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Performance Evaluation of Properties of High Performance Mortars Derived from Metakaolin and Waste Marble Dust

Haider M. Owaid and Hayder M. Al-Khafaji
Department of Civil Engineering, Faculty of Engineering, University of Babylon, Babil, Iraq

Abstract: The purpose of the research is to evaluate the properties of High Performance Mortars (HPMs) produced from Metakaolin (MK) and Waste Marble Dust (WMD) as a partial substitution to Ordinary Portland Cement (OPC) in binary and ternary cementitious mixtures. For this scope, the water/binder ratio utilised to prepare the mortar was 0.30 with a binder content of 640 kg/m^3 totally and a cementitious/sand ratio of 1:2.25. The control mix was prepared from OPC only as the binder while the other mixes consisted of cement replaced with MK up to 10% and WMD up to 20% in binary and ternary mixtures. The workability of fresh HPMs was tested using flow table and slump tests. The compressive strength of the hardened mortars was tested at curing of 3, 7, 28, 56 and 90 days while unit weight and the flexural tensile strength tests were conducted at 28 days. The results indicated that the slump and flow values were gradually decreased for all the binary and ternary mortars blends with increasing the replacement levels of MK and WMD. In addition, the compressive strength decreased generally for all the binary mortars mixtures at 3, 7 days and more, mortars mixtures with the replacement of 10 and 20% of MK and 10% WMD gave the best results from than control mortar, except for the 20% WMD, mortar which decreased from the control for all curing ages. The compressive strength of the mortar mixtures in ternary mortars blends at 28 days were better than that of the control mortar and binary blends systems for the same replacement levels. Moreover, 10% MK and 10% WMD caused a increases in flexural tensile strength of the mortars in the binary and ternary blending mixtures at curing of 28 days.

Key words: Fresh properties, hardened characteristics, High Performance Mortars (HPMs), Iraqi metakaolin, waste marble dust, control mortar

INTRODUCTION

The production of cement in spite of being enhanced significantly with respect to the environment remains polluting and contributes in emitting considerable amount of CO_2. Hence, it needs to be enhanced by minimising the cement consumption through the utilisation of less polluting materials or the substitution of cement by by-products or wastes for the manufacture of concrete and high-performance mortar. Furthermore, cement production can be reduced by replacing a percentage of the cement with waste materials that potentially improve the specifications of fresh and hardened concrete. The result of this is a reduction in the industrial processes number which means enhancing the effectiveness of cost and time while minimising the pollution to the environment. Thus, with the need of large quantities of cement worldwide, the use of agricultural and industrial wastes as a cement replacement can benefit the environment and the economy on a global scale (Nagarajan *et al*., 2014).

Consequently, to minimize these, researches have concentrated on the utilization of waste and pozzolanic materials such as Metakaolin (MK), Rice Husk Ash (RHA), Marble Powder (MP), Fly Ash (FA), Granite Powder (GP) and so on as potential alternatives in the construction industry, especially in concrete construction. Recently, the increasing knowledge on the impact of reducing solid wastes on the environment and human health has motivated researchers to use them with the production of construction materials. These waste do not impose any cementing characteristics of their own; they only do so when Calcium Hydroxide ($Ca(OH_2)$) or calcium oxide is present. The alumina and silica in the pozzolans will also react forming cementitious materials. A component of the composite anisotropic material or ‘‘masonry’’ is mortar. Mortar has a principal role in providing a uniform stress distribution amending the blocks irregularities and allowing for the deformations from shrinkage and thermal expansions. It is crucial to know the hardened and fresh characteristics, so as to maintain an adequate performance of masonry walls. The

Corresponding Author: Haider M. Owaid, Department of Civil Engineering, Faculty of Engineering, University of Babylon, Babil, Iraq

utilisation of Pozzolanic Materials (PM) to replace cement in either mortar or concrete mixtures or in other types of concretes including high performance, reactive powder, lightweight and self-compacting, represents an effective method to reduce environmental issues and provides an improvement to concrete mechanical properties because of hydraulic or/and pozzolanic.

