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Utilization of Metakaolin on Sustainable Concrete Properties

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Abstract: *This paper investigates the effect of metakaolin (MK) and silica fume (SF) on different concrete properties. Twenty-four different sustainable concrete mixes (f_c=29 to 93 MPa) with and without metakaolin and silica fume were prepared with local materials in Egypt. Concrete mixes were cast with 0, 5, 10, 15, and 20% cement replaced by either metakaolin or silica fume. Further investigation is carried out by combined replacement of metakaolin at 5, 10, and 15% with 5% silica fume by weight of cement. The water/cementitious materials ratio ranged from 0.25 to 0.55. The variables include cement content, metakaolin content, silica fume content, and superplasticizer dosage. Performances of metakaolin mixes were compared with control mixes, and mixes incorporating silica fume. Metakaolin is a relatively new mineral admixture for sustainable concrete. It is comparable to silica fume in pozzolanic reactivity, but is lower in price. The mixes were tested for slump, air content, compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity. Test results have indicated that MK exhibits lower pozzolanic activity than SF. These are the filler effect, the acceleration of cement hydration and the pozzolanic reaction with calcium hydroxide. MK concrete mixes showed a better consistency than SF concrete mixes. As the replacement level was increased, the compressive strength and modulus of elasticity of the silica fume concrete increased at all ages similarly to that of the metakaolin concrete. In addition, it was shown that specimens of mixes of MK improved the splitting tensile strength and flexural strength than of mixes with SF. The test results showed that a MK content or SF content of about 15% by replacement of cement gave concrete with the optimum strengths. Based on the results, it can be observed that concrete prepared with a combination of 10% MK and 5% SF indicated increased strengths compared to the controlled concrete. The compressive strength and other hardened properties of concrete with MK were higher than that of reference concrete with the same W/Cm ratio. The improvement in the compressive strength when using MK was (10.0, 21.0, 28.3, and 25.2%) at age 28 days for (5, 10, 15, and 20%) replacement of MK respectively at 350Kg/m^3 cementitious content, whereas the improvement was (11.7, 23.1, 30.7, and 27.1 %) when using (5, 10, 15, and 20%) MK respectively at 450Kg/m^3 cementitious content. Concrete with 15% MK replacement had found to exhibit 51.3, 30.7, 26.0, and 22.6% higher compressive strength at 7, 28, 56, and 91 days, respectively, in comparison to that of controlled concrete with 450Kg/m^3 cementitious content.*

Keywords: *Metakaolin, Silica fume, Mineral admixture, Sustainable concrete, Air content, Compressive strength, Splitting tensile strength, Flexural strength, Modulus of elasticity.*

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I. Introduction and Literature Review

Metakaolin is refined kaolin clay that is fired under carefully controlled conditions to create an amorphous aluminosilicate that is reactive in concrete. Like pozzolans such as silica fume, fly ash and blast-furnace slag, metakaolin reacts with the calcium hydroxide by-products produced during cement hydration. The particle size of metakaolin is generally smaller than cement particles, though not as fine as silica fume. Silica fume as a mineral admixture for concrete has great attention both in research and application. Silica fume is a by-product resulting from the reduction of high purity quartz in an electric arc furnace during the production of silicon metal or silicon alloys. Metakaolin is another pozzolanic material which is a highly efficient pozzolana and reacts rapidly with the excess calcium hydroxide resulting from cement hydration, to produce calcium silicate hydrates (CSH) and calcium aluminosilicate hydrates [1-3].

Cement production is one of the major reasons for carbon oxides emissions into atmosphere during cement manufacturing process. The use of pozzolanas for making concrete is considered efficient, as it allows the reduction of the cement consumption while improving the strength and durability properties of the concrete. MK or SF when used as a partial replacement of cement is known to enhance both the mechanical characteristics and durability of concrete. Hence by partially replacing cement with MK or SF not only reduces carbon dioxide emissions but also increases the service life of constructions [3-5].

Several researchers have investigated the effect of silica fume and Metakaolin by replacing the cement on various parameters, which includes fresh, mechanical and durability properties of concrete. The effect of metakaolin at a constant water/binder ratio of 0.3 on mechanical and durability properties of high strength

concrete was studied. Mixtures with MK by replacement from cement of 5%, 10% and 15% were designed. The experimental results showed that the replacement of cement by 10% MK was the optimum level in terms of compressive strength. Compressive strength of 106 MPa was achieved at 10% replacement. Splitting tensile strength and elastic modulus values have also followed the same trend. In durability properties MK concretes have exhibited high resistance compared to control and the resistance increases as the MK percentage increases [6]. The effect of SF and MK on the properties of concrete was investigated. Experimental investigation with seven concrete mixtures of 0, 5, 10, and 15% by replacement of cement with SF or MK was carried out. The effect of SF or MK on the workability, strength, shrinkage and resistance to chloride penetration of concrete were also studied. The incorporation of both SF and MK in concrete was found to reduce the free drying shrinkage and restrained shrinkage cracking width. The performance of SF was found to be better than MK [1].
Using mineral admixtures like fly ash, iron oxide and MK as cementitious materials in various proportions with cement, five different types of concrete mixtures were prepared and same were used. When cement was replaced up to 42% with MK, it gives strength up to 40.7 MPa at a water cement ratio of 0.40 and at 0.55 ratios; it gave strength up to 25.5 MPa at 56 day. They reported that it was possible to make the concrete economical by 42% replacement of cement with different percentages of mineral admixtures like at 30% fly ash, 10% MK and 2% iron oxide [7]. The use of MK in concrete enhanced the strength properties. The optimum level of replacement of MK was reported as 7.5%. The result showed that 7.5% of MK increased the compressive strength of concrete by 14.2%, the splitting tensile strength by 7.9% and flexural strength by 9.3% [8]. The effect of MK and SF combination in concrete was studied. The optimum combined doses of MK and SF were found out as 15% and 6% respectively. The compressive strength at 28 day of concrete increased with the MK content for at all the SF contents. The compressive strength 7 day of concrete was found to decrease with the increase in MK content for all the Silica fume contents [9]. Inclusion of MK increases the compressive, tensile, flexural strengths and modulus of elasticity of concrete considerably; however, the workability is slightly compromised [4-13].

