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Impact of Incorporating Metakaolin on the Mechanical Performance of High Grade Concrete

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***Abstract:** This paper studies the effect of incorporating metakaolin on the mechanical properties of high grade concrete. Three different metakaolins calcined at different temperature and durations were used to make concrete specimens. Three different concrete mixtures were characterized using 20% metakaolin in place of cement. A normal concrete mix was also made for comparison purpose. The compressive strength test, split tensile test and flexural strength tests were conducted on the specimens. The compressive strength test results showed that all the metakaolin incorporated concrete specimens exhibited higher compressive strength and performed better than normal concrete at all the days of curing. The rate of strength development of all the mixes was also studied. The study revealed that all the three different metakaolin incorporated mixtures had different rate of strength development for all the days of hydration (3, 7,14, 28, 56 and 90), indicating that all the metakaolins possessed different rate of pozzolanic reactivity. Further, from the analysis of the test results, it was concluded that the variation in the rate of strength development is due to the differences in the temperature and duration at which they were manufactured. The results of split tensile strength test and the flexural strength test conducted on the specimens, supported the conclusions drawn from the results of compressive strength test. The paper also discusses, the rate of development of compressive strength and the pozzolanic behaviour of the metakaolins in light of their parameters of calcination and physical properties such as amorphousness and particle size. This paper has been written with a view to make the potential of metakaolin available to the construction industry at large.*

***Keywords:** Amorphousness, Calcination, Concrete, Metakaolin, Pozzolanic reaction.*

I. INTRODUCTION

Supplementary cementitious materials (SCMs) are widely used in construction industry to make High performance concrete (HPC). The most common SCMs used in making of high performance concrete are fly ash (FA), ground granulated blast furnace slag (GGBS), silica fume (SF) and rice husk etc. These SCMs do not have any hydraulic properties in them, but when added to concrete, they react with the calcium hydroxide ($Ca(OH)_2$: a cement hydrated product which is a non strength giving and an unstable compound), to form more stable and strength enhancing C-S-H compounds. [1-4].

Further, these newly formed compounds reduce the porosity of the concrete by filling up the pores in the concrete and makes the microstructure of concrete denser and more compact. Thus, adding SCMs to concrete not only contributes to the strength but also makes the concrete more durable. [5-7]. Metakaolin is one such SCM. It is a highly reactive pozzolana produced from kaolin clay in a controlled way. Kaolin is abundantly available in many states of India. Thermally activating the clay leads to conversion of a major reorganisation in its structure. The crystalline aluminosilicate peaks get reorganised into a highly amorphous form which is highly unstable and reactive in nature. This form of kaolin clay is called metakaolin.

Researchers worldwide (poon et al 2001, Khatib, Badigiaonis etc.) have shown keen interest in developing metakaolin as a pozzolanic material. There are important number of journal papers where the researchers have confirmed that metakaolin could be very well used in concrete to enhance its overall performance, metakaolin has not yet acquired a place in market as a preferred pozzolanic material. [8-13]. One reason for its unpopularity as a preferred pozzolanic material is that while there is a considerable amount of research work done in the field of metakaolin worldwide to understand the kaolin structure, the conversion of kaolinite to metakaolin, there are little efforts made to understand the pozzolanic behaviour of the metakaolin in concrete and its effects on the properties of concrete. There are less tests data available in literature and journals on the performance of metakaolin in concrete compared to other SCMs and the results are contradictory too which retards its application in construction practise. [14-17]. The objective of this paper is to assess the effect of incorporating metakaolin on the mechanical properties of high grade concrete and compare the results with the normal concrete of the same grade to make the potential of metakaolin available to the stakeholders of the construction industry.

II. EXPERIMENTAL INVESTIGATION

The objective of the experiment was to determine the effect of adding metakaolin on the compressive, tensile and flexural strength of concrete. Concrete specimens of M40 grade with w/b ratio of 0.4 were casted. Three different types of metakaolins (abbreviated as MK1, MK2 and MK3), used in the experiment were supplied by a manufacturer based in Vadodara in Gujarat. They differed in the temperature and duration of calcination.

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The chemical composition and their physical properties like loss on ignition (L.O.I) and particle size are displayed in table no. 1 while their different temperature and duration of calcination are shown in table no 2.

Table 1. Chemical composition and physical properties of cement, MK1, MK2 and MK3.

