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STRENGTH PROPERTIES OF LOCALLY PRODUCED REACTIVE POWDER CONCRETE WITH UNREFINED METEKAOLIN

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With the soaring need to use innovative and sustainable materials in the construction industry, a new concrete known as Reactive Powder Concrete (RPC) is currently a material of significant interest globally. The concrete constitutes cement, silica fume, fine sand, quart sand and fibre as its ingredients. However, silica fume and fibre are relatively expensive in Nigeria due to their non-availability. This paper examines the effects of unrefined Metakaolin (MK) as substitute to silica fume and Gear Inner Wire (GIW) as fibre on the properties of RPC. RPC specimens produced with up to 30% MK by weight of cement, and a constant GIW content of 0.25% by weight of concrete were subjected to compressive strength, tensile strength and flexural strength tests. Similarly, RPC produced with 20% silica fume as reference was tested. The results show that 20% MK is the optimum content to produce RPC with the compressive, tensile and flexural strengths values of 64.5N/mm^2, 4.7 N/mm^2 and 18.7 N/mm^2, respectively. These strength values are comparable with that of the reference. Therefore, Nigerian unrefined MK and GIW can be used as ingredients for the production RPC.

Keywords: gear inner wire, reactive powder concrete, strength, unrefined metakaolin

INTRODUCTION

Many research works have been undertaken over the years aimed at achieving high mechanical performance with cementitious matrix materials (Chana, Luo and Sunb 2000, Aitcin, 2003, Momtazi, Ranjbar, Balalaei & Nemati, 2007, Maroliya & Modhere 2010; PatilS, Gupta and Deshpande, 2013 and Shan, Rijuldas & Aiswarya , 2016). Such development of an ultra-high strength and ductile concrete called Reactive

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Powder Concrete (RPC) was first made possible by Richard & Cheyrezy in 1995. It is produced by the application of a certain number of basic principles relating to the composition, mixing and treatment of the concrete.

RPC was developed through microstructure enhancement techniques for cementitious materials which include eliminating coarse aggregates, reducing the water-to-binder ratio, lowering calcium oxide (CaO) to silicon oxide (SiO2) ratio by introducing the silica components and incorporating steel micro-fibres (Yazici, Yardimci, Aydin, & Karabulut, 2009). There are a lot of researches carried out across the globe which indicate that RPC is a future concrete material because of its high mechanical properties.

RPC has a compressive strength of more than 170N/mm2, flexural strength of up to 60N/mm2 (Richard and Cheyrezy 1995) and tensile strength of up to10N/mm2 (Qureshi et al. 2017) using silica fume as the pozzolan. A compressive strength of 80N/mm2, tensile strength of 10 N/mm2 and flexural strength of 20 N/mm2 was achieved using local materials available in Pakistan (Qureshi, Tasaddiq, Ali and Sultan, 2017). RPC exhibits varied compressive strength when cured under different conditions.

The basic mechanical properties of RPC were examined under different curing conditions and the results indicated that the compressive strength at 28 days varied between 170 N/mm2 and 202 N/mm2 for heat treated specimens; up to 400 N/mm2 for autoclaving and between 130 N/mm2 and 150 N/mm2 for non-heat treated specimens (Cwirza, et al., 2008, Maroliya, 2012, Yazici, et al., 2009, Tam et al, 2010, Yazici, et al., 2010). However, the use of cement in conventional RPC is high and silica fume (SF) content is up to 25% (by weight of cement). Some of the shortcomings of SF are high cost, increase heat of hydration which causes shrinkage problems (Peng et al., 2015) and non availability in some countries like Nigeria. Moreover, steel fibre used in the production of RPC is also not available in Nigeria. The non availability of these two major materials of RPC production is becoming worrisome to the Nigerian construction industries as they have to battle between importation cost and delivering projects as an acceptable price to their clients.

