AKADÉMIAI KIADÓ

UNIVERSITY of DEBRECEN

International Review of Applied Sciences and Engineering

13 (2022) 3, 257–262

DOI: 10.1556/1848.2021.00359

ORIGINAL RESEARCH PAPER

Evaluating properties of high performance concrete containing metakaolin as cementitious material

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Received: August 6, 2021 • Accepted: November 12, 2021
Published online: March 28, 2022

ABSTRACT

High performance concrete is extensively used for construction works in recent era. For the preparation of high performance concrete (HPC) mineral and chemical admixtures are used. The addition of mineral admixtures minimizes the utilization of cement and makes concrete more sustainable. The addition of metakaolin as a substitute to cement enhances the properties of concrete. There is need to study the mechanical and micro-structural properties of concrete containing metakaolin as cementitious material. In this work an endeavour has been made to study the properties of HPC employing matakaolin as an alternative for cement. The cement has been replaced with metakaolin by 5%, 10%, 15%, 20%, and 25% respectively for 0.25, 0.3, and 0.35 w/c ratios. The strength and electrical resistivity tests are conducted for all concrete mixes on triplicate. Results confirm that the accumulation of metakaolin increases the properties of HPC. A maximum of 49% increase in compressive strength in concrete was observed by the accumulation of 15% of metakaolin in concrete as substitute to cement for 0.25 w/c ratio in comparison to standard concrete. The development of secondary calcium silicate hydrates and minimal $Ca(OH)_2$ components was revealed by X-ray spectroscopy, indicating that the concrete was denser. The results of this study revealed that metakaolin has a considerable impact on high-performance concrete, particularly in terms of compressive and flexural strength.

KEYWORDS

metakaolin, compressive strength, flexural strength, electrical resistivity

1. INTRODUCTION

Concrete is the most often utilized construction material worldwide, owing to its superior strength and durability. Cement is the most important component of concrete since it serves as a binder [1]. The production of cement consumes natural materials and releases huge amount of global warming gasses into the atmosphere [2]. Due to the rapid rate at which the cement industry is developing, future generations may face a shortage of natural resources as well as harmful environmental circumstances. The utilization of supplementary cementitious materials (SCMs) like fly-ash, rice-husk ash, metakaolin (MK), and silica fume materials as a partial alternative for cement in making of concrete is one way to minimize the utilization of cement [3]. The addition of MK as cementitious material in concrete shows excellent properties against penetration of various aggressive agents [4, 5]. The accumulation of MK enhances the strength and durability of concrete [6, 7, 8]. The SCMs provide a variety of advantages in concrete, including improved ultimate strength, durability, reduced excessive surface cracking, cost savings, and greater sustainability. The extent to which portland cement is replaced by SCMs is determined by their pozzolanic activity [9, 10]. SCMs may also be used to generate a variety of concrete types, including HPC, and high strength concrete. The HPC is being used more and more every day for construction. The strength of HPC is significantly higher than that of regular hard concrete. The utilization of HPC offers a long-term ease of handling, decreases creep and shrinkage and increases compressive, shear,

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tensile strength [11]. The Mineral SCMs, such as silica fume and fly ash, have already been proved to improve concrete characteristics when used as additives [12]. The addition of fly-ash as replacement to cement by 30% considerably enhances the concrete performance [13]. Similarly, accumulation of silica fume as replacement to cement also enhances the mechanical properties of HPC [14]. In recent years, with the growing environmental concerns, the usage of MK as an optional addition has increased the attention [15]. As a SCMs, the MK has anticipated pozzolanic character triggered by tri-calcium silicate and tri-calcium aluminates [16]. While using MK as substitute to cement, MK reacts with portlandite to produce extra CSH gel which enhances the strength and durability. The addition of MK as replacement to cement by 20% shows an enhancement of 50% in compressive strength of mortar [17]. There is a need to study the mechanical and micro-structural properties of HPC using MK as a supplement cementitious material. In this study an endeavour has been made to improve the properties of HPC using MK as substitute to cement. The cement has been replaced with MK by 5%, 10%, 15%, 20%, and 25% respectively for 0.25, 0.3, and 0.35 w/c ratios. Results confirm that the accumulation of MK in concrete increases the overall concrete performance.

