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Experimental Investigation into the Metakaolin Used in Concrete

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ABSTRACT

Today, in most parts of the world, there has been a tremendous development in the technology of concrete to achieve high-strength concrete. The use of metakaolin (MK) in concrete to achieve high-strength and durable concrete has been in the concrete industry for several years. Due to its significant pozzolanic activity and reaction with calcium hydroxide in the cement, this material has reduced porosity and permeability and increased durability and strength in concrete. In the present study, the role of (MK) and its effect on the mechanical properties to achieve the optimum percentage of MK use for high strength and durability have been investigated. In this study, laboratory tests at early and hardened state including temperature change, slump, liquidity examination, water absorption, specific gravity of concrete, electrical strength test (indicating permeability and corrosion rate), and compressive strength test on samples with 0, 10, 15 and 20 percent cement-substituted MK at 7 and 28 days of age were tested on 15cm cube specimens. The results showed that the addition of 10% cement substitute MK in slump test, 15% cement substitute MK in compressive strength test, and 20% cement substituent MK in electrical resistance test had the highest values and 15% cement substitute MK in concrete weight density test. 20% of cement-substituted MK in the experiment showed the lowest water absorption percentage compared to other mixes designs. Microscopic analysis shows the more durable MK replacement in comparison with normal concrete.

Keywords: **Pozzolan, Metakaolin, Durability, Mechanical Properties, Temperature Tests.**