Therefore, using other mineral admixtures in the production of the RPC has been proven to be a feasible solution to the problems of SF (Rougeau & Borys, 2004; Yazici et al., 2009; Yazici et al., 2010; Agharde & Bhalchandra, 2015; Kushartomo et al., 2015). When fly ash was used to replace SF in the production of RPC, compressive strength of between 62.9 N/mm2 to 324N/mm2 and a flexural strength of 8.8 N/mm2 to 32 N/mm2 were obtained (Yazıcı, Yigiter, Karabulut & Baradan 2008; Yazici et al. 2009; Ding 2010; Demiss, Oyawa & Shitote 2018). A compressive strength of 128 N/mm2 to 250 N/mm2 and a flexural strength of between 25.6 N/mm2 to 32 N/mm2 were obtained with ground granulated blast furnance slag (Yazici et al. 2009; Peng, Hu & Ding 2010; Nguyen et al. 2011). Also, Asteray, Oyawa & Shitote (2017) observed that a 28 days compressive strength of 57.3 N/mm2 was achieved when rice husk ash was used to replace the SF in the production of the RPC.

Moreover, other materials were used as fibre in the production of mortar and concrete in areas where conventional fibres are not available and proved to be effective. Some researchers like Foti (2013) studied concrete specimens reinforced with fibers made from waste polyethylene terephthalate (PET) bottles. Jalal (2012) used waste steel fibre recovered from milling and machining in concrete production and the results indicated improvement of the fragile matrix, mostly in terms of toughness, energy absorption and post-cracking behavior. Study on the influence of adding waste materials like lathe waste, soft drink bottle caps, empty waste tins, waste steel powder from workshop at a dosage of 1% of total weight of concrete as fibres was undertaken by Murali et al., (2012). These materials were deformed into rectangular strips of 3mm width and 10mm length. Results showed that a concrete block incorporated with steel powder has increase in compressive strength by 41.25% and tensile strength by 40.81%. Concrete made with soft drink bottle caps exhibited an increase in flexural strength by 25.88%. The effect of polyethylene terephthalate (PET) as fibre using different volume (0%, 0.5%, 1.0% and 1.5%) in mortar production was investigated by Pereira de Oliveira & Castro-Gomes (2011). Results showed that the incorporation of PET fibres significantly improves the flexural strength and toughness of mortars, so also, 1.5% was regarded as optimum for desired workability. More recently, Ibrahim, Garba, Usman and Gambo (2018), used waste gear inner wire as fibre (WGIW) in mortar production. Results showed that the fibred mortar sample has higher compressive and tensile strengths at 56 days by 19% and 21.1% respectively than the unfibred one and concluded that WGIW at 2% volume fraction could be used as fibre in mortar production.

However, for RPC to be produced in Nigeria there is the need to find similar, available and alternative material to SF and steel fibre in terms of performance. These ways, the costs of producing the concrete can be reduced by cutting down importation cost. MK has been found to perform similar to SF on the properties of concrete and is used in the same manner (ACI 232.1R-00). Another advantage of using MK is that it improves tensile strength and bond strength (Vipat and Kulkarni, 2016) and up to 8%MK enhances tensile strength (Haroon, Ashad, Vikas and Alvin, 2017) of concrete but 10% has been reported by Badogiannis (2005) to be more favourable. There are large deposits of kaolinitic clay from which MK is obtained across Nigeria (Getso, 2014). Some percentage (15%) of the SF has been partially replaced with commercial MK in the production of RPC, which indicated savings (Smith et al., 2015). In normal concrete, unrefined metakaolin has been shown to improve the strength and durability properties of concrete similar to the refined one (Badogiannis & Tsivilis 2009). Therefore, further savings can be realized if the refined metakaolin is replaced with the unrefined one in the production of RPC. The Nigeria's large deposits of kaolinitic clay may be used to produce the unrefined metakaolin.

This research, therefore, focused on the production of RPC from locally sourced Gear Inner Wire (GIW) and unrefined metakaolin obtained from the abundant kaolinitic clay deposits in Nigeria as SF is expensive and also not readily available in country. Using the unrefined MK further reduced the cost of producing the RPC by eliminating refining and beneficiating process associated with refined MK.