2. MATERIALS AND METHODS

2.1. Materials

43 grade Ordinary Portland cement (OPC) procured from Ultratech Cements ltd., Raipur having specific gravity 3.1 is employed as a binder in this study. The river sand utilized as a fine aggregate with specific gravity (SG) 2.65. Coarse aggregate having 20 mm nominal maximum size having SG 2.74 is used. Metakaolin used as supplement cementitious material was procured from ASTRRA chemicals, Chennai. The MK sample was tested by Energy Dispersive X-ray technique for identifying the elemental composition. The EDX test has been performed on ZEISS-EVO 18 scanning electron machine. The MK sample utilized in this study is having the SG of 2.5. Elemental composition of MK using EDX analysis is illustrated in Table 1.

2.2. Concrete mix details

Design of concrete mix was done using IS: 10262-2019 [18] and particle packing method. Packing density is a novel way of mix design that is being utilised to design various forms of concrete. This method increases the density of concrete and also the number of pores in the concrete matrix [19]. The mix proportions of the present study are shown in Table 2.

Table 1. Elemental composition of MK using EDX analysis

Elements	Weight %	Atomic %
Si	61.47	73.43
Mg	0.05	0.04
Al	17.55	12.43
Ca	0.15	0.07
Fe	0.32	0.11
O	20.46	13.92

3. RESULTS AND DISCUSSION

3.1. Workability

Workability may be described as the amount of energy needed to overcome the friction between the particles in the concrete in order to accomplish complete compaction [20]. In this study, the slump test is utilized to determine the workability as per IS: 1199-1959 standards, Reaffirmed 2004 [21]. Slump is the most frequently utilised test to determine the workability. The particle shape, size, temperature, water-cement (w/c) ratio, and quantity of additive added to the concrete mix all have a direct impact on the workability [22]. The slump test has been conducted to all mixes after the mixing of concrete. The slump test results of all concrete mixes along with standard deviations are illustrated in Fig. 1. From Fig. 1 it is noticed that the accumulation of MK diminishes the slump values. The accumulation of 5% of MK as replacement to cement shows 5%, 3.6%, and 2.3% reduction in slump values of concrete as compared to standard mix for 0.25, 0.3, and 0.35 w/c ratios. As the dosages of the MK increase the slump values diminish. A maximum of 18.4%, 15.8%, and 10.4% reduction slump values of concrete are noticed by the addition of 25% of MK for 0.25, 0.3, and 0.35 w/c ratios. This indicates that the accumulation of MK as substitute to cement diminishes the workability. Similar trend in results are also noticed in [23], as the dosages of MK enhance the workability of concrete diminishes. The accumulation of MK decreases the availability of water in concrete due to its high reactivity. Also MK is having smaller particle size, which will also increase the water demand in concrete [24].

3.2. Compressive strength

The concrete compressive strength is the most frequently utilised parameter in structural engineering and design. For all concrete mixtures, 100 × 100 × 100 mm cubes are cast, and kept in the moulds for one day. After one day the cubes are separated from the moulds and kept in curing in potable water available in the laboratory. The test was conducted to all mixes in triple as per the IS: 516-1959 standards [25]. Figure 2 shows the 7-day strength results samples. From Fig. 2 it is noticed that the addition of MK up to 15% as replacement to cement increases the strength. There is a maximum of 40%, 38%, and 35% improvement in strength noticed as compared to standard mix for 0.25, 0.3, and 0.35 w/c ratios. While the addition of 25% of MK in concrete shows 10%, 8%, and 6% improvement in strength in comparison to standard mix for 0.25, 0.3, and 0.35 w/c ratios.