Parameters	Cement	MK1	MK2	MK3
SiO_2 (%)	21.42	58.31	50.30	53.48
Al_2O_3 (%)	5.67	37.47	47..3	41.78
Fe_2O_3 (%)	3.16	2.15	1.33	2.3
CaO (%)	63.8	0.17	0.09	0.70
MgO (%)	1.20	-	-	-
Na_2O (%)	0.20	-	-	-
K_2O (%)	0.87	0.23	0.116	0.30
TiO_2 (%)	0.98	1.64	1.11	1.4
SO_3 (%)	2.4	-	--	--
Loss on Ignition	1.18	7.5	0.8	3.5
Particle	-	0.65	0.76	0.95

Table 2. The parameters of process of Calcination of MK1, MK2 and MK3: Temperature and duration of calcinations

Type of metakaolin	Calcination temperature	Duration of calcination
	(° C)	(minutes)
MK1	800	45
MK2	1000	60
MK3	800	90

A Mix proportion

Four different mixes of grade M40 were being identified for the purpose. Three out of the four mixes had 20% metakaolin being replaced by cement in them and are termed as MKC1, MKC2 and MKC3 in the paper. The fourth mix was normal concrete mix having 0% metakaolin in it and is abbreviated as NC. The table no. 3 shows the details of the mix proportion for M40 grade of concrete.

Table 3 Details of mix proportion (kg/m3)

Ingredients	NC (0%MK)	MKC1 (20%MK1)	MKC2 (20% MK2)	MKC3 (20% MK3)
Cement	392	333	333	333
Water (kg)	157.6	157.6	157.6	157.6
Fine aggregates (kg)	495	495	495	495
20mm aggregates (kg)	720	720	720	720
10mm aggregates (kg)	388	388	388	388
Metakaolin (kg)	0	59	59	59
Super plasticizer (l)	3.42	3.42	3.42	3.42

B Specimens casting

Specimens were casted from the four different mixes for compressive strength test, split tensile test and flexural test. For compressive strength test concrete cubes of 150 x 150 x 150 mm were casted from the mixes. Cylinders of dimensions 300 mm and 150 ø mm and beams of 100 x 100 x 500 mm dimensions were casted for split tensile strength test flexural strength test respectively. The specimens after being casted were kept in the moulds for another 24 hours with water saturated gunny bags on them. After 24 hours they were demoulded and kept in normal water for curing till the day of testing.

Compressive strength tests were conducted on 3, 7, 14, 28, 56 and 90 days. Split tensile and flexural test were conducted on 28, 56 and 90 days of curing.

III. RESULTS AND DISCUSSIONS

The compressive strength results of specimens are shown in table no 3.

Table 4 Compressive Strengths of MKC1, MKC2, MKC3 and NC

Mix	Compressive strength (MPa)					
	3 days	7 days	14 days	28 days	56 days	90 days
NC	12.0	19.0	27.4	39.0	41.5	42.7
MKC1	15.0	26.5	31.6	41.3	41.2	41.9
MKC2	21.0	29.5	36.0	42.3	44.7	53.2
MKC3	18.0	21.0	31.5	41.4	49.0	53.0

The compressive strength table shows that all the metakaolin incorporated concrete mixtures: MKC1, MKC2 and MKC3 exhibit higher strength than the control concrete in the early days of hydration: 3, 7 and14 days. MKC2 exhibits highest compressive strength on these days indicating a higher rate of pozzolanic reactivity of MK2 than MK1 and MK3. The compressive strength values of all the metakaolin incorporated concrete becomes equal to that of NC at 28 days of curing. The table shows that after 28 days on 56 and 90 days there is again an increment in the compressive strength values of MKC2 and MKC3 whereas the compressive strength of MKC1 remains the same as that on its 28 days value. These observations it can be said that MK2 and MK3 are pozzolanic in nature whereas MK1 does not possess any later days pozzolanic reactivity.

Figure 1 shows the relative strength of the metakaolin concrete in relation to age and type of metakaolin. Relative strength is the ratio of the compressive strength of metakaolin concrete to the strength of normal concrete at a particular curing time. The rate of strength gain in normal concrete is governed by the hydration of clinker whereas as found in literature, in metakaolin concrete it is also influenced by other three factors: (a) filler effect, (b) the dilution effect and (c) the pozzolanic reaction. Thus, the relative strength-time graph gives an insight into the rate of hydration mechanism in the metakaolin concrete relative to the normal concrete.

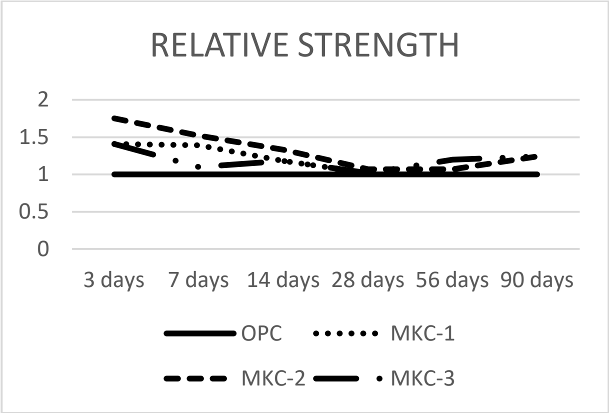

Figure 1. Relative strengths of MKC1, MKC2, MKC3 mixes.