1. INTRODUCTION

High reactivity metakaolin (MK) is one of the recently developed supplementary cementing materials for high-performance concrete. It is produced by calcining purified kaolinite clay in a specific temperature range (650 to 800°C) to drive off the chemically bound water in the interstices of kaolin and destroy the crystalline structure. Unlike industrial products, such as silica fume, fly ash, blast-furnace slag, MK has a light color and controls its particle size. The particle size of MK is generally less than 2µm [1], which is significantly smaller than cement particles, though not as fine as silica fume. They incorporated into the concrete to replace 5-20% of cement mass. Two main components in MK are silicon dioxide and aluminum oxide that react with calcium hydroxide to form secondary C-S-H. However, MK was found to improve concrete properties while offering good workability [1, 2, and 3]. In recent years, metakaolin, which is the result of the thermal activation of kaolin clay, has been considered as an alternative to cement, and its consumption in the cement industry is increasing [1, 2]. Meta-kaolin has been commercially available in the road and building industry since the mid-1990s. It is one of the newest cement replacement materials for the manufacture of high-strength concrete [3]. The first documented use of this material was in concrete in 1962 in the Brazilian Jupiah Dam. The use of MK in the concrete industry is short-lived, but it has quickly been accepted as an effective pozzolanic substance, having been marketed since 1994 [4]. The use of MK in the production of durable and high-performance concrete is increasing day by day. Extensive research has been reported in articles on various properties of MK in the paste and hardened concrete, including pozzolanic reaction, cavity structure, compressive strength, and concrete durability [1, 2]. MK is classified as N class pozzolans (raw or calcined pozzolans such as calcined materials) in the ASTM C618 classification [3, 5]. Because the MK production process must be controlled in some cases known as an engineered pozzolan. This production is associated with lower pollution and lower energy consumption. In recent years, the use of MK as a substitute for part of cement has been extensively studied in various countries, and these studies indicate that MK is a highly active pozzolan and promotes the mechanical properties of concrete in the short and long term. In addition, due to the effect on the concrete color made due to the light color of this material the use of MK-containing concrete is recommended for specific architectural applications [1, 6]. In Iran, despite the existence of numerous and diverse kaolin mines, so far, there has been no production of MK [4, 5]. In the present study, some of the mechanical properties and reliability of MK-containing concrete in the market have been evaluated. Tsai-Lung Weng et al. [4] investigated the basic mechanical and microscopic properties of cement produced with metakaolin and quantified the production of residual white efflorescence. Cement mortar was produced at various replacement ratios of metakaolin (0, 5, 10, 15, 20, and 25% by weight of cement) and exposed to various environments. Compressive strength and efflorescence quantify (using Matrix Laboratory image analysis and the curettage method), scanning electron microscopy, and X-ray diffraction analysis were reported in this study. Specimens with metakaolin as a replacement for Portland cement present higher compressive strength and greater resistance to efflorescence; however, the addition of more than 20% metakaolin has a detrimental effect on strength and efflorescence. This may be explained by the microstructure and hydration products. The quantity of efflorescence determined using MATLAB image analysis is close to the result obtained using the curettage method. The results demonstrate the best effectiveness of replacing Portland cement with metakaolin at a 15% replacement ratio by weight. In conclusion In the M5, M10, M15, and M20 samples, the area affected by efflorescence was lower than that of the control specimens; the M15 specimens were the least affected by efflorescence. In SEM micrographs, materials produced with metakaolin developed denser, smoother structures. XRD results indicate that the number of main hydration products in cement-based materials with replacement metakaolin performed significantly. The results conclusively demonstrate that cement-based materials with 15% replacement metakaolin have superior performance with considerable potential for application in engineering [4]. Metakaolin (MK) is one type of calcined clay, and it comes from the calcination of kaolin clay; and there have been some interests in the use of MK in recent years. For example in the United Kingdom, the coal-fired power industry will come to a close in the next 10 years, and fly ash will cease to be generated [7, 8]. Alternative pozzolanic materials are required to be used in order to improve the properties of concrete such as durability and reduce the amount of cement used in concrete production. The use of MK as a partial substitute for cement in paste, mortar, or concrete was investigated. The mechanical, physical, and durability properties of cementitious systems will be reported based on the literature available. The use of other pozzolanic materials such as fly ash or ground granulated blast furnace slag in conjunction with MK has also examined the use of alkali materials in the presence of materials [2, 3].In this study, experimental investigation including liquidity examination, water absorption percentage, the specific gravity of concrete, electrical resistance test (indicating corrosion and permeability), and compressive strength test on samples with 0, 10, 15, and 20 percent cement-substituted MK at 7 and 28 days of age were tested on 15 cm cube specimens. A comprehensive experimental study was carried out by Abdolmelek and Lublov [9] to evaluate the performance of high-strength paste exposed to elevated temperatures up to 900 °C. Several factors have been investigated at the age of 90 days, i.e. metakaolin (MK) dosages, water to binder ratio (w/b) as well as elevated temperatures. Results proved that MK improves the relative residual compressive strength and relative residual bending strength showing a gain up to 52% and of 71% at 500 °C, respectively, compared to the pure cement paste in case of 0.3 w/b. The maximum use of MK is not more than 12%, and the optimum dosages were 9, 12, and 12% of MK replacements for 0.3, 0.35, and 0.4 w/b, respectively. The optimum dosage could change with changing w/b ratio and this up to the density of the microstructure which is controlled by the amount of w/b ratio and the packing effect of MK amount. In addition to the mechanical properties, the adoption of MK decreases the cracking of the specimens at elevated temperatures. SEM investigations show the positive physical morphology contribution of MK, specific surface area, and chemical composition for decreasing the, Ca(OH)2 effect. Different phases that formed during temperatures elevation are illustrated by TG (Glass Transition Temperature) analysis. Results showed the reason behind using MK on the cracking enhancement and mechanical properties improvement after high temperatures exposure. Meanwhile, the obtained optimum MK dosages at ambient temperature are not similar to those obtained at elevated temperatures. It was concluded that the relative residual compressive strength, 9% of MK content has the highest value among other ratios at high temperatures for w/b ratio of 0.3. According to the relative residual compressive strength, 12% of MK content has the highest value among another ratio at high temperatures for w/b ratio of both 0.35 and 0.4. The optimum relative residual bending strengths have been obtained in the ranges of MK replacement level by results of relative residual compressive strengths. MK has a significant influence on surface cracks due to elevated temperatures. The more the paste contains MK, the less the cracks occur. Excessively increasing the amount of MK leads to an increase in the probability of spalling. Different amounts of w/b ratio have a significant effect on optimum MK dosage at both ambient and elevated temperatures. The risk of spalling was higher for prisms than for cubes, which could be explained according to the different shapes and sizes of the specimens. Metakaolin is an imminent mineral admixture extracted from the mineral ore kaolinite, enhancing the interfacial zone by more efficient packing at the cement paste-aggregate particle interface, thus reducing the bleeding and producing a denser, more homogeneous transition zone microstructure. This paper depicts the various repercussions of the pozzolanic material metakaolin in the fresh and hardened properties of concrete when replaced with cement infinite amounts. Also, it states the behavior of high-performance concrete and self-compacting concrete with metakaolin [10]. 10% of replacement of MK with 0.4 w/b ratios developed maximum compressive strength The finer nature of MK lowers the porosity. Thus a much permeable concrete is developed, which provides resistance to chloride attack, sulfate attack, and acid attack. The less CH content in the MK concrete tends to introduce high strength and durability to withstand the elevated temperatures. A good gain in compressive strength was noted in MK concrete for up to a replacement level of 20% and the inflation in tensile strength, which is comparatively lower than the former one. Workability gets affected at higher MK replacement levels [10]. Presently the use of metakaolin is gaining much importance in the partial replacement of cement. It is because metakaolin has increased various strengths of concrete and improved durability [11]. Using 25% MK to replace cement increases strengths of all basic properties viz. compressive strengths, flexure strengths, split strengths, tensile strengths, etc., and durability improvement. Water permeability, absorption was much improved in the use of metakaolin which leads to an increase in the density of concrete. Use of metakaolin in preparing acid resistance concrete such as chloride permeability, sulfate resistance also better improvement in flowability of concrete and cement mortar. MK. reduces efflorescence which occurs when calcium is transported by water to the surface. It combines with carbon dioxide from the atmosphere to make calcium carbonate, precipitating the surface as a white residue [11]. It enhances the workability and finishing of concrete it reduces shrinkage due to particle packing. It can be used to form high-performance, high-strength, and lightweight concrete, precast and poured-mold concrete, fiber cement and ferrocement products, glass fiber reinforced concrete [11]. The mechanical property (e.g., stress-strain relationship, strength, and deformation performance) and microstructure characteristics of MK-based geopolymer cemented silty clay are investigated [29] using unconfined compressive strength (UCS), nuclear magnetic resonance (NMR), and scanning electronic microscopy (SEM) tests. In addition, strength increase coefficient (ζs) and elasticity modulus increase coefficient (ζe) are defined to evaluate the effects of curing time on the mechanical property of MK-based geopolymer cemented silty clay [12]. SEM results reveal that the microstructure of the sample modified by 2% MK is most homogeneous and dense compared with other MK content groups. With the increasing curing time, the size of both micro-pores and micro-cracks decreases which contributes to improving its strength and elastic modulus [12]. In research by Venkatasunee et al. [13] eggshell powder used with metakaolin in concrete to investigate the properties of the concrete was carried out. Different combinations of MK and eggshell powder (ESP) as partially replaced cement. This study demonstrated that the combination of ESP and MK has improved compression behavior, split tensile property, and flexural strength of concrete. When the cement is partial supplant by eggshell powder up to 10% attained maximum compressive strength. Similarly, split tensile-based strength and flexural behavior of concrete also increased and then decreased beyond 10%. Similarly, flexural and split tensile strengths of concrete increased and continue to decrease beyond 10%. Maximum compressive, spilled tensile and flexural strengths are attained when the cement content is supplanted with metakaolin and eggshell powders at 10% and 5%, respectively [13].