Figure 3 shows the strength results of different concrete mixes for 28-day cured samples. From Fig. 3 it is noticed that the addition 15% of MK as replacement to cement

Table 2. Concrete mix details (kg m^{-3})

Mix Details	Cement	MK	Fine Aggregate	Coarse Aggregate 20 mm	Coarse Aggregate 12.5 mm	Coarse Aggregate 10 mm	Water	Super Plasticizer
For 0.25 w/c ratio								
CM	564	0	600	723	144.6	337.4	141.4	6.768
MK5	536	28	587	707	141.6	330.4	141.4	6.768
MK10	508	56	573	691	138	322	141.4	6.768
MK15	479	85	559	673	134.7	314.3	141.4	6.768
MK20	451	113	545	656	131.1	305.9	141.4	6.768
MK25	423	141	532	641	127.8	298.2	141.4	6.768
For 0.3 w/c ratio								
CM	507	0	607	732	146	341	152.1	6.084
MK5	481	26	587	707	141.6	330.4	152.1	6.084
MK10	456	51	583	702	140	327	152.1	6.084
MK15	431	76.05	570	686	137	320	152.1	6.084
MK20	405	102	551	663	132.6	309.4	152.1	6.084
MK25	380	127	546	658	131.4	306.6	152.1	6.084
For 0.35 w/c ratio								
CM	435	0	630	750	151.8	354.2	152	5.25
MK5	413	22	619	746	148.8	347.2	152	5.25
MK10	391.5	43.5	604	728	145.5	339.5	152	5.25
MK15	369.75	65.25	592	713	142.5	332.5	152	5.25
MK20	348	87	552	665	132.6	309.4	152	5.25
MK25	326.25	108.75	547	660	131.7	307.3	152	5.25

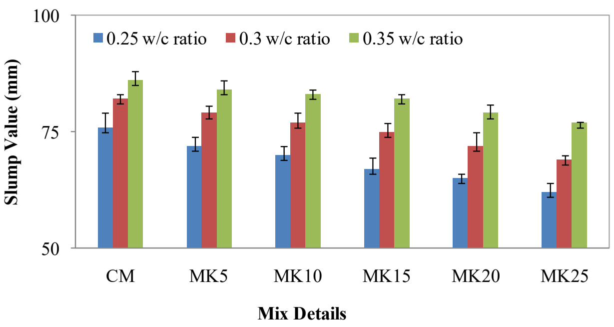

Fig. 1. Slump cone test results of all concrete mixes

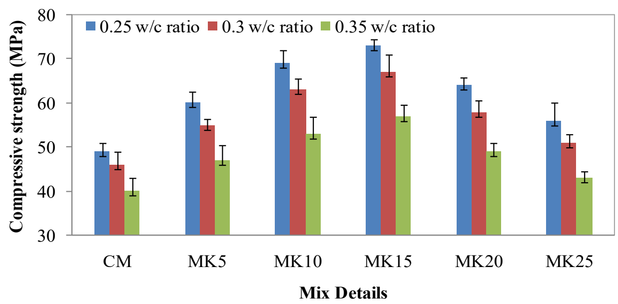

Fig. 3. Compressive strength results of 28-day cured samples

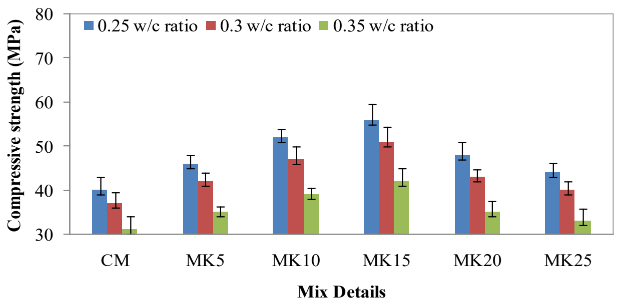

Fig. 2. Compressive strength results of 7-day cured samples

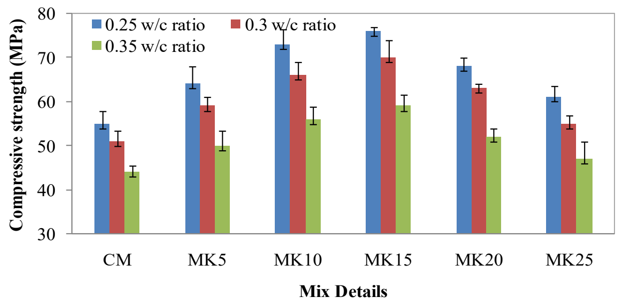

Fig. 4. Compressive strength results of 56-day cured samples

shows 49%, 45%, and 42% enhancement in strength in comparison to standard mix for 0.25, 0.3, and 0.35 w/c ratios. As the dosages of MK increase beyond the 15% strength of concrete diminishes slightly.