One of the most promising types of natural high-quality pozzolans is the Metakaolin (MK). MK is obtained by the calcination of kaolinite which is used in this study. It is common to include the MK in the concrete or mortar mixtures and its usage have led to a significant improvement in the durability and mechanical characteristics of the mixtures. MK is a pozzolanic material that conforms to Anonymous (2003) and ASTM (2003), Class N pozzolan specifications. It is obtained by the calcination of kaolinitic clay at a temperature ranging between 600-800°C with Kaolin as the main raw material. MK ($Al_2Si_2O_7$) reacts with $Ca(OH)_2$ at ambient temperature producing CSH gel as well as alumosilicate hydrates and calcium aluminate hydrates (C2ASH8, C4AH13 and C3AH6). Thus, MK has great promise as a pozzolanic material as it can enhance many concrete properties while reducing cement consumption.

Certainly, the efficient management to the various wastes contributes in maintaining the sustainability of construction. Waste is any material which is disposed after main utilisation or it is without value, benefit and utilisation. Throughout the world, the fundamental problem in waste management strategies is the utilisation of waste materials. The recycling of waste materials is associated with many advantages represent by lowering environmental pollution, minimizing the pressure on landfill and natural materials (Thomas and Gupta, 2013). In a similar manner, the incorporation of waste materials such as marble powder, granite powder, etc., in mortar and concrete as supplementary cementitious materials can be an attractive solution and can potentially enhance the characterizations of fresh and hardened mortar and concrete if they subject to test indicating its suitability.

Marble can be indicated as a metamorphic rock that comes from the transformation of limestone. It composes mainly of Calcite ($CaCO_3$) and/or dolomite. It has been normally utilised as a construction material, especially, for the purpose of decoration for centuries and from the ancient time. The disposing of marble produced in marble industry which is a very fine powder is considered as one of the environmental issues throughout the world now a days. One of the principle wastes gained as a by-product of marble during cutting, shaping and polishing is the Waste Marble dust (WMP). During this manufacture, around 20-25% of the marble is transformed into the powder. Due to the availability of large quantity of waste produced in the marble factory, this study has been planned and preceded for examining the possibility of utilising it in mortar and concrete manufacture.

Workability is often indicated by slump test which the oldest and widely utilised test. Brooks and Johari (2001) found that the MK-blended cement had a workability poorer than that of PC blend when cement and MK were incorporated at the same dosage within the blend and at same superplasticizers and water/binder ratio. Cassagnabere *et al*. (2013) investigated the flow properties (slump and flow time) of OPC-MK based mortars. They reported that there was a decrease in slump when metakaolin was incorporated, this reduction was ascertained when the subsitition of cement increased from 12.5-25%. In addition, they found that physical and chemical properries of metakaolins significantly affects the flow of the mortars. Li and Ding (2003) studied that the addition of MK and slag and the affinity between them and superplasticizers. The results indicated an increase in the fluidity of MK-slag blended cement paste in addition to the enhancement in the fluidity of the blended cement paste in compared to MK blended cement only. Vardhan *et al*. (2015) conducted a study to examine the relative fluidity of cement paste when marble powder was added. They found that the increase in the addition of marble powder caused decrease in flow time of the mixes for W/B ratios of 0.48. Belaidi *et al*. (2012) examined the fresh properties of Self-Compacting mortar (SCC) made of natural pozzolana and marble powder as replacement to OPC in the binary and ternary systems. The results revealed that the utilisation of pozzolana and marble powder enhanced the workability of SCC. The use of metakaolin to partially replace the cement improved concrete compressive strength, though the optimum MK substitution was found to be about 10-20% that provided the long-term maximum strength improvement (Brooks and Johari, 2001; Li and Ding, 2003). Badogiannis *et al*. (2005) monitored that the properties and the hydration procedure of cements containing metakaolin with 0, 10 and 20%. Vardhan *et al*. (2015) found that cement can be replaced by marble powder up to 10% without affecting the technical properties of the mixture. They concluded that the use of MK in 10% is generally more beneficial than a 20% content.

However, there is not any detailed study found in the literature that focused on the impact of using both Waste Marble Dust (WMD) and Metakaolin (MK) on the characteristics of concrete or mortar. Thus, the consumption of those materials in cement and concrete construction can also contribute to preserving the natural resources (sand, stone) as well as in sustainable high-performance mortar and high-performance concrete construction. This research provides an experimental study on the impact of utilising MK and WMD as partial replacements of cement in binary and ternary blends to produce high-performance mortars. For this, fresh properties, compressive strength, unit weight and the flexural tensile strength tests of HPMs were carried out. Control mortar was used for comparing the results of the all applied tests.