2. MATERIALS AND METHODS

The sand used in the was washed sand, and the aggregate is irregularly fractured in two sizes 9.5 and 19 mm, which meet the requirements of the ASTM C33 standard. The aggregates used are presented in Table 1.

Table 1. Physical Properties of Aggregates Used in Sample Making

aggregate	Max. size of aggregate(mm)	Specific density gr/cm^3	% absorb water	Specific weight (gr/ cm^3) in SSD
Large aggregate	19	2.64	0.48	2.63
Small aggregate	9.5	2.62	0.91	2.61
sand	4.75	2.59	1.67	2.58

2.1. MATERIAL GRADING CHART

The sand-aggregate size used in this work was drawn by red line in the standard chart given in Ref. 13.

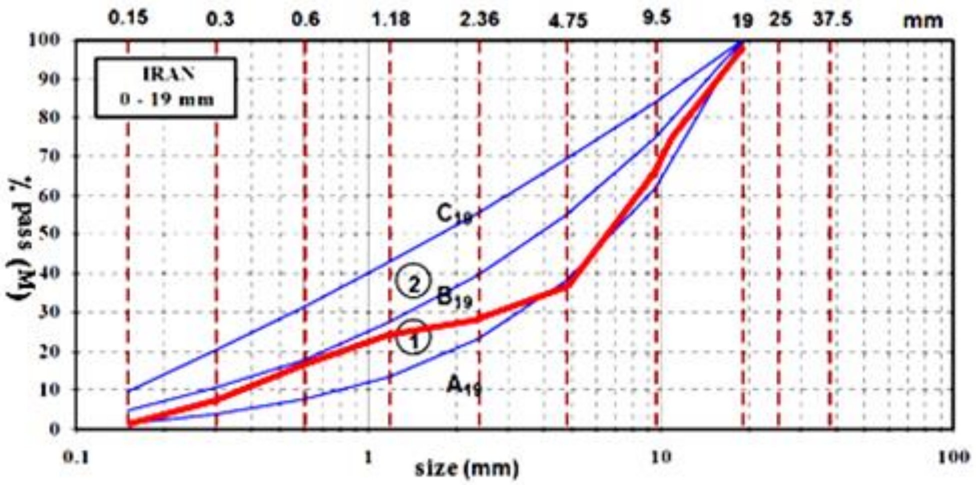


Figure 1. Grading curve used in construction designs (National Concrete Mix Design Method Diagram [14])

From Figure 1, it can be seen that the aggregate used in this work is within the limit. This shows the suitability of the aggregate. Consumable cement in this research, all the mixing designs of Portland cement type II were prepared by Khuzestan Cement Company, which met ASTM C150-84. The water used for concrete samples is drinking water that meets the requirements of ASTM D1129. The MK used as mineral additives was obtained from Easy Trade Co. of Tehran, and its elemental analysis specifications by XRF are presented in Table 2

.

Table 2. Elemental Analysis Results of MK XRF Test

Composition	Blaine (cm^2/gr)	SiO_2 %	Al_2O_3%	Fe_2O_3%	CaO%	MgO%	TiO_2%	Na_2O %	K_2O%
MK	22000-25000	52-54	44-46	0.6-1.2	0.09	0.03	0.65	0.10	0.03

2.2. KAOLIN

Kaolin is a type of fine-grained mineral soil generally formed by the breakdown of feldspars, granites, and aluminum silicates. As shown in Figures 2 and 3, the color of this material is white, light gray, or slightly colored and is commonly used in ceramic and porcelain making [15].

Figure 2. Kaolin Mine

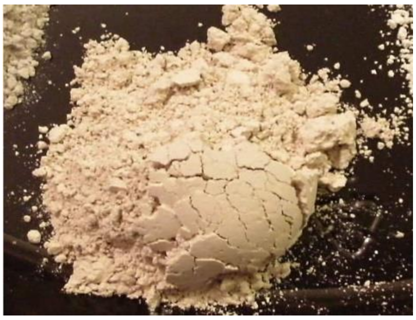


Figure 3. Kaolin

2.3. METAKAOLINE

The primary raw material for the production of MK is kaolin clay. The clays are not pozzolan and cannot exhibit a significant reaction with lime unless the crystalline structure of the Alumina-silicate minerals in the clay is transformed into an amorphous or irregular structure by heat treatment [16]. Therefore, for the production of MK, the clay is heated to 700 to 900 ° C, the end product being

MK [1, 3, and 17]. The color of this material is white, as shown in Figure 4.

Figure 4. Meta-kaolin

The active pozzolan is widely used globally and in various industries, especially as an effective pozzolan in improving the strength and durability of concrete. The reserves of this valuable material in the world in 2001 were estimated at 20 billion tons, with our country having an estimated 40 million tons [18]. The main difference between MK and other synthetic consumptive pozzolans such as silica fume and fly ash is that these materials are byproducts or secondary. At the same time, MK is a primary product, so MK can be obtained by the controlled process to obtain the desired product [2].