II. Experimental procedures

2.1 Materials

2.1.1 Cement

Ordinary Portland Cement CEM I–52.5 N was used in all mixes. Testing of cement was carried out as the Egyptian Standard Specifications ESS 4756-1/2009 [14]. The physical and chemical properties of CEM I shown in Table (1).

TABLE 1 Properties of Cementitious Materials

Properties	CEM I	Silica Fume	Metakaolin
Physical			
Specific gravity	3.15	2.15	2.4
Specific area cm^2/gm	3350	200000	110000
Colour	Grey	light Grey	Light Pink
Chemical compositions (%)			
Silicon dioxide (SiO_2)	19.90	97.00	59.70
Aluminum oxide (Al_2O_3)	6.30	0.20	30.90
Ferric oxide (Fe_2O_3)	3.70	0.50	2.60
Calcium oxide (CaO)	61.90	0.20	1.20
Magnesium oxide (MgO)	2.10	0.50	0.15
Sulphur trioxide (SO_3)	2.50	0.15	0.03
Potassium oxide (K_2O)	0.78	0.50	0.60
Titanium dioxide (TiO_2)	-	-	1.90
Sodium oxide (Na_2O)	0.80	0.20	0.50
Loss on Ignition (LOI)	1.71	0.70	1.72

2.1.2 Aggregates

Fine aggregate used in this experimental work was natural siliceous sand, clean and rounded fine aggregate with a specific gravity of 2.66, a bulk unit weight of 1685 Kg/m^3 and fineness modulus of 2.90. The coarse aggregate used was local crushed limestone (dolomite) with a specific gravity of 2.71, a bulk unit weight of 1710 Kg/m^3 and maximum nominal size of 12 mm, according to the requirement of ESS 1109/2002 [15].

2.1.3 Metakaolin

Metakaolin used by local material was brought from Abo zenima quarry in Sinai desert, Egypt. To produce metakaolin was thermally treated kaolin by an electric furnace. The calcinations temperature and the time of calcinations at that temperature adopted in this study were 750˚C and 3 hours respectively. The chemical and physical properties are given in Table (1).

2.1.4 Silica fume

In this research, silica fume was locally produced from Egyptian Ferro Alloys Company in Edfu, Aswan, Egypt having a silica content of 97.0% was used. The properties of SF shown in Table (1).

2.1.5 Superplasticizer (High Rang Water- Reducing Admixtures)

A high performance superplasticizer admixture of aqueous solution of modified polycarboxylate basis (Viscocrete-5930) was used to increase workability of the concrete mixes. Viscocrete-5930 complies with ASTM-C-494 types G and BS EN 934 part 2: 2001, with a specific gravity of 1.12. The dosage ranged about 3.0 % for mixes of cementitious content 450 kg/m^3.

2.1.6 Water

As shown in Table (2), water to cementitious materials ratio (w/cm) was used as 0.55 for mixes of cementitious content 350 kg/m^3, and 0.25 for mixes of cementitious content 450 kg/m^3.

2.2 Mix proportion

To achieve the objectives of this work, two groups of concrete with a total numbers of 24 mixtures were prepared and investigated. Table (2) illustrates the mix design of all mixtures. The mixtures were divided into two groups representing the variables in the study. The first group with 350 Kg/m^3 cementitious content (mixes from 1 to 12), mix 1 possesses neither metakaolin nor silica fume (control mix), while the mixes from 2 to 5 contains metakaolin with a percentages of 5, 10, 15 and 20%, as replacement of cement used, and the mixes from 6 to 9 contains silica fume with a percentages of 5, 10, 15 and 20%, as replacement of cement, but the mixes from 10 to 12 contains combined replacement of metakaolin at 5, 10, and 15% with 5% silica fume by weight of cement. The second group with 450 Kg/m^3 cementitious content (mixes from 13 to 24), mix 13 possesses neither metakaolin nor silica fume (control mix), while the mixes from 14 to 17 contains metakaolin with a percentages of 5, 10, 15 and 20%, as replacement of cement, and the mixes from 18 to 21 contains silica fume with a percentages of 5, 10, 15 and 20%, as replacement of cement, but the mixes from 22 to 24 contains combined replacement of metakaolin at 5, 10, and 15% with 5% silica fume by weight of cement. The compressive strengths of the different mixes were in the range of 29 to 93 MPa.