MATERIALS AND METHODS

Experimental program: Portland cement, Metakaolin (MK), Waste Marble Dust (WMD) and natural sand were utilised for the preparation of High-Performance Mortars (HPMs) mixtures. The locally available Ordinary Portland Cement Type I (OPC) was utilised in all the mixes, conforming to Iraqi specification standard No. 45/1984 (Anonymous, 1984). Metakaolin was utilised for producing binary mixes by partially replacing the OPC. For the production of the MK, kaolin clay was taken from Dewekhla Region, Al-Anbar Governorate, Iraq. This clay was grinded then it was burned for 2 h in a furnace at a temperature up to 8°C±20°C. After burning, the material was left to cool for 24 h to room temperature. This procedure is according to Ambroise *et al*. (1994) and Liew *et al*. (2012).

After that the MK was grinded by the air blast technique in AL-Zahra'a Shop in Baghdad to obtain a reactive material with more fineness. On the other hand, the waste marble dust is a by-product of the marble masonry manufacturing. WMD was gathered in this study as a sludge from masonry plants located in the Middle Euphrates area of Iraq, Al-Hilla city. It was the waste of marble shaping and sawing. Chemical and physical characterisations were carried out on the WMD waste, so as to assess its usage possibility in the production of concrete or mortar. The chemical compositions as well as the physical characteristics of OPC, MK and WMD are listed in Table 1 and 2, respectively. Local natural river sand with 4.75 mm maximum size which conform to ASTM (2006) was utilised as the fine aggregate. It was obtained from Al-Najaf Sea Region, Iraq. The specific gravity of the sand was 2.65 while its fineness modulus equaled 2.86 and its water absorption rate equaled 1.72%. Moreover, in order to provide the required workability, the polycarboxylates type new generation High-Range Water Reducing Admixture (HRWRA) was utilised in all mortar mixtures. This Superplasticizer (SP) is commercially known as Glenium 54 and it conforms to ASTM C494/C494M-08a, (2008). It was available in Whitish to straw coloured liquid form.

Mixture proportions and concrete works: High-Performance Mortar (HPM) mixtures containing MK, WMD and the combination of MK plus WMD were utilised to partially substitute cement to about 30% by total binder weight. Four binary and two ternary blends of HPM mixtures. The Control Mortar (CM) was fabricated by using OPC only as the binder. Binary blended cement containing 10 and 20% level of MK while those of WMD were 10 and 20% by weight of binder. Ternary blended binders consists of cement containing MK plus WMD content (10MK10WMD and 10MK20WMD) mixtures. All the mortar mixes consisted of Water/Binder (W/B), total cementitious materials content and Sand: Binder (S/B) ratios at 0.35, 688 kg/m^3 and 1:2.25, respectively. In order of having the required slump of mortar indicated in BS EN 206: Part 1 (Anonymous, 1989) of 65±20 mm an appropriate amount of superplasticizer was incorporated in the mixtures. The absolute volume method of the ACI 211.1-91 (ACI., 2000), design code was used for designing the control mortar. Trial mixtures were utilised to adjust the proportions of the materials. Details of the mix proportions and mix design for mortars mixtures are summarised in Table 3.

In the manufacture of HPM, to ensure that all mixtures have the same homogeneity and uniformity, the mixing process was remained constant. Firstly, as indicated in ASTM C109, a standard mixer was utilised for drily mixing the cement, WMD, MK and sand to 1 min. This is followed by adding Superplasticizer (SP) with water and mixing for an another 4 min. Flow table and slump tests were used to examine the compatibility of fresh HPMs mortar mixtures to indicate workability before casting in moulds. Throughout the slump flow test, bleeding and segregation were also examined using visual inspection. All the mixtures were manufactured utilising molds with dimensions of 50×50×50 mm to obtain specimen for compressive strength and unit weight of mortar and (40×40×160 mm) prism to obtain specimens for flexural strength. These molds were cleaned and their

Table 1: Chemical characterisation of OPC, MK and WMD

Chemical characteristics (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	P_2O_5	LOI	LSF	C_3S	C_2S	C_3A	C_4AF
OPC	19.36	4.82	3.28	62.43	3.0	0.07	0.44	2.26	-	2.17	0.96	58.49	11.38	7.22	9.98
MK	53.6	36.8	1.97	0.78	0.32	0.43	0.84	0.17	0.26	4.83	-	-	-	-	-
WMD	1.47	0.84	0.34	82.1	0.40	1.17	0.08	0.68	0.28	2.83	-	-	-	-	-