2.4. EVALUATION OF THE PROPERTIES OF MK

Comparative experiments have shown that the properties of this pozzolan improve the sustainability and mechanical properties similar to silica fume [1] and can improve the mechanical properties of concrete in the short and long term [3, 17]. It is also recommended to use this material in bulk concrete because of its relatively low hydration temperature.

2.5. PHYSICAL PROPERTIES AND CHEMICAL COMPOUNDS

The input raw material for the production of MK is kaolin clay. At 100 and 200°C, kaolinite, which is the main constituent of kaolin, loses its absorbed water due to further dehydration by Relation (1) [3, 17, 19].

Relationship (1): The process of taking water from kaolin [3]

$$(OH)_4 \longrightarrow Al_2O_32SiO_2 + 2H_2O\ Al_2Si_2O_5 \qquad (1)$$

This heating removes the chemical water of the kaolin and destroys its crystalline structure and turns the product into an amorphous aluminum silicate (A_2S) [1, 3].
MK is a silica-based product that reacts with Ca $(OH)_2$ to produce the usual temperature of the CSH gel. MK also contains alumina, which reacts with CH (2) to produce alumina phases containing C_4AH_{13}, C_2ASH_8, and C_3AH_6 [2, 3, and 17].

Relationships (2)

$$MK + CH + H \longrightarrow C\text{-}S\text{-}H,\ C_4AH_{13},\ C_3AH_6,\ C_2ASH_8 \qquad (2)$$

In order to produce MK, it raises the kaolin clay temperature to 700 to 900 °C. These thermal interactions are known as a "calcination" of a mineral [3]. Substances such as MK that contain more alumina tend to consume C-H and form C-S-H according to (2) and exhibit a high activity. What are presented in Equations (3) and (4) are the cation hydration reaction and the pozzolanic reaction after C-H production [18]. Portland cement:

$$C_3S + H \xrightarrow{\text{Fast}} C\text{-}S\text{-}H + CH \qquad (3)$$

Portland cement – Pozzolan

$$Pozzolan + CH + H \xrightarrow{\text{Slow}} C\text{-}S\text{-}H \qquad (4)$$

2.6. MK PERFORMANCE ON THE DURABILITY OF CONCRETE

Using MK improved the microstructure of concrete and is enhanced the strength and durability against the ingress of chloride and sulfate ions. Also is resists and controlled the AAR reaction (Alkali Aggregate Reaction); MK is needed less water-retarder than silica fume [1]. Research carried out so far in this field shows that MK is enhanced the flexural and torsion strength, reducing water immersion, and increasing strength and resistance AAR and migration of chloride, and also reduced creep. MK in concrete should be in proportion to the amount C-H induced by cement hydration and water that existed in the system, the amount of C3A in cement, and the rate of cement replacement to exhibit the best performance [1,18].

Table 3 presents the physical properties, and Table 4 shows the chemical composition of a sample of MK and its comparison with kaolin and Portland cement type 2.

Table 3. Physical properties of consumed MK compared to a type of kaolin and cement consumed Relationships (3)

Physical characteristic	MK	kaolin	OPC type II
Density(gr/cm^3)	2.6	2.26	3.1-3.15
Blain (cm^2/gr)	22000-25000	3500	3150
% of loss of heat due (LOI)	1.00	15.00	1.10
Size of particles (mµ)	1-2	-	10-15

Comparing the Blain numbers and particle size distribution of both Portland cement and MK cement in Table (3) illustrates the MK are a smaller particle size ratio than cement particles. Also, a 1% LOI in MK and comparing it with the loss from combustion in primary kaolin (15%) indicates that a large amount of kaolin water has evaporated in the process of converting kaolin to MK. This leads to an increase in oxides such as silica and alumina in MK to kaolin [3]. Comparison of MK with cement showed that the total percentage of silica and aluminum in MK was more than three times that of cement. However, the percentage of calcium oxide (CaO) in MK is negligible, and the major drawback of MK is its chemical composition [1], which is well visible in Table 4.

Table 4. Chemicals of MK consumed compared to one type of kaolin and cement

Chemical composition	MK	kaolin	OPC type II
SiO_2	52-54	42.00	22.08
Al_2O_3	44-46	35.00	5.02
Fe_2O_3	0.6-1.2	1.30	3.22
CaO	0.09	3.10	63.54
Mgo	0.03	1.80	2.50
K_2O+Na_2O	0.03+0.10	0.17+0.10	0.58+0.24
SO_3	0.20	0.10	1.97

2.7. EXPERIMENTAL PROGRAM

The mixing scheme used in constructing the control concrete in this study is by ACI-211-89 [20]. In this study, 4 mixing schemes were used, one of which was used as control concrete and the other 3 with constant water/cement ratio of 0.5 and change in cement content by replacing 10%, 15%, and 20% of MK. The general specifications of these schemes are presented in Table 5.

Table 5. Design Specifications

Material	MK 0.00 %	MK 10.00 %	MK 15.00 %	MK 20.00 %
Sand (kg/m3)	780	780	780	780
Small agg. (kg/m3)	510	510	510	510
Large agg. (kg/m3)	510	510	510	510
Water (lit)	185	185	185	185
Cement (kg/m3)	370	333	314.5	296
MK (kg/m3)	0	37	55.5	74
Water to ementious %	0.5	0.5	0.5	0.5

2.8. SAMPLE DETAILS

In this study, different laboratory tests were performed on conventional concrete as control concrete and with (10, 15, and 20%) MK replacement cement consumed at 7 and 28 days of age on a 15 x 15 cm cube separately. After molding, the specimens were placed in the wet cloth to prevent evaporation, and after 24 hours in wet conditions, the mold was removed from the mold and immersed in water. Then some samples were treated for up to 7 days and others up to 28 days according to the type of test and standard. After 7 and 28 days of water treatment, the samples were removed from the water to schedule the experiment.