TABLE 2 Proportions of Concrete Mixes

Group	Mix No.	CEM I	Fine Agg. Sand	Coarse Aggregate		Metakaolin	Silica Fume	Super Plasticizer	W/Cm
		Kg/m^3	%	Type	%	%	%	%	
I	M1	350	40	Dolomite	60	0	0	0	0.55
	M2	332.5	40	Dolomite	60	5	0	0	0.55
	M3	315	40	Dolomite	60	10	0	0	0.55
	M4	297.5	40	Dolomite	60	15	0	0	0.55
	M5	280	40	Dolomite	60	20	0	0	0.55
	M6	332.5	40	Dolomite	60	0	5	0	0.55
	M7	315	40	Dolomite	60	0	10	0	0.55
	M8	297.5	40	Dolomite	60	0	15	0	0.55
	M9	280	40	Dolomite	60	0	20	0	0.55
	M10	315	40	Dolomite	60	5	5	0	0.55
	M11	297.5	40	Dolomite	60	10	5	0	0.55
	M12	280	40	Dolomite	60	15	5	0	0.55
II	M13	450	40	Dolomite	60	0	0	3	0.25
	M14	427.5	40	Dolomite	60	5	0	3	0.25
	M15	405	40	Dolomite	60	10	0	3	0.25
	M16	382.8	40	Dolomite	60	15	0	3	0.25
	M17	360	40	Dolomite	60	20	0	3	0.25
	M18	427.5	40	Dolomite	60	0	5	3	0.25
	M19	405	40	Dolomite	60	0	10	3	0.25
	M20	382.5	40	Dolomite	60	0	15	3	0.25
	M21	360	40	Dolomite	60	0	20	3	0.25
	M22	405	40	Dolomite	60	5	5	3	0.25
	M23	382.5	40	Dolomite	60	10	5	3	0.25
	M24	360	40	Dolomite	60	15	5	3	0.25

2.3 Test Procedure

The consistency of concretes is measured in terms of slump values according to ASTM C143/C143M - 15a [16], and the air content values according to ASTM C231/C231M - 17a [17] of the fresh concrete were tested. The compressive strength test of concrete was tested using cubes (150 mm) according to BS 1881: part 116 - 2004 [18]. This test was conducted at the ages of 7, 28, 56, and 91 days. The splitting tensile strength test at 28 days was carried out according to ASTM C496/C496M - 11 [19]. A cylindrical specimen of dimensions (150×300 mm) was used for this test. The flexural strength test at 28 days was performed in accordance with ASTM C78/C78M - 16 [20]. The prism specimens of 100×100×500 mm for flexural strength were used. The average of three specimens was recorded for each testing age and all strengths. While the modulus of elasticity at 28 days was conducted on the cylinder specimens of dimensions (150×300 mm) according to ASTM C469/C469M - 14 [21].

III. Results and discussion

The test results of slump, air content, and compressive strength, splitting tensile strength, flexural strength and modulus of elasticity are shown in Table 3.

3.1 Consistency

It is noting that the effect of metakaolin and silica fume on the consistency of fresh concrete should be distinguished in two different ways; when metakaolin or silica fume are used as a replacement of cement at 350 kg/m^3 cementitious materials, and when its are used at 450 kg/m^3 cementitious materials. In the first case, Fig. 1 shows the slump value of concrete mixes with 350 kg/m^3 cementitious materials and without superplasticizer. It can be seen that the addition of MK or SF up to 20% of replacement by weight of cement decreased the slump value from 95 mm (control) to 65 mm (20%MK), and to 60 mm (20%SF) respectively, indicating the effect of MK or SF in providing water-tightness at water to cementitious ratio of 0.55 due to smaller particle size and higher surface area of MK or SF. Similar observation was also found by Steve W. et al. [22]. In the second case, the effect of MK and SF on the slump of concrete containing 450 kg/m^3 cementitious materials with 3% superplasticizer at different replacement levels is shown in Fig. 2. Where MK or SF increased the cohesiveness of concrete thus required the addition of superplasticizer (high range water reducing admixtures) to achieve desired workability. The use of superplasticizer was very essential in concrete containing fine particles like MK or SF to achieve well dispersion and better results. It can be seen that MK offered a much better workability than did SF for the given mixture proportions. The concrete mixtures with 5 to 20% MK had a slightly higher slump than the control mix. Even when the replacement level of MK was increased to 15%, the slump was increased by approximately 60% and was still about 120 mm. The results, also indicated the concrete with SF, the slump value showed increase at the replacement level of 15%, however, an increase of the slump about 40% higher than the control mix.

3.2 Air content

The test results reported in Table 3 show that MK or SF content up to 20% lead to insignificant reductions in air content, while when the content of MK or SF increased from 0 to 20%, the air content decreased to about 20% and 30% for mixes with 350 kg/m^3 cementitious materials and mixes containing 450 kg/m^3 cementitious materials, respectively. The measured air contents were 1.7, 1.5, 1.4, 1.3, and 1.2% for concrete mixes (450 kg/m^3 cementitious materials) containing 0, 5, 10, 15, and 20% of MK, respectively.