Table 2: Physical properties of OPC, MK and WMD

Property	OPC	MK	WMD
Specific gravity	3.12	2.61	2.68
Fineness (SSA), m^2/kg	338	1650	569
Pozzolanic activity index 7 days (%)	100	96	68
28 days (%)	100	102	83
Color	Grey	Off-white	Light grey
Median particle size (μm) (d_{50})	16.8	13.3	24.8

Table 3: Mix proportions of constituent materials of mortar mixtures

				Amount of ingredient (kg/m^3)						
	Type of binder (%)			Binder						
Mix No.	OPC	MK	WMD	OPC	MK	WMD	Fine aggregate	SP (%)	W/B ratio	S/B
Control Mortar (CM)	100	0	-	688	-	-	1548	1.2	0.35	2.25
10MK	90	10	-	619.2	68.8	-	1548	1.2	0.35	2.25
20MK	80	20		550.4	137.6	-	1548	1.2	0.35	2.25
10WMD	90	-	10	619.2	-	68.8	1548	1.2	0.35	2.25
20WMD	80	-	20	550.4	-	137.6	1548	1.2	0.35	2.25
10MK10WMD	80	10	10	550.4	68.8	68.8	1548	1.2	0.35	2.25
10MK20WMD	70	10	20	481.6	68.8	137.6	1548	1.2	0.35	2.25

internal surfaces were oiled to avoid adhesion with mixture after hardening. The casting was carried out in layers of 50 mm deep and compaction was performed by means of a vibrating table. Each layer was subjected to compaction for enough time to possibly extrude all entrained air. Then the mortar surfaces are leveled by means of trowel and the specimens are covered with nylon sheets to assure a humid air for about 24 h to avoid plastic shrinkage cracking. Usually, the opening of molds of mortar occurred after 1 day then until the date of the test, the specimens were placed in a water bath at room temperature of 25±2°C.

Test methods of mortars in in the fresh and the hardened states: The flow table and slump tests were used to evaluate the fresh characteristics of mortar mixes. Flow test was performed according to ASTM C230 Standard. Whilst, the values of the slump test of the fresh mortar mixes were gained by following the specification described in BS 1881: Part 102 (Anonymous, 1983, 1984). While, the compressive strength, flexural strength and dry unit weight tests were used for examining the mortar's hardened properties. The measurement of the compressive strength was achieved by using a hydraulic testing machine with 0.24 MPa/sec loading rate and after 3, 7, 28, 56 and 90 curing days. The reported compressive strengths were the average of 3 samples for each mix. The average of three specimens was recorded for each testing while flexural strength and the dry unit weight tests were conducted after curing in water for 28 days in according to the ASTM C348 and ASTM C642, Standard, respectively. For each property, the average value of the three samples was determined. A hydraulic testing machine was utilised for carrying out the test of compressive strength with 3, 7, 28, 56 and 90 days of curing periods and 0.24 MPa/sec loading rate of at of curing. The reported compressive strengths were the average of 3 samples for each mix which was recorded for every curing period.

RESULTS AND DISCUSSION

Chemical and physical characterization of materials: The oxide composition in addition to the chemical properties represent another two significant parameters in a binder activation. The results of Loss of Ignition (LOI) and oxide composition tests will be shown and discussed in details as. The chemical compositions of the Metakaolin (MK) and marble dust powder are presented in Table 1. It was found that the main components of MK were silica and alumina oxides (53.6and 36.8 %), respectively which play a main role in the secondary hydration and the pozzolanic reaction of concrete or mortar. The sum of the amount of SiO_2, Al_2O_3, Fe_2O_3 oxides was more than 70% for MK, higher than the lowest value of 70% given in the reference (ASTM, 2006), standards for class "N" pozzolans which is a high-quality pozzolan category. The chemical constituents of the Marble Dust Powder (MDP) were determined and tabulated in Table 1. It is indicated from the table that the CaO was the major composition of the MP with a very small percentage of Al_2O_3, SiO_2, MgO and Fe_2O_3, given an indication of its carbonate nature. On the other hand when a material is heated to 1000°C, all moisture is dried and CO_2 is released and the weight loss is known as the Loss on Ignition (LOI). Table 1 presents the LOI result of the MK and MDP. It is shown that the MK had a greater LOI than the MDP, though it remained lower than that of 19% given in the American Society for

Testing and Materials (2003a, b). Whilst, LOI of marble dust powder was 2.83% which was lower than the 10% value of the American Society for Testing and Materials (2003c).