3. RESULTS AND DISCUSSION

3.1. WORKABILITY (SLUMP TEST)

Metakaolin absorbs more water than cement due to its smaller particle size, resulting in a workability reduction of fresh concrete. There are, however, examples of MK that even increase the number of concrete slumps.

However, despite this, the results of experiments conducted in this study according to ASTM C143 showed that the liquidity and workability changes of concrete containing different percentages of MK compared to control concrete. The results of this experiment are presented in Figure (5).

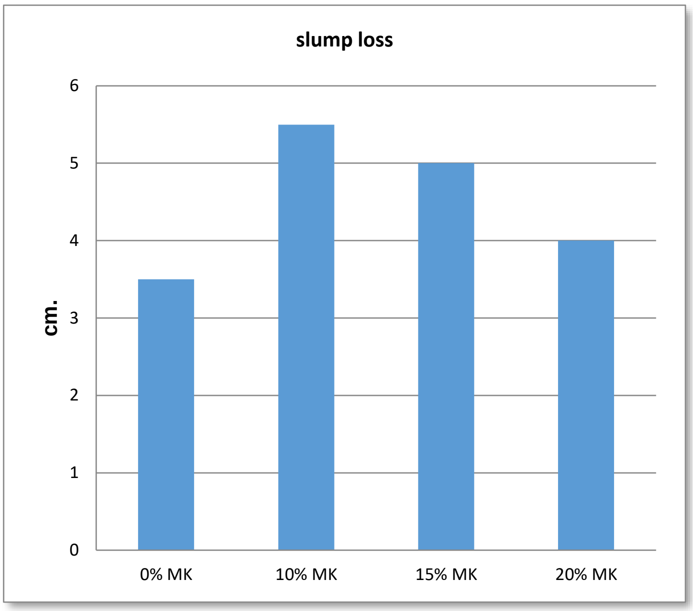
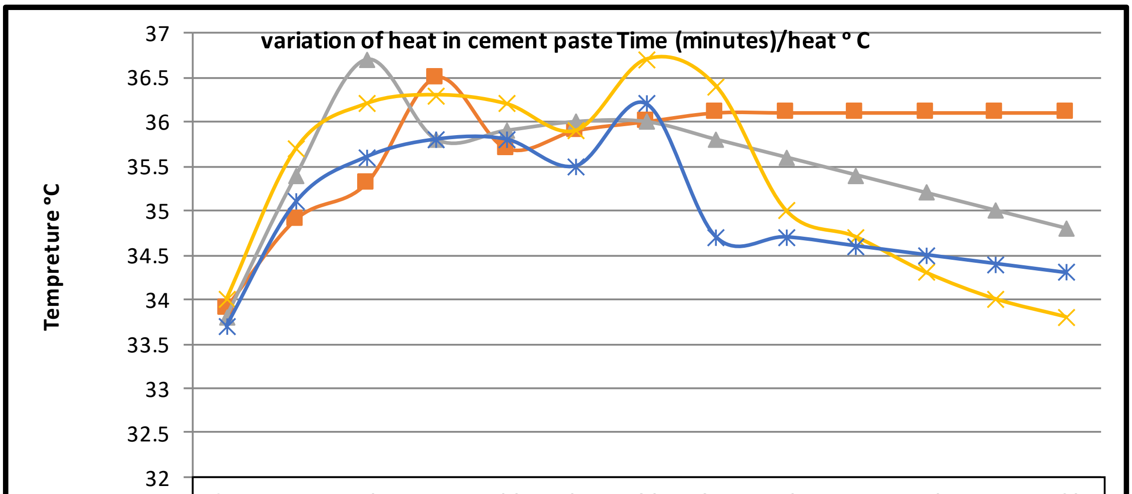


Figure 5. Slump loss Rate

Although it was expected due to the water depletion of fine particles of MK and a loss of workability of pozzolanic concrete, the slump loss is obtained. However, it was not observed, indicating that the workability of the concrete was maintained by adding MK. So it can be said that MK has a lubricating effect in itself and can positively affect concrete workability.

3.2. INVESTIGATION OF TEMPERATURE CHANGES

The results of this experiment, which were measured for one hour on the paste containing (0, 10, 15, 20) MK according to ASTM C1064 / C1064M-03, are presented in Figure (6). The ambient temperature was varied between 30 and 35 degrees Celsius, the water temperature between 30 and 32 degrees Celsius, and air humidity was about 55 percent.



	CT	5	10	15	20	25	30	35	40	45	50	55	60
0% MK	33.9	34.9	35.3	36.5	35.7	35.9	36	36.1	36.1	36.1	36.1	36.1	36.1
10%MK	33.8	35.4	36.7	35.8	35.9	36	36	35.8	35.6	35.4	35.2	35	34.8
15%MK	34	35.7	36.2	36.3	36.2	35.9	36.7	36.4	35	34.7	34.3	34	33.8
20%MK	33.7	35.1	35.6	35.8	35.8	35.5	36.2	34.7	34.7	34.6	34.5	34.4	34.3