TABLE 3 Fresh and Hardened Properties of Test Results

Mix No.	CEM I Content	Metakaolin	Silica Fume	Slump (mm)	Air Content (%)	Compressive Strength (MPa)				Splitting Tensile Strength (MPa)	Flexural Strength (MPa)	Modulus of Elasticity (GPa)
	Kg/m^3	%	%			7d	28d	56d	91d	28d	28d	28d
M1	350	0	0	95	2.0	19.5	29.0	32.3	34.7	2.5	4.7	22.1
M2	332.5	5	0	90	1.9	24.3	31.9	34.0	35.2	2.7	5.1	23.8
M3	315	10	0	85	1.8	27.1	35.1	37.3	38.8	2.8	5.6	26.1
M4	297.5	15	0	75	1.7	29.5	37.2	39.7	41.1	2.9	5.8	27.5
M5	280	20	0	65	1.6	28.9	36.3	38.8	40.2	2.7	5.6	26.6
M6	332.5	0	5	85	1.8	25.1	32.5	34.4	35.7	2.6	5.0	23.9
M7	315	0	10	80	1.7	27.9	35.8	37.9	39.3	2.7	5.5	26.2
M8	297.5	0	15	70	1.6	30.1	38.0	40.3	41.8	2.8	5.7	27.6
M9	280	0	20	60	1.6	29.6	37.0	39.3	40.7	2.6	5.5	26.7
M10	315	5	5	85	1.7	27.5	35.5	37.8	39.1	2.7	5.5	26.1
M11	297.5	10	5	80	1.6	29.8	37.7	40.3	41.5	2.9	5.8	27.7
M12	280	15	5	70	1.5	29.2	36.6	39.1	40.5	2.7	5.6	26.8
M13	450	0	0	75	1.7	47.6	70.0	78.0	83.5	5.3	10.9	52.5
M14	427.5	5	0	100	1.5	60.2	78.2	83.7	87.2	5.6	11.9	57.5
M15	405	10	0	105	1.4	67.2	86.2	92.4	96.2	6.0	12.8	63.0
M16	382.8	15	0	120	1.3	72.0	91.5	98.3	102.4	6.2	13.5	66.4
M17	360	20	0	115	1.2	71.1	89.0	95.6	98.9	5.7	13.0	64.1
M18	427.5	0	5	85	1.4	62.2	79.8	85.4	88.5	5.5	11.8	57.9
M19	405	0	10	100	1.2	69.2	87.7	94.0	97.4	5.8	12.7	63.1

M20	382.5	0	15	105	1.1	74.4	93.1	100.0	103.8	6.0	13.4	66.6
M21	360	0	20	105	1.1	73.0	90.5	97.1	100.9	5.5	12.9	64.3
M22	405	5	5	100	1.4	68.1	86.8	92.9	96.7	5.9	12.7	63.4
M23	382.5	10	5	110	1.3	73.5	92.4	99.4	102.7	6.1	13.5	67.2
M24	360	15	5	110	1.2	72.0	89.5	96.1	99.5	5.6	13.0	64.5

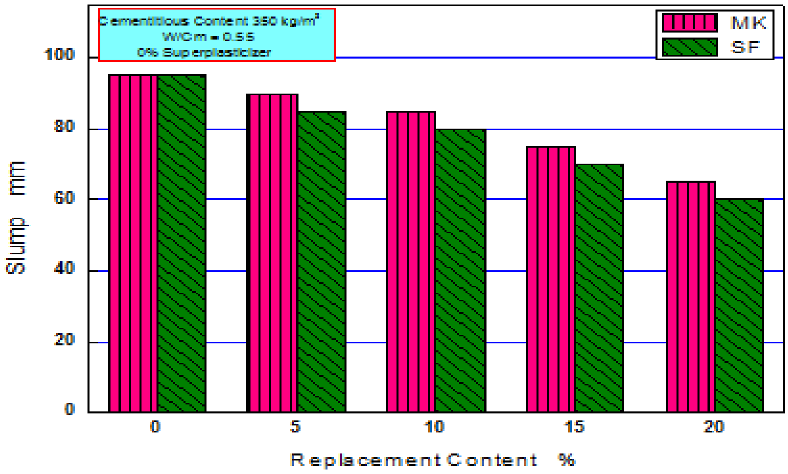

Fig. 1 Effect of metakaolin and silica fume on the slump of mixes with 350 kg/m^3 cementitious materials

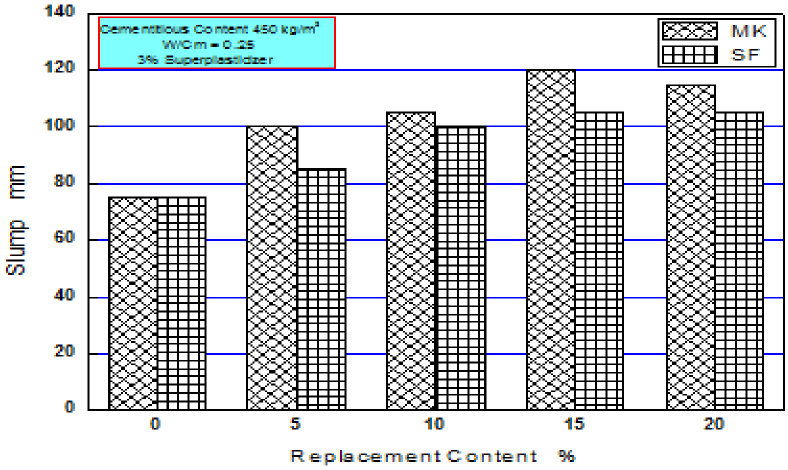

Fig. 2 Effect of metakaolin and silica fume on the slump of mixes with 450 kg/m^3 cementitious materials

3.3 Compressive strength

The compressive strength at 7, 28, 56, and 91 days are shown in Table 3 and Figures 3 and 4. In general, the addition of MK or SF as a replacement of cement up to a particular percentage resulted in a corresponding increase of the compressive strength. The test results indicate that the particular content of MK or SF, which may be referred to as the optimum content, is about 15%. At the optimum content, MK and SF are sufficient to react with all liberated calcium hydroxide produced from the cement hydration process to produce calcium silicate hydrates.