The MK and MDP physical properties are tabulated in Table 2. The specific gravity represents a significant property used for understanding a material's weight and relative density. From the table, the specific gravity equaled 3.12 for OPC, 2.61 for MK and 2.68 for MDP.

Thus, the specific gravity of MK and MDP used was lower than that of cement. MK had also a greater Specific Area (SSA) than cement or MDP (Table 2) because of transformations. The high SSA of the MK was determined to be 1650 m^2/kg whereas those of MDP and OPC were 569 m^2/kg and 338 m^2/kg, respectively. It is obvious that all the pozzolanic materials possessed greater SSA than the OPC. The high specific surface area of the pozzolanic materials prepared for this study is a good presumption that they possess the right quality to potentially be an effective pozzolan. The particle size distribution of MK and MDP ranged from 0.1-90 μm with the mean diameter (d50) of 13.3 and 24.8 μm, respectively.

Fresh mortar properties: The mix proportions, environmental conditions and the materials are the main parameters affecting the workability of fresh mortar and concrete. In general, workability of mortar incorporating pozzolanic and waste materials decreases in workability with the increase of the replacement contents. The fresh properties such as flow and slump tests of the mortar mixtures were determined in the laboratory. The results of the flow and slump showed that by changing the ratio of water to binders, the flow and slump can maintain their desired respective range of 40±5% and 65±20 mm. The flow and slump values of cement, MK, WMD and MK+WMD mortars mixtures are given in Table 4.

Figure 1 and 2 show that the slump and the flow values decreased with the increase in the substitution of cement by MK, WMD and MK+WMD from 0% (control mortar) to 30% (10MK20WMD. It is obvious that HPM mixtures containing MK and WMD in binary and ternary blends system demanded more water, though the consistency of mixtures containing MK and WMD mixes reduced with the increment in their levels of cement replacement. It can be seen from Fig. 1 that the values of the slump of all fresh mortars were in the range of 45-85 mm which defined workability as medium slump range. These workability values were achieved at a water-cement ratio of 0.35 and 1.2%, superplasticizer (glenium-54) added to enhance the workability. Thus, it was apparent that when the content of MK and WMD increased in all binary and ternary blended mixes, the values of flow and slump gradually reduced in comparison

Table 4: Flow and slump values of mortar mixes

Mix No.	OPC	MK	WMD	Flow (%)	Slump (mm)
Control Mortar (CM)	100	0	-	68	85
10MK	90	10	-	52	50
20MK	80	20	-	43	45
10WMD	90	-	10	63	70
20WMD	80	-	20	54	60
10MK10WMD	80	10	10	51	55
10MK20WMD	70	10	20	40	45

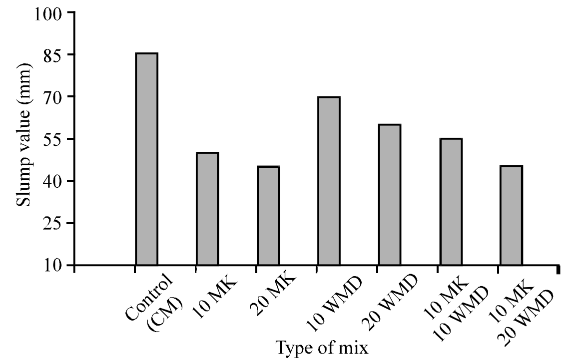

Fig. 1: Slump values of MK, WMD, MK+WMD mortars mixes

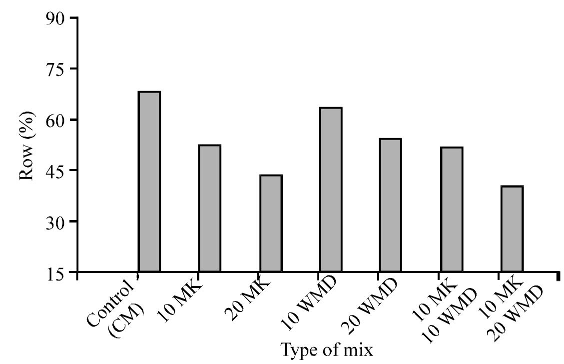

Fig. 2: Flow values of MK, WMD, MK+WMD mortars mixes

with High-Performance Control Mortar (HPCM) (Guneyisi and Gesoglu, 2008). During the tests, it was noted that addition of MK makes concrete sticky and decreased its workability comparing with WMD mortar and the control mortar. This was due to the fine particles of MK particles from than WMD. The results also revealed that the water demand in mortar increased with increasing the quantity of the MK. This was due to the MK high specific surface area, the replacement amount and the increment in the silica content in the mix.