Figure 4 shows the 56-day strength results of various concrete mixes. The strength results follow the same pattern as 28- and 7-day cured samples. From Fig. 4 it is noticed that the 15% accumulation of MK as substitute to cement is optimum for preparation of HPC. The accumulation of 15% of MK as replacement to cement shows 38%, 37%, and 34% improvement in strength in comparison to standard mix for 0.25, 0.3, and 0.35 w/c ratios. Because MK is a very reactive pozzolana, the $Ca(OH)_2$ content present in concrete can be minimized by its incorporation. This gives dense structure to concrete and increases the strength of concrete [26, 27]. The contribution of MK becomes less efficient at larger w/c ratios, because of the increase in porosity [28]. Thus, strength improvement is minimum in higher w/c ratio concrete mixes. Similarly, at higher dosages of MK also minimum strength improvement was noticed in all three w/c ratios. At higher dosages of MK micro-cracks are formed due to availability of high specific surface area; which increases the water demand in concrete. Furthermore, the addition of higher dosages of a material which do not directly participate in hydration process reduces the compressive strength [28].

3.3. Flexural strength

The flexural strength test determines the capacity of a concrete beam to resist bending failure. The flexural strength of concrete is evaluated using a concrete beam specimen of 100 × 100 × 500 mm. The beams are casted after mixing of concrete and kept in moulds for one day. After one day the beams are separated from the moulds and kept in curing in potable water available in the laboratory. The beams are tested in triplicate for all concrete mixes at 28 and 56 days, for 0.25, 0.3, and 0.35 w/c ratios. The test has been carried out as per the IS: 516-1959 standards [25]. Figure 5 depicts the flexural strength findings of several concrete mixes after a 7-day curing time.

From Fig. 5 it is identified that the accumulation of MK improves the strength in comparison to standard concrete. The accumulation of 5% of MK as substitute to cement shows 15%, 11.7%, and 9% enhancement in strength in comparison to standard mix for 0.25, 0.3, and 0.35 w/c ratios. The accumulation of 15% of MK as replacement to cement in concrete shows 35%, 31%, and 29% optimum percentage enhancement in strength of concrete for 0.25, 0.3, and 0.35 w/c ratios in comparison with control concrete. While the accumulation of MK as substitute to cement more than 15% diminishes the strength. However, the accumulation of MK up to 25% as substitute to cement shows comparable results with control concrete. The accumulation of 25% of MK as substitute to cement shows 10%, 7%, and 4% enhancement in strength in comparison with standard mix.

Figure 6 illustrates the strength results of 28-day cured samples. From Fig. 6 it is noticed that the addition of 15% of MK shows optimum development in strength. Also, the flexural strength results followed a similar trend as of compressive strength. The accumulation of 15% of MK in concrete as replacement to cement shows 45.5%, 41%, and 33% enhancement in flexural strength in comparison with standard mix at an age of 28 days correspondingly. Figure 7 shows the 56-day cured samples flexural strength results. From Fig. 7 it is observed that the accumulation of MK as replacement to cement has a positive effect on flexural strength for all three w/c ratios. The addition of MK as 15% replacement to cement shows 35%, 32%, and 28% enhancement in flexural strength in comparison to standard mix for 0.25, 0.3, and 0.35 w/c ratios. While the accumulation of MK as replacement to cement more than 15% slightly diminishes the strength of concrete.