The development of compressive strength with age for all mixes investigated is presented in Figures 5 and 6. From the plot it is clear that the MK and SF mixes attains higher compressive strength values than the control mix. The compressive strength development depends upon the MK or SF content and ages of concrete. At 15% replacement of MK or SF from cement had higher ultimate strength than concrete made with cement. Results show that the addition of 15% MK improved the compressive strength, where 51.3, 28.3, 22.9, and 18.4% improvement in compressive strength is observed at 7, 28, 56, and 91 days, respectively of mixes with 350 kg/m^3 cementitious materials. While, for concrete containing 450 kg/m^3 cementitious materials and 15% MK, the increase of compressive strength are 51.3, 30.7, 26.0, and 22.6% for ages 7, 28, 56, and 91 days respectively. With 450 kg/m^3 cementitious materials and 15% SF, the compressive strength was increased by

56.3, 33.0, 28.2, and 24.3% at 7, 28, 56, and 91 days, respectively. Therefore, the effectiveness of MK or SF in improving the compressive strength is reduced with the increase of age of concrete. In this study that the improvement of compressive strength is more significant at early age than the later ages. The early age strength increases could be due to the aluminum content and finer particle size of MK, which accelerates the hydration reaction and packs into cement particles gaps. In the other hand, the long term strength of concrete is increased through pozzolanic effect.

Figure 7 and 8 demonstrates the effect of MK and SF on the 28-day compressive strength at different replacement levels. It is clear that at the same replacement level, MK increased compressive strength at 450 kg/m^3 cementitious materials to almost the same extent as SF did about 11.7, 23.1, 30.7, and 27.1% at 5, 10, 15, and 20% of MK respectively. By increasing the replacement level from 0 to 15%, the strengthening effect of MK increased. The compressive strengths of the mixes at 5, 10, 15, and 20% of MK were about 11.7, 23.1, 30.7, and 27.1% respectively higher than that of the control concrete at 28 days; 14.0, 25.3, 33.0, and 29.3% higher at SF concrete mixes. The compressive strength of concrete incorporating SF is comparable and sometimes better than MK concrete. The test results showed that a MK content or SF content of about 15% by replacement of cement gave concrete with the optimum strengths. Based on the results, it can be observed that concrete prepared with a combination of 10% MK and 5% SF indicated increased strengths compared to the controlled concrete.

3.4 Splitting tensile strength

The effect of metakaolin and silica fume on the splitting tensile strength for different cementitious content is shown in Table 3 and Figures 9 and 10. All cylinder specimens were tested after 28 days. In general, the results of splitting tensile strength increase with the increase of MK or SF content. For all cementitious content, the average increase of the tensile strength were 7.0, 12.5, 16.5, and 8.0% for mixes containing 5, 10, 15, and 20% MK, and the average increase of the tensile strength were 4.0, 9.0, 12.5, and 4.0% for mixes with 5, 10, 15, and 20% SF, respectively. The addition of 15% MK or 15% SF by a replacement of cement increases the tensile strength by factors of 16.5, and 12.5%, respectively.

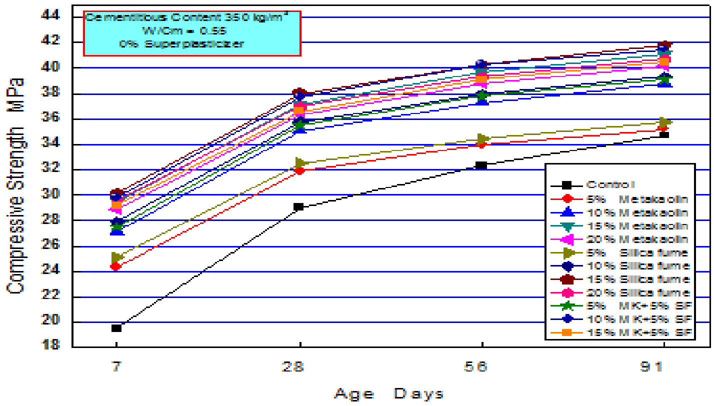

Fig. 3 The compressive strength of mixes with 350 kg/m^3 cementitious content at different ages

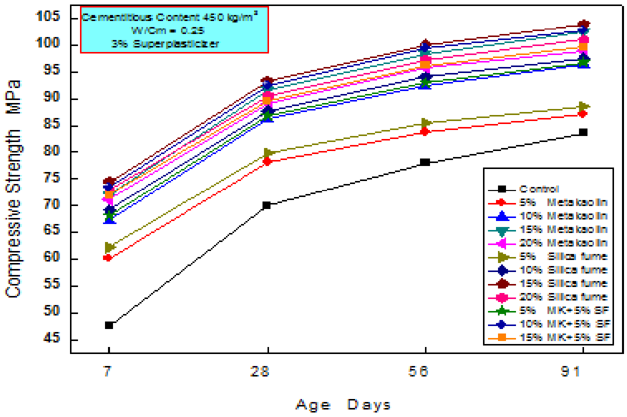

Fig. 4 The compressive strength of mixes with 450 kg/m^3 cementitious content at different ages