MATERIALS AND METHODS

Materials

The cementitious materials used for this research are cement; metakaolin (MK) and densified silica fume (SF). The cement is Dangote brand of Portland Limestone. MK was produced by heating unrefined kaolin at 750oC for 2 hrs in an electric furnace. The kaolin was sourced from a kaolinitic clay deposit situated in Getso, Kano State. As shown in Figure 1, there is complete transformation of kaolinite mineral to metakaolin after heating, and that the major crystalline phases of MK are quartz and Phengite. The silica fume was supplied from Malaysia. The chemical composition and physical properties of the cementitious materials are presented in Table 1. Based on its chemical compositions and physical properties, the MK can be satisfied as N- Class pozzolan as recommended in the ASTM C 618 requirements. Gear Inner Wires (GIW) cut into pieces was used as fibre. The GIW are characterized by different diameters of 0.28mm, 0.32mm and 0.39mm which was determined using digital vernia caliper. The GIW with highest aspect ratio (43) was selected and used in the entire experiment. Sable & Rathi, (2012) states that the higher the aspect ratio of a fibre, the more the compressive and tensile strengths of concrete will be. It is on this basis that the selection was made. The geometry of the fibre is shown in Table 1. Polycarboxylate ether based super plasticizer (Conplast SP 430) conforming to ASTM C 494 was used to achieve the required consistency of the mixes. Naturally occurring river sand with particle sizes of 600μm - 150μm and absorption of 4% was used as fine aggregate.

Table 1: Properties of Gear Inner Wire (GIW) as Fiber

S/No.	Diameter (mm)	Length(mm)	Aspect Ratio (L/D)	Tensile Strength (N/mm^2)
1.	0.28	12	43	1623
2.	0.32	12	38	1888
3.	0.39	12	31	1657

Mix proportioning

Mix design of the RPC produced evolved from several trials due to the absence of an established design method. However, the formulation used by Richard and Cheyrezy (1995) was adopted as a basis for the trial and error. The ingredients used in this study for the control mix of RPC include cement, silica fume, fine sand, GIW as fibre, superplasticizer, and water. The specimens were then produced by totally replacing the SF content with MK. The MK was used in different percentages (10%, 20% and 30%) of the weight of cement. Quartz powder was not used in the RPC because it is only used for heat-treated RPC (Richard and Chereyzy, 1995). The mix proportions of the RPC specimens are presented in Table 2. Different mixes were labeled for identification, based on the type and content of the pozzolanic material used in their production. For instance, 20SF means, the specimen was produced with 20% silica fume (SF) while 10MK is that specimen produced with 10% metakaolin (MK).

Table 2: Mix proportion of RPC specimens

Specimen ID	20SF	10MK	20MK	30MK	20SF	10MK	20MK	30MK
	Non fibred				Fibred			
Cement	1	1	1	1	1	1	1	1
Silica fume	0.20	0	0	0	0.20	0	0	0
Metakaolin	0	0.10	0.20	0.30	0	0.10	0.20	0.30
Sand (150-600μm)	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Crushed quartz	-	-	-	-	-	-	-	-
Superplasticizer	3.5	2.8	3.8	4.5	3.6	3.2	3.9	5.0
(GIW) L=12mm	-	-	-	-	0.02	0.02	0.02	0.02
Water	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Comp. press.	-	-	-	-	-	-	-	-
Heat treatment temp. (°C)	27	27	27	27	27	27	27	27

Note: Cement Content = 900Kg/m^3; Fibre Content= % of weight of concrete, SP content=% of binder

Specimens preparation

To prepare the specimen, the cementitious materials were dry mixed in a mortar mixer for about one minute at low speed of 10 rpm. Premixed water (about 80% of the mixing water) and superplastizer were added into the mixer and the mixing continued for three minutes at medium speed (140 ± 5 rpm). Fine sand and GIW as fibre were then added into the mixer and mixing continued for another four minutes. The remaining mixing water (about 20%) was then added to the mixer and mixed at high speed (285 ± 10 rpm) for additional four minutes. Finally, the mixer was then returned to the medium speed (140 ± 5 rpm) and mix for three minutes. This mixing method was adopted from Hiremath & Yaragal (2017). All the fresh mixes had consistency of 270±5 mm. After mixing, the fresh specimens were cast and kept in moulds for 24 hours in the laboratory condition (27 ± 2oC). Cube moulds of 50x 50 x 50 mm, cylindrical moulds of 50mmx100mm and prismatic moulds of 40x40x160mm were cast the specimens for compressive strength, split-tensile strength and flexural strength tests, respectively. Specimens were then taken out from the moulds and cured in water until the testing ages of 7, 14 and 28 days.