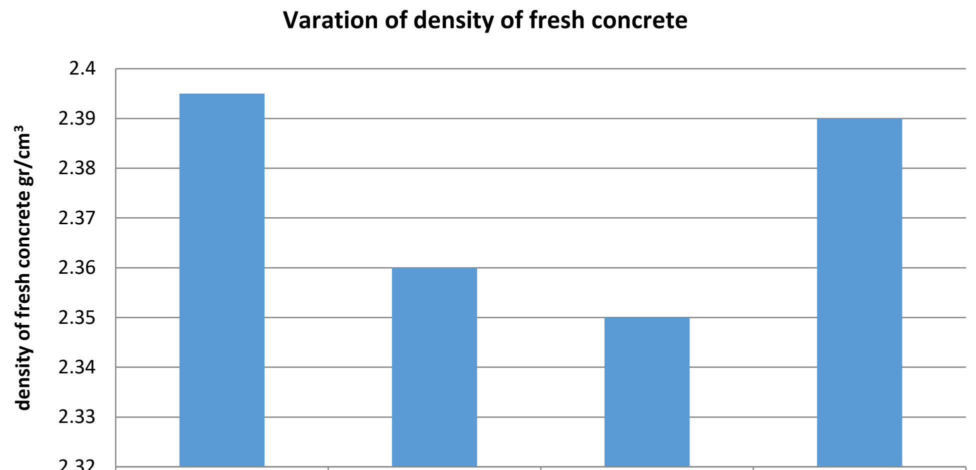
minutes from casting concrete

Figure 6. Temperature variations of cement paste designs

The results of this experiment, according to the diagrams in Fig. 4, show an increase in heat inducing in type 2 cement pastes, but with slight temperature changes that stopped after 35 minutes of increasing temperature. However, with the replacement of (10-15- 20%) to cement paste, the decrease in temperature in cement paste was observed, 15% of MK showed the most decreasing temperature change up to 2.5°C, and afterward, there was a decrease in temperature at 20% and 10% MK with 1.5 and 1.2 degrees Celsius, respectively.

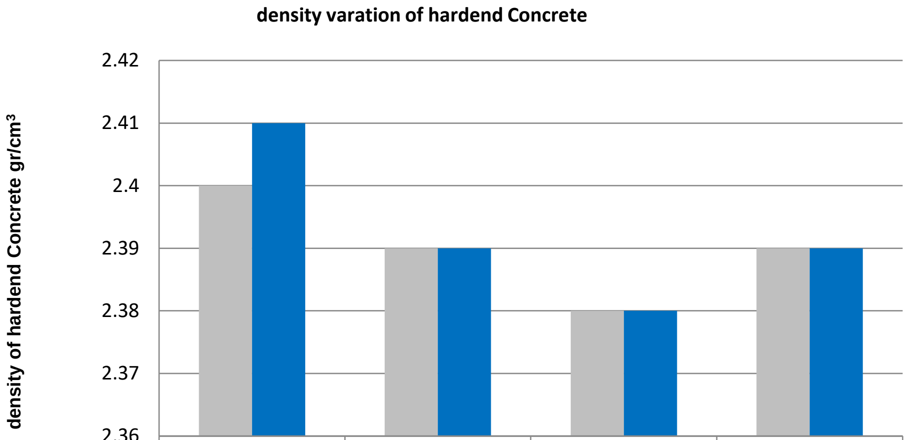
3.3. SPECIFIC DENSITY OF FRESH AND HARDENED CONCRETE

The results of this test, which are in accordance with BS EN 12390-1: 2012, are shown in Figures (7) and (8).



	0% Mk.	10% Mk.	15% Mk.	20% Mk.
density	2.395	2.36	2.35	2.39

Figure 7. Specific weight changes for fresh concrete



	0% MK	10% MK	15% MK	20% MK
densitye in 7 days	2.4	2.39	2.38	2.39
densitye in 28 days	2.41	2.39	2.38	2.39

Figure 8. Specific gravity changes for hardened concrete

This experiment showed a decrease in specific gravity for fresh and hardened concrete by increasing 10 and 15% of MK compared to the control concrete, and the highest amount of fresh weight for fresh concrete was related to the 15% MK design. However, 20% cement substituted MK and increased with increasing MK content of fresh concrete, but still, they are less than the specific gravity of hardened concrete

.

3.4. WATER ABSORPTION

The test was performed by BS 1881 - Part122 [21], and the results of the coring samples (Figure 9) to obtain the 28-day water absorption percentage are presented in Figure 10.