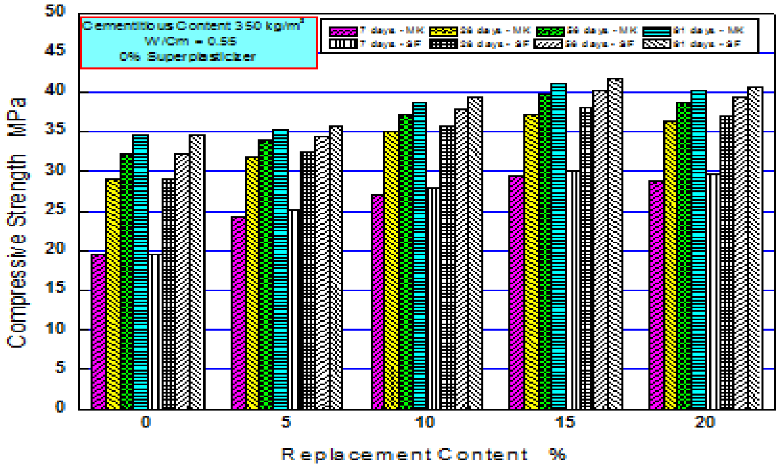

Fig. 5 Effect of metakaolin and silica fume on the compressive strength of mixes containing 350 kg/m^3 cementitious content at different ages

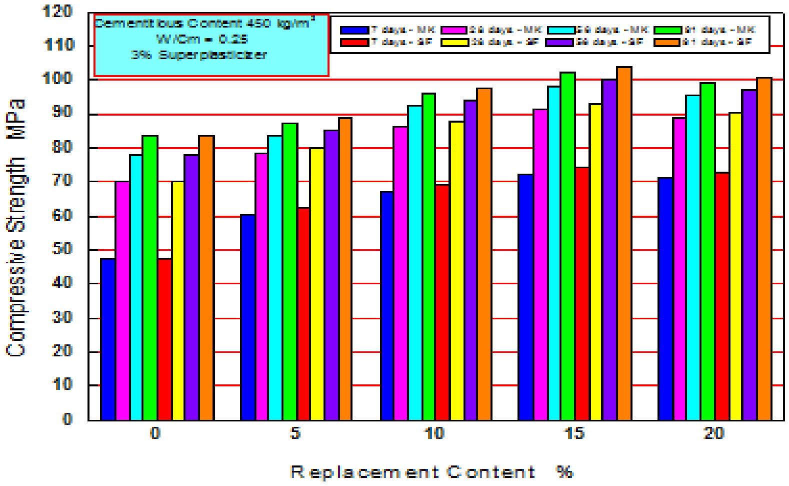

Fig. 6 Effect of metakaolin and silica fume on the compressive strength of mixes containing 450 kg/m^3 cementitious content at different ages

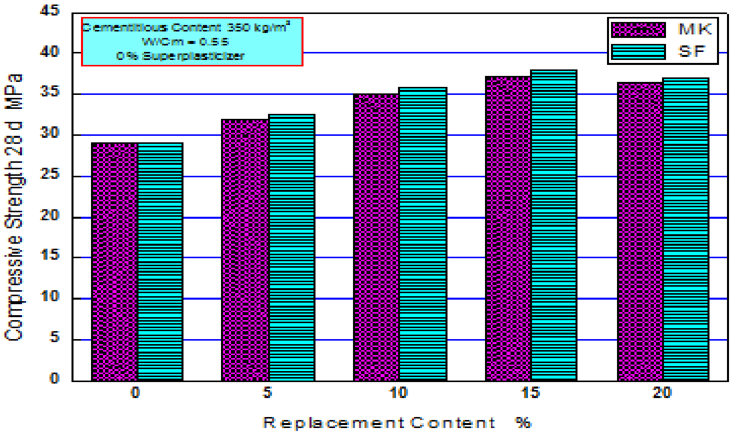

Fig. 7 Effect of replacement content on the compressive strength at 28 days of mixes with cementitious materials 350 kg/m^3

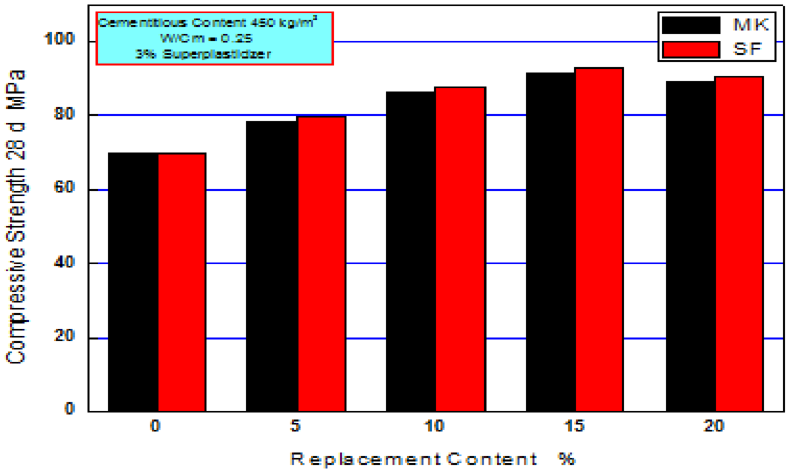

Fig. 8 Effect of replacement content on the compressive strength at 28 days of mixes with cementitious materials 450 kg/m^3