Testing Methods

Flowability

The Flowability of the different mixes was tested using a flow table in accordance with ASTM C143. This was conducted by filling a mini-slump cone. The cone was then carefully removed to allow the mix to flow under the influence of gravity. The flow of the mix was obtained by measuring the spread using a measuring tape. Average of four measurements of the spread was reported for each mix.

Strength properties

Compressive strength, split-tensile strength and flexural strength tests on the specimens were carried out according to BS EN 12390-3:2002, ASTM C496, ASTM C78 respectively. The average of five measurements was reported for each test.

RESULTS AND DISCUSSIONS

Characterization

Tests conducted under characterization include XRD, chemical composition and strength activity of MK, so also the geometry of the Gear Inner Wire.

X-Ray diffraction

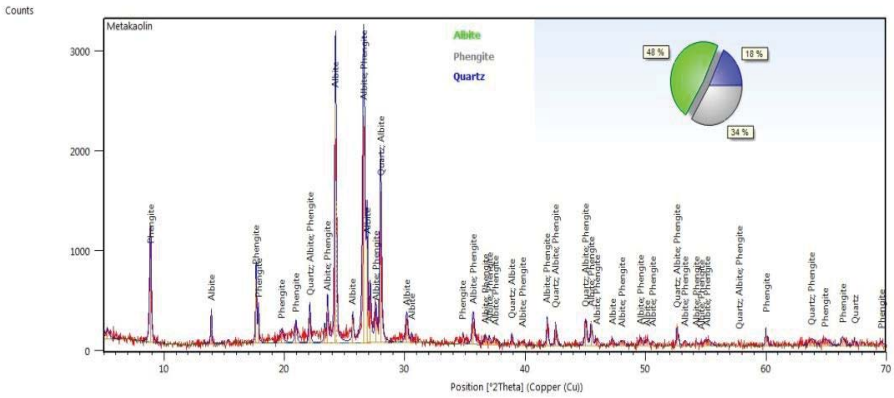

Figure 1: XRD result of Metakaolin

Figure 1 shows the XRD result of MK which showed a product of low crystallinity. Crystalline phases consisted of quartz and Phengite, mainly Albite. Phengite is a high silica variety of muscovite on the chemical join between muscovite, celadonite, and aluminoceladonite while Albite, a common feldspar mineral, is a sodium aluminosilicate (NaAlSi3O8) that occurs most widely in pegmatites and felsic igneous rocks such as granites. Figure 1 also shows no sign of kaolinite on the fix and the 2θ value (between 10 -30) shows hallow in shape. This indicates that the material used in the experiment is MK.

Chemical composition

Table 3: Oxide c compositions and physical properties of RPC constituents

Oxide (%)	Sand	Cement	Silica fume	Metakaolin
SiO_2	86.53	17.519	92.00	65.05
Fe_2O_3	2.94	2.768	0.50	2.59
Al_2O_3	1.64	4.74	0.70	20.65
CaO	0.40	71.297	0.50	0.82
CuO	0.00	0		0.02
NiO	0.00	0	0.015	0.03
MnO	0.01	0.072	0.128	0.08
Cr_2O_3	0.00	0	0.006	0.03
TiO_2	0.00	0.105	0.071	0.00
MgO	0.60	0	0.50	1.66
SO_3	0.10	0.00	0.00	0.18
ZnO	0.00	0.007	0.006	0.01
$SiO_2 + Al_2O_3 + Fe_2O_3$				88.29
LOI	0.84	3.492	3.00	1.80
Physical properties				
Surface area (m^2 /kg)			2 0, 000	509.0
Strength activity index (%)			-	87
Specific gravity			2.21	2.53