The principle factor controlling the cementitious characteristics when utilising pozzolan in blended cement systems is the fineness of the particles which is asociated with the SSA of MK. Researchers such as Cassagnabere *et al*. (2013), Thomas and Gupta (2013) and

Al Menhosh *et al*. (2018) have reported the common properties among pozzolans which are the lower ability to flow and the higher amount of water needing to get the desired consistency. The mixture incorporating the highest amount of WMD have workability less than that of the control cement mixture. The slump and flow tests decreased with increasing WMD level up to 20% by weight. It was found that the flow values of the OPC, 10, 20MK and 10 and 10WMD are 68, 52, 43, 63 and 54%, respectively. While slump of the OPC, 10MK and 10WMD and 10WMD are 85, 50, 45, 70 and 60, respectively as seen in Fig. 1 and 2 (Cassagnabere *et al*., 2013; Arikan *et al*., 2009; Sadek *et al*., 2016).

Figure 2 shows the results for mortar flow indicate the results of combination of MK and WMD in ternary blends mortar mixtures revealed considerable decreases in flow and slump values with increase the amount of WMD at all the MK contents. This is similar to the results found by Srivastava *et al*. (2012). High performance mortars containing 20 MK gave the lowest flow and slump values followed by mixtures incorporating binary blends of 10MK, 10WMD, 20WMD and ternary blends of 10MK10WMD, 10MK20WMD in comparison with control mixture. From the results, it can be clearly seen that the flowability of mortars decreased with increasing the cement content substituted by MK and WMD in the binary and ternary cementitious blends.

Hardened properties of mortars

Unit weight: Self-weight of any structure is completely dependent on the unit weight (Bulk density) of the ingredient materials. Thus, it is a considerable parameter for mortar or concrete. Therefore, dry unit weight of mortar was determined as the weight per unit volume of mortar. The average value of the three specimens was used to calculate the unit weight of mortar. Figure 3 shows the effects of MK, MK+MP and OPC mortar mixes on bulk density under curing of 28 days of hydration. The figure reveals that the densities of all the types of mortars, both in binary and ternary blends, increased with age. The results indicated a decrease in bulk density with increasing the contents of the MK and WMD used in the preparation of the high performance mortars in comparison with HPM-CM mixture.

The specific weight of the MK and WMD materials is lower than that of the OPC, hence, the bulk density values of the samples decreased with an increase in the substitution levels of pozzolanic and waste materials (MK, WMD and MK+WMD). The lowest bulk density value was obtained from the mixture 10MK+20WMD substitution. The observation possibly occurred because the particle size and specific gravity of MK and WMD

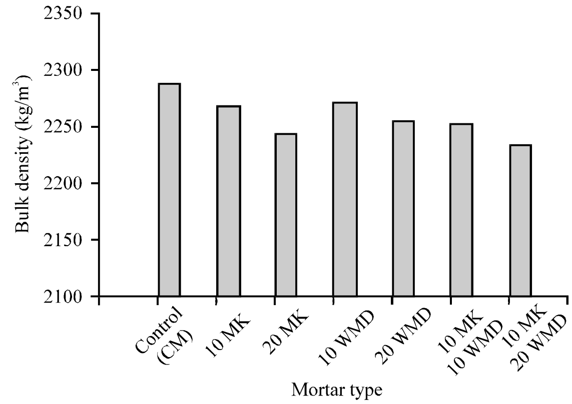

Fig. 3: Bulk densities of MK, WMD, MK+WMD mortars mixes at 28 days

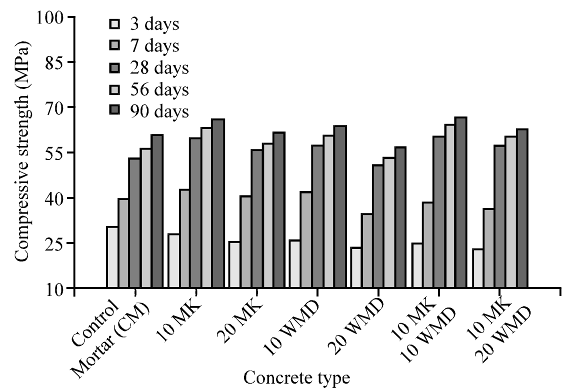

Fig. 4: Compressive strength of MK, WMD and MK+WMD mortars mixes at different ages

were significantly smaller than that of OPC which decreased the mass per unit volume. It was found that OPC mortar showed a unit weight of 2287 kg/m^3 while values of MK, WMD and MK+WMD were in the range of 2267-2233 kg/m^3 for the binary and ternary mortar blends mixes.