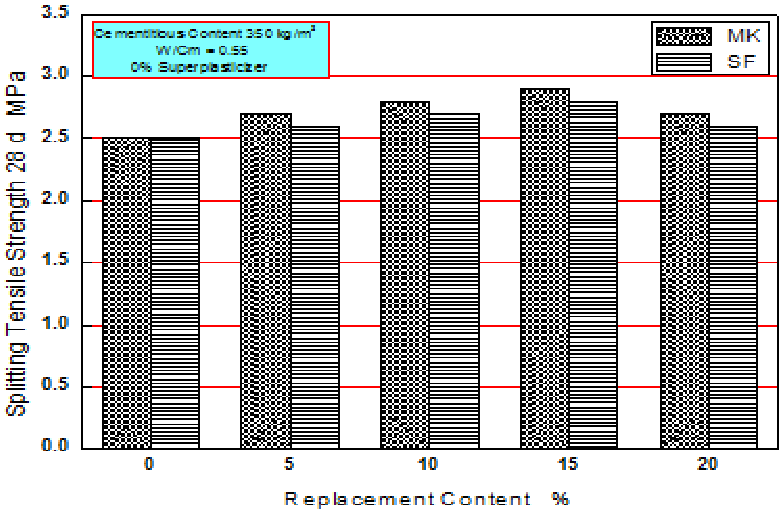

Fig. 9 Effect of metakaolin and silica fume on the splitting tensile strength at 28 days of mixes with cementitious content 350 kg/m^3

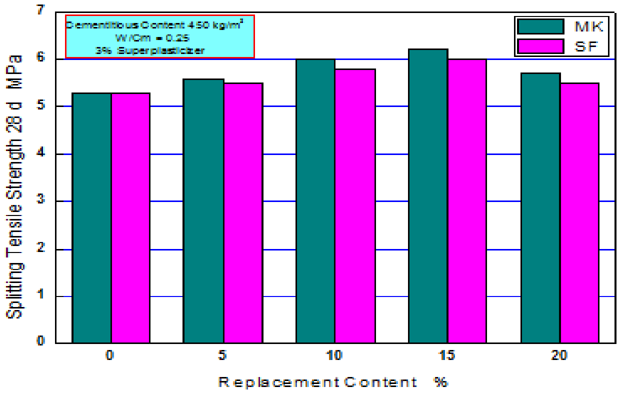

Fig. 10 Effect of metakaolin and silica fume on the splitting tensile strength at 28 days of mixes with cementitious content 450 kg/m^3

3.5 Flexural strength

The results of flexural strength at 28 days are shown in Table 3 and are illustrated in Figures 11 and 12. It shows that the flexural strength of concrete mix also increases with increase in MK or SF replacement of cement. The flexural strength for the mixes with 5, 10, 15, and 20% MK gain of 9, 19, 23, and 19% was obtained respectively in comparison with control mix. The maximum value of flexural strength was obtained for 15% MK or 15% SF as a replacement of cement.

3.6 Modulus of elasticity

The test results of modulus of elasticity for 24 different mixtures at different cementitious content after 28 days are shown in Table 3 and Figures 13 and 14. The results shown in Figures 13 and 14 indicated that the mix having MK and SF suffered significant increase in modulus of elasticity at different cementitious content. The modulus of elasticity for concrete mixes with 350 kg/m^3 cementitious content was increase by about 8, 18, 24, and 20% to using 5, 10, 15, and 20% Mk or SF as replaced of cement, respectively. While the modulus of elasticity for concrete mixes with 450 kg/m^3 cementitious content was increase by about 10, 20, 26, and 21% to using 5, 10, 15, and 20% Mk or SF, respectively. It is worthy of note that, the optimum value of modulus of elasticity was obtained for 15% MK or 15% SF as a replacement of cement.

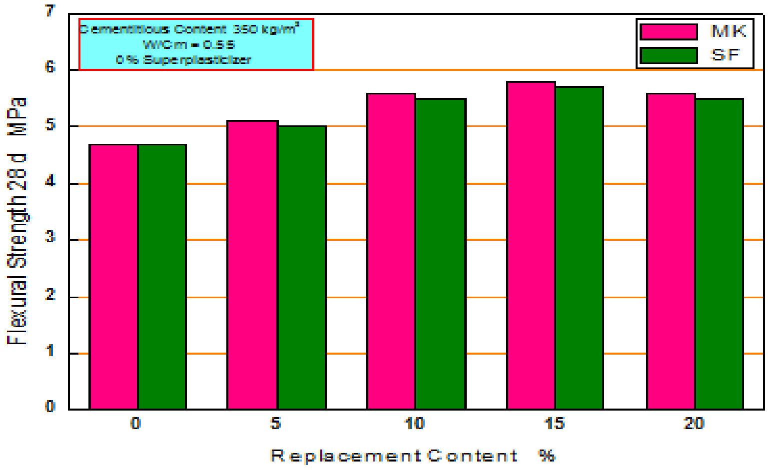

Fig. 11 Effect metakaolin and silica fume on the flexural strength of mixes with 350 kg/m^3 cementitious materials

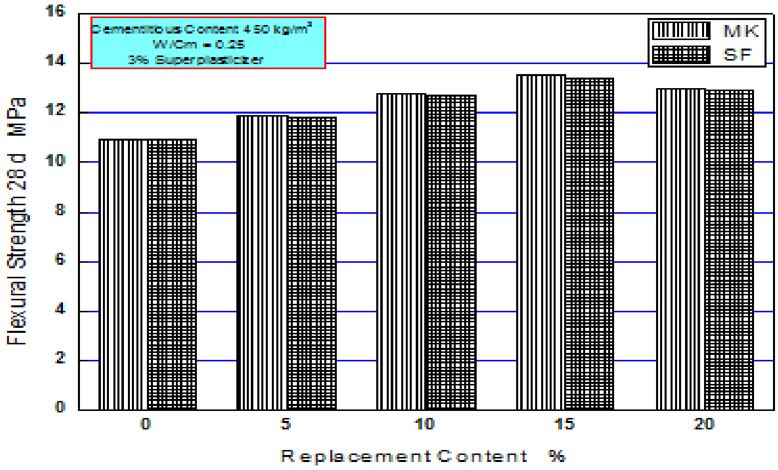

Fig. 12 Effect of metakaolin and silica fume on the flexural strength of mixes with 450 kg/m^3 cementitious materials