Flowability of RPC

(a) During pouring (b) During measuring

Figure 2. Flowability of RPC

Figure 2 shows the flowing nature of the RPC produced. RPC is considered to be self flowing concrete. ASTM C143 (AASHTO T119) states that for concrete to be regarded as self compacting concrete, the flow value or workability of such concrete should be > 190mm and ASTM C1611 states that the value should be ≤600mm (24 in). Therefore, it was based upon this range and series of trials that the flow value of the RPC produced was fixed at 270±5mm. This value was achieved by the addition of superplasticizer. Figure X shows the effect of MK and SF on the consumption of superplasticizer to achieve the targeted flow (270±5mm) of RPC. It can be observed that the superplasticizer (sp) dosage for RPC increased with the increasing MK content. The dosage of sp required for the RPC specimens produced with 10%MK, 20%MK, 30%MK and 20% SF, were x, y, z, respectively. The increasing sp demand of MK can be ascribed to its high surface area.

Compressive strength of RPC

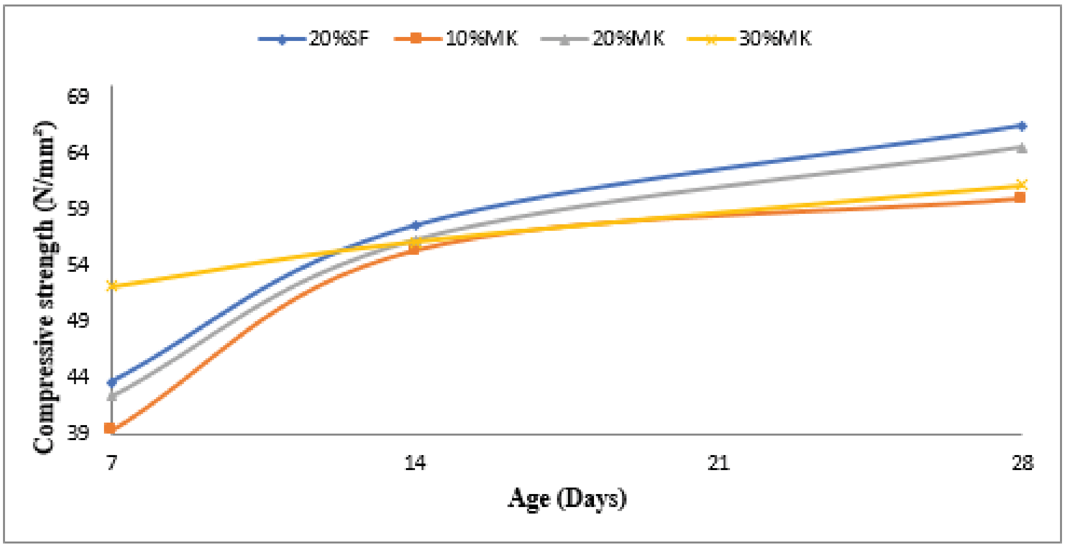

Figure 3. Effect of MK content on the compressive strength of unfibred RPC

Figures 3 and 4 show the effect of MK content on the compressive strength of unfibred and fibred RPC at different ages, respectively. For the fibred and unfibred specimens, increase in compressive strength with age can be observed. At 7 and 28 days, the compressive strengths of unfibred specimen with 20% MK were comparable to those for the reference (20%SF). However, the specimen with 30%

MK showed higher strength at 7 days but lower at 28 days. The improved strength exhibited by the specimen with 30%MK could be due to the fast pozzolanic reaction of MK at the early age due to the presence of more SiO2 that reacted with the Ca(OH)2 liberated during hydration to produce additional cementitious compounds such as C-S-H and CSAH.. On the other hand, the control concrete has higher early compressive strength compare to 10%MK due to high pozzolanic activity and finer particle sizes of the SF than the MK. At 28 days, the compressive strengths of specimens with 10%MK, 20%MK and 30%MK are 89.1%, 97.1% and 91.3% of that of the control (64.5 N/mm2). Hence, 20% seems to be the optimum content of MK to produce RPC with comparable compressive strength to that of the control.