Compressive strength: The strength development of HPMs with OPC, MK, WMD and MK+WMD were investigated for different ages. The averaged compressive strength of cube specimens in the binary and ternary system made of MK, WMD and MK+WMD mortars were measured at 3, 7, 28, 56 and 90 days of curing are given in Fig. 4. As noticed the compressive strength of all mix combinations increases continuously over time. It can be seen that the most influential factors controlled the compressive strength development are the substitution level of MK and WMD as a partial replacement of cement in binary and ternary systems. Generally (Fig. 4), all HPM mortars mixes containing MK, WMD and MK+WMD exhibited slight reduction in strength at early age 3 days compared with the reference mortar. This can be indicated by the substitution of the cement with a quietly slow reaction. While there was a continuing improvement in the performance of the mixtures from 7 days onwards, compared to that of the control mortar is most probably because of the effect of pozzolanic reaction and the fineness (higher surface area) MK and WMD particles achieved the highest strength and the fastest rate of strength gain. The compressive strength of binary binder's mortar mixes with the replacement of 10MK, 20MK and 10WMD gave the best result at different ages (7, 28, 56 and 90 days). Conversely, at the level of cement replacement of up to 20 % of WMD, it gives slightly lower than the than control mortar as presented in Fig. 2. It was observed that 20WMD specimens had lower strength values than the control mortar specimens due to potential reduction in the in the cement which was commonly known as the dilution of the pozzolanic reaction of materials (Ergun, 2011).

The values of compressive strength ranged between 23.2-65.8 MPa with 20WMD tested after 3 curing days had the lowest value and 10MK tested after 90 curing days had the highest value. Generally, in comparison to the control mortar, MK and 10WMD mortars had the larger strengths up to 90 curing days. This improvement in strength was likely due to presence of several factors which are the MK and WMD contribution to the improvement in strength when utilised as a partial cement replacement in binary blends such as filler effect; the MK and WMD rapid pozzolanic reaction with $Ca(OH)_2$: the OPC hydration acceleration and the compounding effect which made the greatest contribution to strength to the enhancement of strength at later ages. Thus, it can be stated that the replacement of cement with 10% MK and WMD is the optimum limit. It can be concluded that up to 10% of WMD can be utilised for having the best advantages regarding the compressive strength and the workability. For this reason, there were MK and WMD optimum replacements for HPM. The compressive strength reduction of 20 MK in comparison with 10 MK can be attributed to a clinker dilution effect which was caused by the replacement of some of the cement by a similar amount of MK. The similar observations were made several other researchers (Li and Ding, 2003; Vardhan *et al.*, 2015; Parande *et al.*, 2008; Corinaldesi *et al.*, 2010; Shirule *et al.*, 2012)

On the other hand, there was a reduction in the compressive strength of ternary blended cement high-performance mortar mixes of 10 and 20% WMD with 10% MK replacement at the early ages of 3 and 7 days. This was in comparison to the binary blends systems made from partially replacing cement with MK and WMD as demonstrated in Fig. 4. Thereafter, the strength of the mortar mixtures in a ternary system at 28 curing days was better than that of the binary blends systems for the same replacement levels as well as of the control mortar. The compressive strength of 10MK+10WMD and 10MK+20WMD mortar mixes exhibited the highest strength as presented in Fig. 2. The compressive strengths at 28 days for HPMs mortar mixes of 10MK+10WMD and 10MK+20WMD were 60.1 and 57.4 in comparison with OPC, 10MK, 10WMD and 20WMD were 52.8, 59.6, 57.1 and 50.7 MPa, respectively. The increment in the compressive strength of the mortars mixtures 10MK+10WMD and 10MK+20WMD were approximately 13.8 and 8.7% at 28 days compared to the Control Mortar (CM). Therefore, it can be concluded that the use of MK in ternary blended cement system was of a beneficial impact on the improvement in compressive strength of the system. This was because of the greater pozzolanic reaction and the MK finer particles than the WMD.