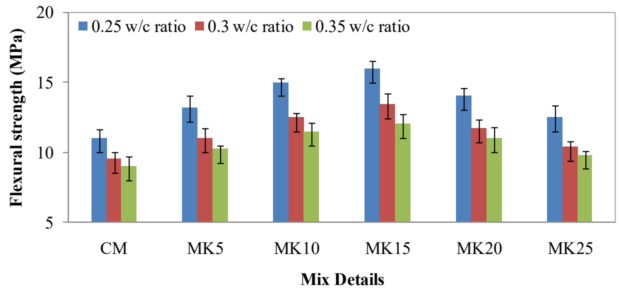

Fig. 6. Flexural strength results of 28-day cured samples

3.4. Electrical resistivity

To know the quality of concrete in terms of voids and internal cracks electrical resistivity (ER) test was performed. Bulk Electrical Resistivity Test was performed in this study conforming to the guidelines of ASTM C 1202 [29]. The 100 × 100 × 100 mm size cubes are casted and kept in mould for one day. After one day the cubes are separated from the moulds and kept in water curing. These samples are utilized for testing electrical resistivity. The test has been performed using a Leader RCON™ concrete electrical resistivity meter. Figure 8 illustrates the ER test results of all concrete mixes for a curing period of 28 days. The results confirm that the accumulation of MK as replacement to cement minimizes the pores in concrete and increases durability. The control concrete shows an ER of 18.1 kΩ-cm, 17.8 kΩ-cm, and 16.4 kΩ-cm for 0.25, 0.3, and 0.35 w/c ratios at an age of 28 days. While the addition of 15% of MK as replacement to cement shows an ER of 40.1 kΩ-cm, 37.7 kΩ-cm, and 33.9 kΩ-cm for 0.25,

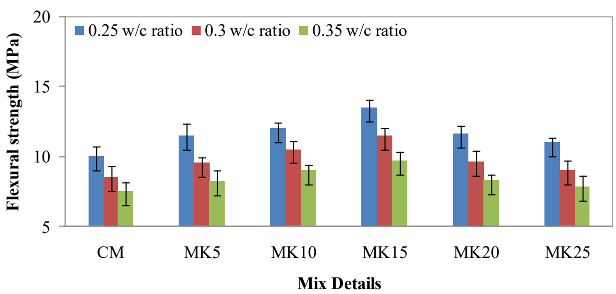

Fig. 5. Flexural strength results of 7-day cured samples

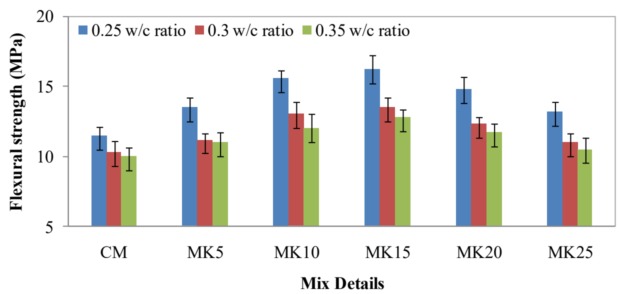

Fig. 7. Flexural strength results of 56-day cured samples

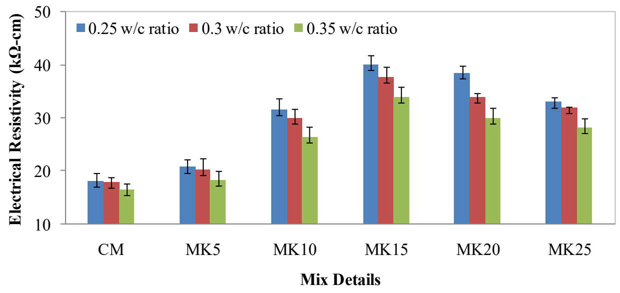

Fig. 8. Electrical resistivity test results of 28-day cured samples

0.3, and 0.35 w/c ratios at an age of 28 days respectively. The addition of MK as replacement to cement of more than 15% slightly diminishes the ER of concrete.

Figure 9 depicts the 56-day cured samples ER test results. From Fig. 9 it is noticed that the trend pattern is followed as similar to 28-day ER test results. The control concrete shows an ER of 20.9 kΩ-cm, 19.7 kΩ-cm, and 18.4 kΩ-cm for 0.25, 0.3, and 0.35 w/c ratios at an age of 56 days. Similar to 28-day test results the addition of 15% of MK as replacement to cement shows optimum improvement in ER of concrete. The accumulation of 25% of MK as substitute to cement improves the ER of concrete in comparison to control mix in all three w/c ratios. The MK is a reactive pozzolanic material, it reacts with $Ca(OH)_2$ present in concrete and develops secondary C-S-H [30]. This decreases the pores and micro-cracks present in concrete and improve the ER of concrete. The addition of higher dosages of MK as replacement to cement reduces the available water in concrete [31]. This leads to development of micro-cracks in concrete and reduces the ER of concrete.