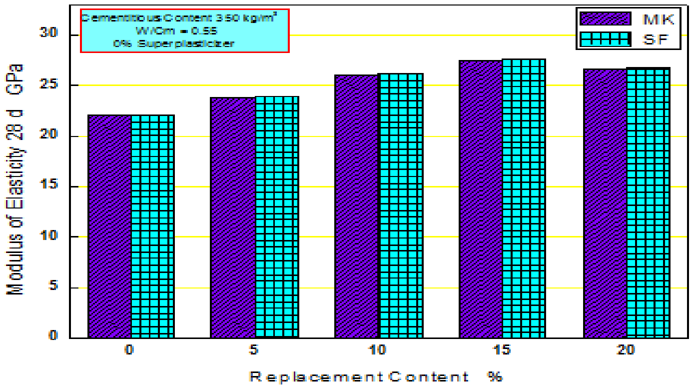

Fig. 13 Effect of metakaolin and silica fume on the modulus of elasticity of mixes containing 350 kg/m^3 cementitious materials

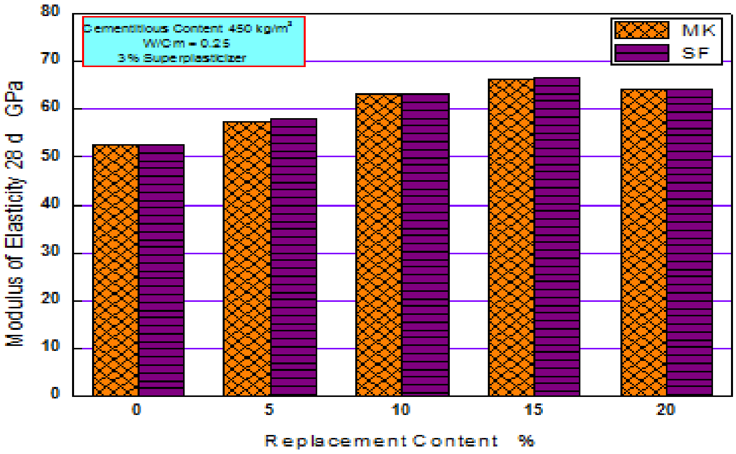

Fig. 14 Effect of metakaolin and silica fume on the modulus of elasticity of mixes containing 450 kg/m^3 cementitious materials

V. Conclusions

Based on the experimental results presented in this research have been performed to investigate the effect of MK and SF as a partial replacement of cement on fresh and mechanical properties, the following conclusions may be drawn:

1. Consistency of concrete was decreased with the increase in MK content without superplasticizer, but the use of superplasticizer was very essential in concrete containing fine particles like MK or SF to achieve well dispersion and better results.
2. In mixes with 3% superplasticizer, when the replacement level of MK or SF was increased to 15%, the slump was increased by approximately 60% and 40% respectively.
3. When the content of MK or SF increased from 0 to 20%, the air content decreased to about 20% and 30% for mixes with 350 kg/m^3 cementitious materials and mixes containing 450 kg/m^3 cementitious materials, respectively.
4. The improvement in the compressive strength when using MK was (10.0, 21.0, 28.3, and 25.2%) at age 28 days for (5, 10, 15, and 20%) replacement of MK respectively at 350Kg/m^3 cementitious content, whereas the improvement was (11.7, 23.1, 30.7, and 27.1 %) when using (5, 10, 15, and 20%) MK respectively at 450Kg/m^3 cementitious content.
5. Concrete with 15% MK replacement had found to exhibit 51.3, 30.7, 26.0, and 22.6% higher compressive strength at 7, 28, 56, and 91 days, respectively, in comparison to that of controlled concrete with 450Kg/m^3 cementitious content.
6. The mixes containing 15% SF as a replacement had found to exhibit 56.3, 33.0, 28.2, and 24.3% higher compressive strength at 7, 28, 56, and 91 days, respectively, in comparison to that of controlled concrete with 450Kg/m^3 cementitious content.

7. For all cementitious content, the average increase of the splitting tensile strength were 7.0, 12.5, 16.5, and 8.0% for mixes containing 5, 10, 15, and 20% MK, and the average increase of the tensile strength were 4.0, 9.0, 12.5, and 4.0% for mixes with 5, 10, 15, and 20% SF, respectively.
8. The flexural strength for the mixes with 5, 10, 15, and 20% MK gain of 9, 19, 23, and 19% was obtained respectively in comparison with control mix.
9. The modulus of elasticity for concrete mixes with 350 kg/m^3 cementitious content was increase by about 8, 18, 24, and 20% to using 5, 10, 15, and 20% Mk or SF as replaced of cement, respectively. While the modulus of elasticity for concrete mixes with 450 kg/m^3 cementitious content was increase by about 10, 20, 26, and 21% to using 5, 10, 15, and 20% Mk or SF, respectively.
10. The test results showed that a MK content or SF content of about 15% by replacement of cement gave concrete with the optimum strengths.
11. Concrete prepared with a combination of 10% MK and 5% SF indicated increased strengths compared to the controlled concrete.
12. The compressive strength and other hardened properties of concrete with MK were higher than that of reference concrete at the same W/Cm ratio.

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