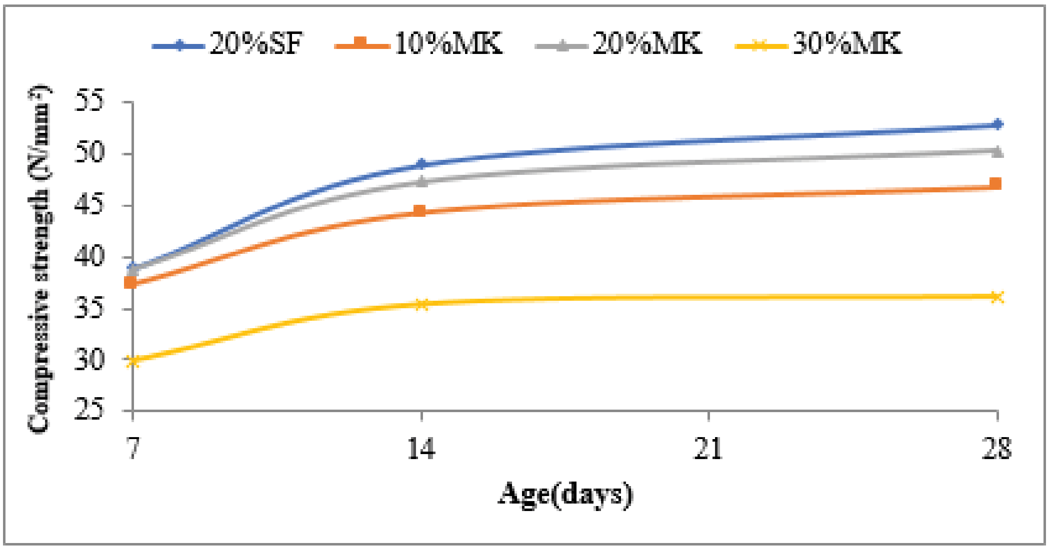

Figure 4. Effect of MK content on the compressive strength of fibred RPC

However, the fibred specimens showed variation in compressive strength compared to the unfibred as shown in Figure 4. At 7 days, the compressive strengths of the fibred specimens with 20%SF, 10%MK, 20%MK and 30%MK are 38.9N/mm2, 37.4 N/mm2, 38.8 N/mm2 and 29.9 N/mm2 respectively. While at 28 days, the compressive strengths of the specimens with 10%MK, 20%MK and 30%MK were 87.2%, 100% and 86.5% of that of control (50.3N/mm2). Apparently, the introduction of fibre caused reduction in strength probably due to its slippery surface that could hinder adequate bond between the fibres and cement paste. This is line with what Iqbal, Ali, Holschemacher and Bier, (2015) reported that there is around 12% reduction in compressive strength with increase of steel fiber content from 0% to 1.25%. The compressive strength of RPC produced with 20%MK in this study is superior to those obtained when rice husk ash (RHA) and fly ash were separately used as reported by Asteray, Oyawa & Shitote (2017) and Demiss, Oyawa & Shitote (2018) respectively.