Flexural strength: The tensile to compressive strength ratio of concrete or mortar depends on the general level of compressive strength of concrete or mortar. The flexural strengths of MK and MK+WMD high-performance mortars with different cement replacement levels by MK and WMD in binary and ternary systems at 28 days curing age are presented in Fig. 5. From this figure, the results of the flexural strength were similar to those of the compressive strength. The flexural strengths values of mortar with 10% of total binder of MK and WMD were better than that obtained from control mortar mixture and then the strength was considerably reduced at greater replacement levels of WMD (20%). Similar trends were reported by Sounthararajan and Sivakumar (2013). Hence,

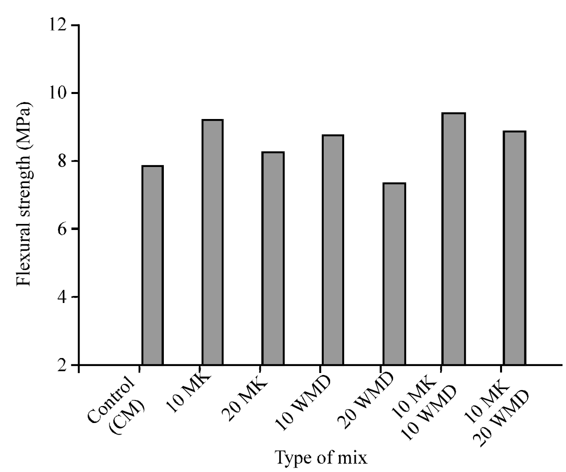

Fig. 5: Flexural strength of MK, WMD and MK+MP mortars mixes at 28 days

it is revealed that 10% of total binder weight is the optimum replacement of cement by MK and WMD to gain the highest flexural strength at a later age. This occurred due to the pozzolanic influence of the MK and WMD discussed above.

In the ternary blended mixture, the utilisation of 10 MK significantly increased the flexural strength with increasing the level of substitution with WMD in compared with binary blends and control mixture at 28 days in Fig. 3. The development of strength is the critical point controlling the mechanical activation of MK and the strength of MK at 28 days is good. Usually, flexural strength to compressive strength has a ratio ranged between 10-15% for concrete (Mhaiskar and Naik, 2012) while this ratio is quite different for mortar. This ratio is found to be 14.4% and 13.8 for MK10 and WMD10 mortar mixes, respectively.

CONCLUSION

The results of specific gravity showed that considered pozzolanic and waste materials (MK and WMD) were lighter than cement. The results of the flow and slump showed that by changing the ratio of water to binders, the flow and slump can maintain their desired respective range of 40±5% and 65±20 mm. Binary and ternary blended cement mixtures with MK and WMD showed a noticeable trend that the slump and flow results reduced gradually with the increment in the cement substitution by the MK or the WMD in comparison with High-Performance Control Mortar (HPCM). High-performance mortars with binary blends of 20 MK showed lowest flow and slump values followed by mixtures incorporating binary blends of 10MK, 10WMD, 20WMD and ternary blends of 10MK10WMD, 10MK20WMD comparing to control mixture.

The bulk density values of the samples decreased with an increase in the substitution levels pozzolanic and waste materials (MK, WMD and MK+WMD) in binary and ternary blended binders used in the high-performance mortars preparation in comparison with HPM-CM mixture. The lowest bulk density value was obtained from the mixture 10MK+20WMD substitution.

High-performance mortars mixes containing MK, WMD and MK+WMD exhibited a minor reduction in strength at 3 days while the strengths were continually improved at later ages (7 and 28 days) all in comparison to the strength of the control mortar. The compressive strength of binary binder's mortar mixes with the 10MK, 20 MK and 10 WMD cement replacement gave the best result at various curing ages of 7, 28, 56 and 90 days. Conversely, at the substitution of cement by up to 20% of WMD, a slightly lower strength was obtained than the control mortar.

Considering the strength criteria, the mortar mixtures in ternary cementitious blends system at 28 days were better than that of the control mortar and binary blends systems for the same replacement levels. The compressive strength of 10MK+10WMD and 10MK+20WMD mortar mixes exhibited the highest strength.

The flexural strengths values of mortar with the MK and WMD level of 10% of total binder weight were better than that obtained from control mortar mixture and then the strength was considerably reduced at greater replacement levels of WMD (20%). In ternary cement mortars, the utilisation of 10MK significantly increased the flexural strength by increasing the WMD replacement percentage when compared with binary blends and control mortar mixes at 28 days.

In general, HPMs contains WMD and MK as a substitution material in binary and ternary blends may be used as a sustainable binder in the near future by producing HPM and could contribute in reducing cement demand, declining CO_2 emission rate and pollution due to consumption of mentioned wastes.

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