Figure 9. Core taken from cube specimens to measure water absorption

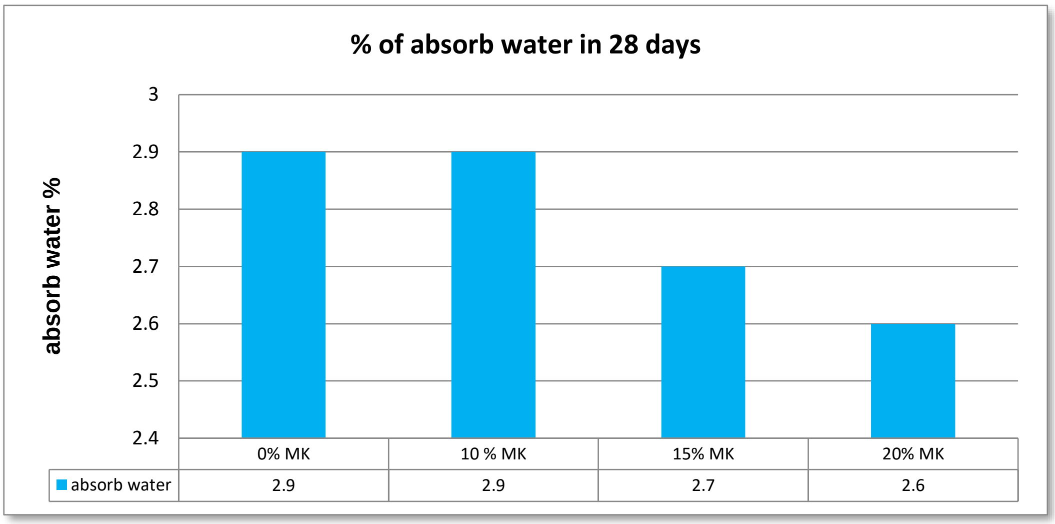


Figure 10. Water absorption percentage at 28 days

According to the results of this study, by increasing the amount of MK to 20%, the percentage of water absorption in the samples decreased. So, the lowest water absorption percentage is related to 20% MK. Therefore, the replacement of 20% MK with cement is considered as the optimum percentage for water absorption. Therefore, the presence of MK in concrete can reduce water absorption. Values obtained in this experiment are also compared with the standards in Table (6); we will see positive results showing the positive effects of MK on the construction of low permeable and more durable concrete for severe environmental conditions B and C.

Table 6. Permissible values from reinforced concrete permeability tests for durability under environmental conditions in the area [22, 23]

Experiment	The permissible limit		
	Condition A	Condition B and C	Condition D and E
Half hour absorption BS 1881,Part122,1983	Max 4 %	Max 3 %	Max 2 %
Water immersion in 28 days BS EN 12390-8:2000	Max 50 mm	Max 30 mm	Max 10 mm
Chloride immersion in 28 days ASTM C 1202,1994	Max 3000 Coulomb	Max 3000 Coulomb	Max 1500 -2000 Coulomb for D and E

Note: 1000-2000 coulombs indicate low permeability due to chloride immersion 2000-4000 coulombs indicate moderate permeability due to chloride immersion, and that 4000 coulombs indicate high permeability due to chloride immersion.

3.5. ELECTRICAL RESISTANCE OF CONCRETE

In this study, electrical resistivity tests were performed on 7 and 28-day-old cubic specimens according to ASTM Standard C1202-10. The method of reading the numbers in this experiment was that three readings were made on three sides of each sample and the results and mean values of electrical resistance of the three samples in 7, 28 days are presented. Also for comparison and growth of electrical resistance changes of samples of each design at 7, 28 days their results are plotted in Figure 12. Correlation of electrical resistance of concrete with corrosion rate according to Standard C1202-10 is given and compared the results. Overall, the electrical resistivity of concrete can be described as the ability of concrete to withstand the transfer of ions subjected to an electrical field. In this context, resistivity measurement can be used to assess the size and extent of the interconnectivity of pores. Corrosion is an electro-chemical process. The rate of flow of the ions between the anode and cathode areas, and therefore the rate at which corrosion can occur, is affected by the resistivity of the concrete [24]. To measure the electrical resistivity of the concrete a current is applied to the two outer probes and the potential difference is measured between the two inner probes. Empirical tests have arrived at the following threshold values which can be used to determine the likelihood of corrosion.

- When $\rho \geq 12$ kΩ-cm corrosion is unlikely
- When $\rho = 8$ to 12 kΩ-cm corrosion is possible
- When $\rho \leq 8$ kΩ-cm corrosion is fairly certain

These values have to be used cautiously as there is strong evidence that chloride diffusion and surface electrical resistivity is dependent on other factors such as mix composition and age [25]. The electrical resistivity of the concrete cover layer decreases due to [26]:

- Increasing concrete water content
- Increasing concrete porosity
- Increasing temperature
- Increasing chloride content
- Decreasing carbonation depth

When the electrical resistivity of the concrete is low, the rate of corrosion increases [27, 28, 29]. When the electrical resistivity is high, e.g., in dry and carbonated concrete, the rate of corrosion decreases.

To determine the electrical resistance of samples at 7 and 28 days of age, an apparatus was used. The apparatus used in this study to measure the electrical resistance of the specimens was a four-branch resistor called Resisto-meter, which is a tool for the electrical conductivity of concrete. Concrete electrical resistance can provide good information about concrete resistance in the face of aggressive factors. The method of reading the numbers in this experiment was that three readings were made on each side of the sample, and the average obtained electrical resistance criterion was considered. How to read and use the device is illustrated in Figure 11, and a comparative graph of the electrical resistance of the drawings is shown in Figure 12.