Tensile strength

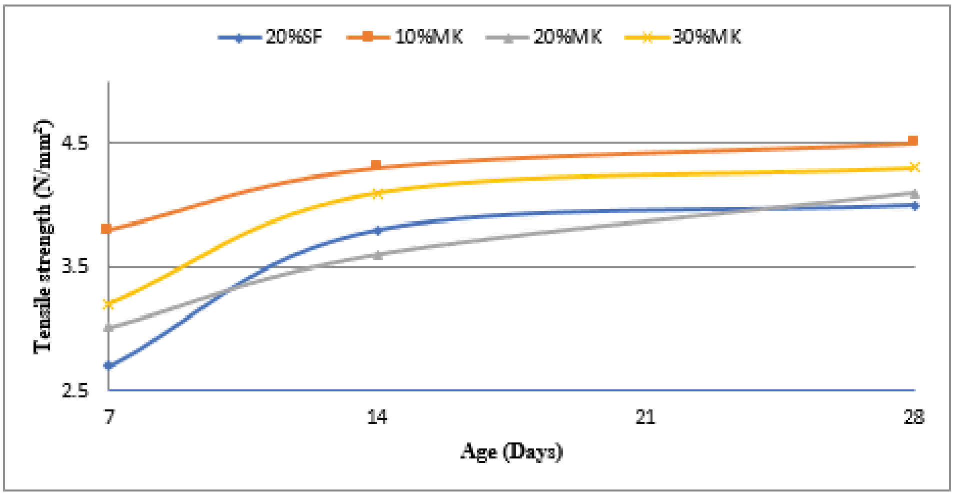

Figure 5. Effect of MK content on the tensile strength of unfibred RPC

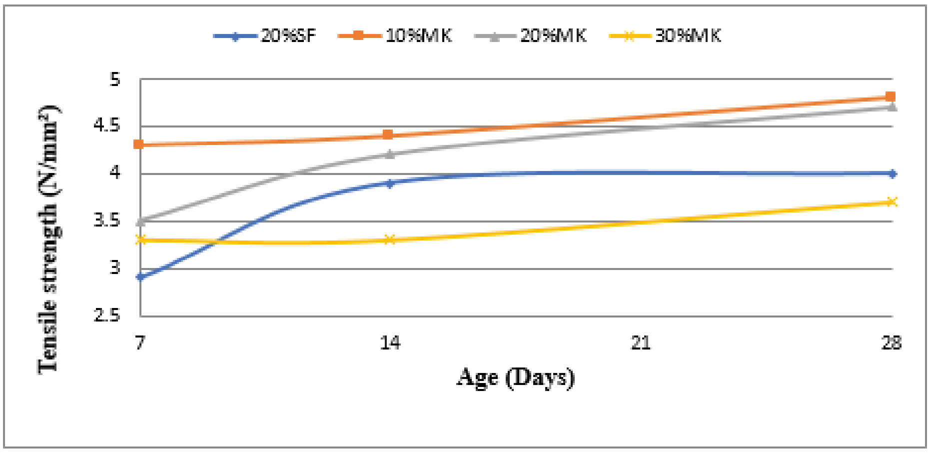

Figure 6. Effect of MK content on the tensile strength of fibred RPC

Figures 5 and 6 depict the split tensile strength of unfibred and fibred RPC samples respectively. As shown in Figure 5, the tensile strength of unfibred specimens with MK at all ages were generally higher than that of the control. At 7 days, the tensile strength of the 20%SF, 10%MK, 20%MK and 30%MK are 2.7 N/mm2, 3.8 N/mm2, 3.01 N/mm2 and 3.2N/mm2 respectively. At 28 days, the strengths for 10%MK, 20%MK and 30%MK were higher than that of the control by 29%, 10% and 16% respectively. The improvement in the tensile strength of the specimens with MK could be due to the filler and pozzolanic effects of MK that enhance the microstructure of RPC (Vipat and Kulkarni, 2016).

For the fibred specimens, as shown in Figure 6, it is clear that the inclusion of fibre improve the tensile strengths of all the specimens. And that the strength improvement reduces with the increasing MK content at all ages. The tensile strengths of the specimens with 20%SF, 10%MK, 20%MK and 30%MK at 7 days are 2.9 N/mm2, 4.3 N/mm2, 3.5 N/mm2 and 3.3N/mm2 while those at 28 days are 4 N/mm2, 4.8 N/mm2, 4.7 N/mm2 and 3.7N/mm2 respectively. Hence, up to 30% MK can be used to develop fibred RPC with improved tensile strength.