From the relative strength graph, it is seen that the metakaolin incorporated concrete mixes: MKC1, MKC2 and MKC3 have maximum relative strength values at 3 days of age. The relative strength values of MKC1, MKC2 and MKC3 are 1.41,1.75 and 1.41 on the 3rd day of curing. This means that the MKs possess maximum pozzolanic reactivity between 0-3 days of curing. This initial high pozzolanic reactivity is attributed to the highly reactive amorphous alumina present in the metakaolin that reacts with the cement hydration products to form calcium alumino hydrates and the extremely fine size of the particle which accelerates the cement hydration processes. The graphs then show a decreasing trend and keeps decreasing till their relative strength value becomes almost equal to 1 at 28 days. This means that at 28 days the compressive strength of all the metakaolin incorporated becomes equal to that of the NC strength value.

After 28 days the relative strength graphs of all the metakaolin incorporated mixtures show a different trend. The graphs again show an increasing trend after 28 days till 90 days except in case of MK1. This increase in compressive strength in MKC2 and MKC3 is due to the pozzolanic reaction of silica of metakaolin with the cement hydrates forming strength enhancing CSH gel and aluminosilicate hydrates such as stratlingite, hydrogarnet etc.

The graph of MKC1 remains parallel and coincides with that of the NC. From this observation can be said that MK1 does not posses the later days pozzolanicity that is observed in MK2 and MK3. The reason for its non reactive nature can be attributed to the duration of calcination. The duration was not enough to convert the crystalline peaks to amorphous form.

The relative strength graph of MKC2 remains parallel from 28 to 56 days and then show an increasing trend whereas the MKC3 graph shows a continuous increasing trend. This difference in their behaviour can be explained from their temperature of calcination. The temperature of calcination of MK2 was 1000 C at which the amorphous silica gets recrystallized into a highly crystalline crystoballite requiring a higher alkaline medium for entering into pozzolanic reaction. Whereas MKC3 was calcined within its temperature range.

Tensile strength

Table 5 shows the split tensile strength value of all the mixes at 28, 56 and 90 days. At all the days of testing all the metakaolin mixes exhibited higher tensile strength value compared to the NC mix. At 28 days the split tensile strength value of MKC1, OPC, MK2 are 2.2, 2.2 and 2.4 which corresponds to almost 5.5% of their compressive strength value which lesser than the range of 1/10th of the compressive strength value and which is consistent with the results of research work of Yogendra et al, 1987, Haque and kayali 1998. [18,19,20]. At later days of curing i.e. at 56 and 90 days, the tensile strength value follow the same trend as in compressive strength with MKC2 and MKC3 exhibiting values higher than OPC. All the MK mixes show higher values than OPC. The tensile strength value of MKC3, MKC2 and MKC1 are 21, 28 and 7% higher than OPC at 90 days. It is seen from the results that similar to the compressive strength values the MKC2 and MKC3 mix exhibited higher values compared to OPC and MKC1.

Table 5 Tensile strengths of MKC1, MKC2, MKC3 and NC

	Tensile strength (N/mm^2)		
Mix	28 days	56 days	90 days
NC	2.2	2.7	2.8
MKC1	2.2	3.0	3.0
MKC2	2.4	2.7	3.6
MKC3	2.9	3.0	3.4

Elastic modulus

Table no 6 shows the value of modulus of elasticity of all the mixes at 28, 56 and 90 days. From the values it is clear that the modulus of elasticity also follows the same trend as compressive strength with MKC3 and MKC2 exhibiting higher values at all the ages. The modulus of elasticity is related to the compressive strength of concrete. But the relation between the two is not linear and hence the increase in modulus of elasticity is not in proportion to the increase in compressive strength.

Table 6 Flexural strengths of MKC1, MKC2, MKC3 and NC

	Flexural strength (N/mm^2)		
Mix	28 days	56 days	90 days
NC	11.4	12.1	12.1
MKC1	13.95	14.5	14.4
MKC2	14.4	15.6	14.6
MKC3	11.7	18.6	18.9

IV. CONCLUSIONS

The purpose of this work was to determine the effect of three different metakaolins in high grade concrete. The following are the conclusions drawn from the study.

All the metakaolins: MK1, MK2 and MK3 are highly reactive pozzolanic material and have the potential to enhance the strength of high grade concrete when incorporated in concrete.

The rate of pozzolanic reactivity of all the metakaolins was higher in their early days (0-3 days) of hydration as compared to the later days (3-28 days) of hydration. They exhibited maximum pozzolanic reactivity at 3 days of age which then decreased as the hydration progressed. (3-28 days).

Comparison of the strength results of the mixes revealed that all the three metakaolin incorporated mixes: MKC1, MKC2 and MKC3 had different rate of strength development, which led to the conclusion that all the three metakaolins possessed different rate of pozzolanic reactivity.

It was also concluded that, among all the three metakaolins, MK2 is the most reactive pozzolanic material. It exhibited early days as well as later days pozzolanic reactivity. Further, the in depth study of the test results led to conclusion that MK1 is reactive only in the initial days of hydration and remains unreactive during the later days (after 28 days) of hydration, whereas MK2 and MK3 did exhibit later days pozzolanic reactivity.

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