3.5. XRD analysis

The X-ray diffraction (XRD) test identifies the mineralogy of concrete by amorphous/crystalline phases present by using X'-PERT HighScore software. The control mix and MK15 mix samples of 0.3 w/c ratio were utilized for this study. The concrete pieces were ground to powder sample having sizes less than 75 micron and used in XRD analysis. The XRD test has been performed on PANalytical 3 kW X'pert Powder – Multifunctional instrument. Figure 10 shows the XRD analysis of concrete samples. The hydration products CSH, $Ca(OH)_2$, and calcite are noticed in XRD analysis for control mix and MK15 mix. In the control mix the peaks of $Ca(OH)_2$

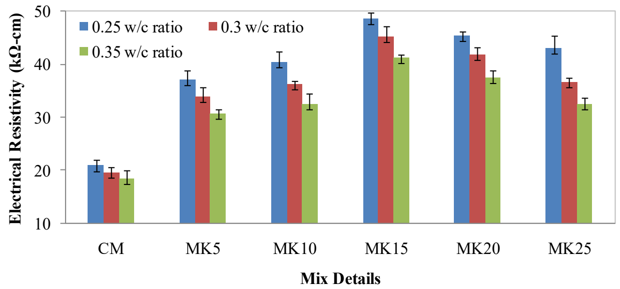

Fig. 9. ER test results of 56-day cured samples

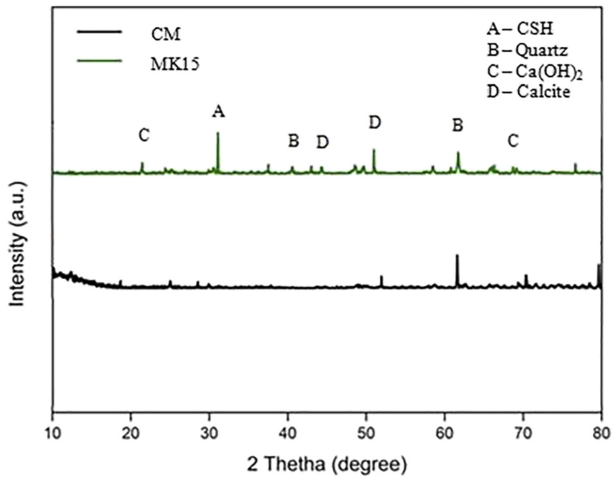

Fig. 10. XRD analysis of concrete samples

are observed to be higher. The amount of calcite peaks are similar to both the control mix and MK15 mix. However, the MK15 mix shows minimum peaks for $Ca(OH)_2$, which confirms that the accumulation of MK utilizes $Ca(OH)_2$ and develops secondary CSH in concrete. This increases the denseness and minimizes the pores and micro-cracks in concrete. Similar trends in results are also identified in [32] as the addition of MK improves the micro-structure of concrete.

4. CONCLUSIONS

The effect of MK on properties of HPC is tested in this study. The MK is added in concrete as partial alternative to cement. The results confirm that the accumulation of MK in concrete enhances the performance. The accumulation of 15% of MK as replacement to cement shows optimum results in strength. The accumulation of higher dosages of MK slightly diminishes the strength. The strength increases due to increase in the amount of CSH in concrete due to pozzolanic activity of MK, as was confirmed by using XRD analysis. There is a good correlation between the amount of CSH developed and strength of concrete in the mix MK15. The accumulation of MK in concrete increases the denseness of concrete by minimizing the pores in concrete, as was confirmed by ER test of concrete. The test results confirm that the accumulation of MK as substitution to cement increases the performance of concrete.

Conflict of interest: Authors do not have any conflict of interest.

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