Flexural strength

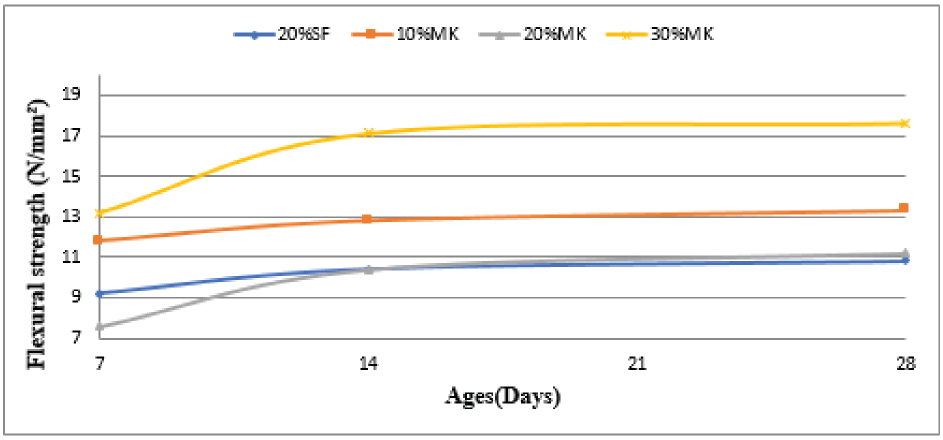

Figure 7. Effect of MK content on the flexural strength of unfibred RPC

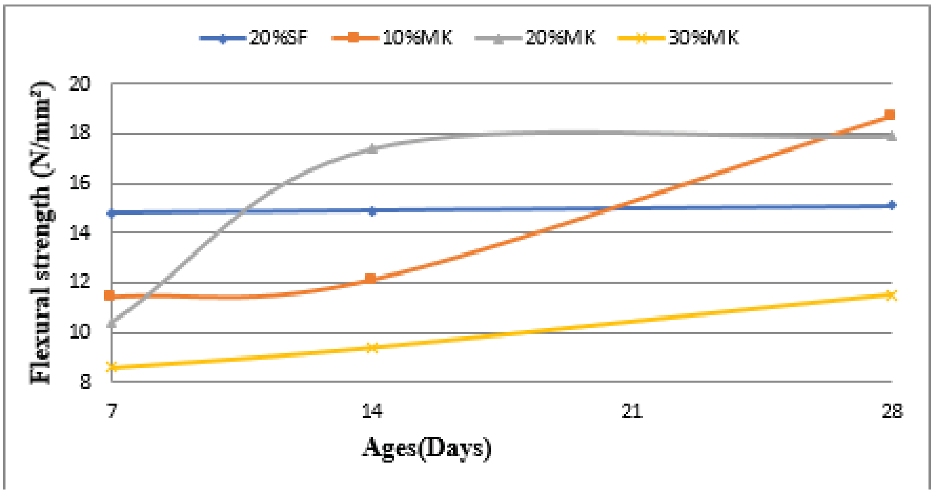

Figure 8. Effect of MK content on the flexural strength of fibred RPC

The flexural strengths of fibred and unfibred RPC are presented in Figures 7 and 8. Compared to the control, MK improved the flexural strength of unfibred RPC, and the improvement goes along with the increase in MK content. At 28 days, the range of flexural strength of the MK based RPC is 11.23- 17.6 N/mm2. However, the flexural strength of the control is 11.2 N/mm2. As shown in Figure 8, fibre improved the flexural strengths of all the specimens. However, extent of improvement over curing ages is more pronounced with the specimens made with MK but low with SF. Overall, 20% MK outperformed the other specimens at all ages. Hence, the 20% is the optimum MK content for flexural strength enhancement. The improvement in the flexural strength of the MK RPC could be due to the micro filling effect and pozzolanic reaction of MK (Vipat and Kulkarni, 2016). Results similar to this study was also reported by (Haroon, Ashad, Vikas and Alvin, 2017) and Demiss, Oyawa & Shitote (2018).

CONCLUSIONS

The unrefined metakaolin and gear inner wires have been found to be suitable in the production of reactive powder concrete (RPC). Unrefine metakaolin of up to 20% by the weight of cement and GIW of up to 0.25% could be used in the production of the RPC with compressive, tensile and flexural strengths of up to

64.5N/mm2, 4.7 N/mm2 and 18.7 N/mm2 respectively. However, GIW has been found to decrease the compressive strength and improves tensile and flexural strengths of the RPC. Reactive powder concrete of this type can easily be produced without necessarily the need for pressure and heat treatment. Moreover, the use of the unrefined MK and GIW can lead to production of cheaper and sustainable RPC by cutting down importation cost of both SF and fibre materials.

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