Figure 11. The method to measure electrical resistivity of the sample

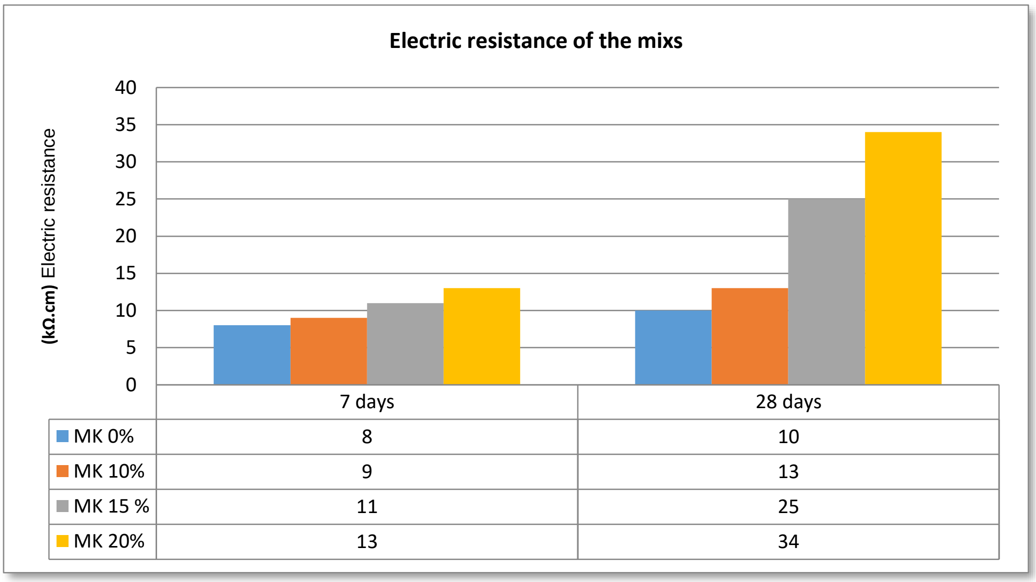


Figure 12. Average electrical resistance of designs

Based on the results presented in Figure 12 the corrosion is unlikely for 20% MK, which is above 12 kΩ-cm at 7days and 28 days on MK10%, MK15%, and MK20% no corrosion will be expected. In the Control specimen, MK0% at 7 and 28 days corrosion is possible. This study shows that with the addition of MK, electrical resistance in all designs mix increased in the early and late stages, which may be due to the decrease in porosity and permeability of concrete hence more durability. It can also be observed that this resistance is low at an early age but increases dramatically with increasing age. Therefore, the 15% and 20% designs show the highest resistance growth in the long run. For the 20% MK specimen at 28 days, the electrical resistance about 2.6 times higher than the 7 days; for 15% MK, the electrical resistance at 28 days about 2.2 times higher than the 7 days. Therefore, in this experiment, the highest amount of electrical resistivity was observed in the design containing 20% MK, and it seems that with increasing more than 20% MK, we will continue to experience electrical resistance in concrete.

3.6. EFFECT OF METAKAOLIN ON MICROSCOPY CHARACTERISTICS SEM IMAGES

This study employed SEM observations to characterize the microstructural compounds produced with/without replacement metakaolin. Careful analysis of microstructures can reveal the pozzolanic reaction and the gel development. SEM magnification was set at 3,000 times [4] to directly observe the development of cement hydration and pore structure. SEM observation was performed on control specimens after 28 days of aging, shown in Figure 13; large capillary pores indicated in the image, CH, and pore interconnectivity were observed.

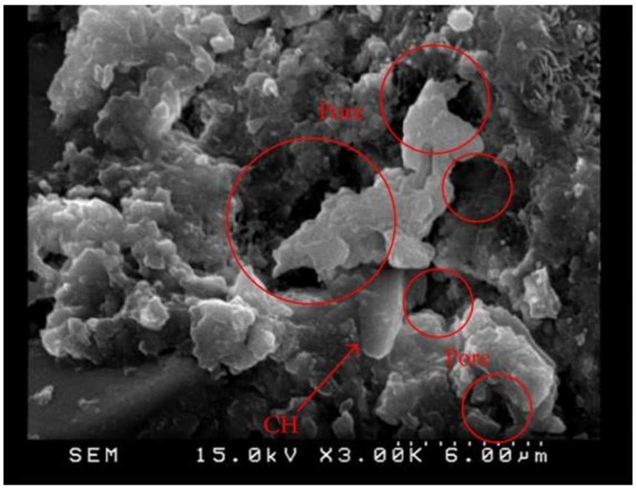


Figure 13. SEM images for 0% MK

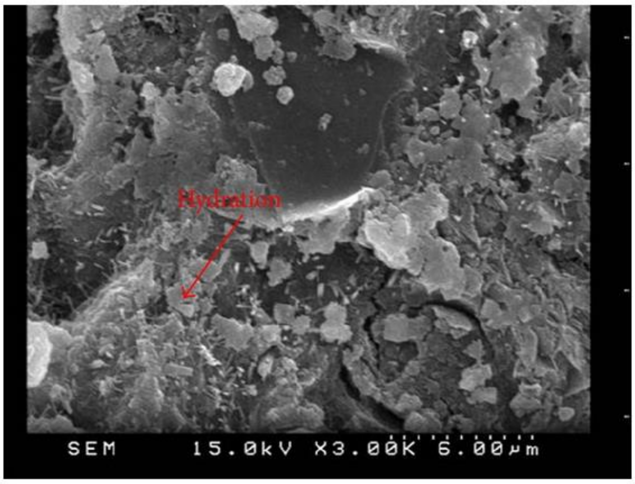


Figure 14. SEM images for 15% MK

Effects of Metakaolin on Microscopy Characteristics to characterize the microstructural compounds produced with/without replacement metakaolin were evaluated. Due to higher compressive strength by 15% MK replacement, SEM present in Figure 14 shows pozzolanic reaction and gel development. Also, it can be observed the development of cement hydration. SEM observation was performed on control specimens after 28 days of aging, shown in Figure 13; large capillary pores, CH, and pore interconnectivity were observed. Cement-based paste specimens with replacement metakaolin developed a more compact, denser pore structure.

3.7. RESULTS OF COMPRESSION STRENGTH IN COMPARISON WITH OTHER RESEARCH

Compression tests were carried out based on BSI (1983a): Part 116: [30]. For each designed mix, the average compressive strength of 5 specimens at 7 and 28 days of age and under the same curing conditions was considered the compressive strength criterion. The temperature laboratory was at the time of testing 27°C and relative humidity 22%. The standard deviation was about 6-7 kg/cm2. The results of this experiment are presented in Figure 15.

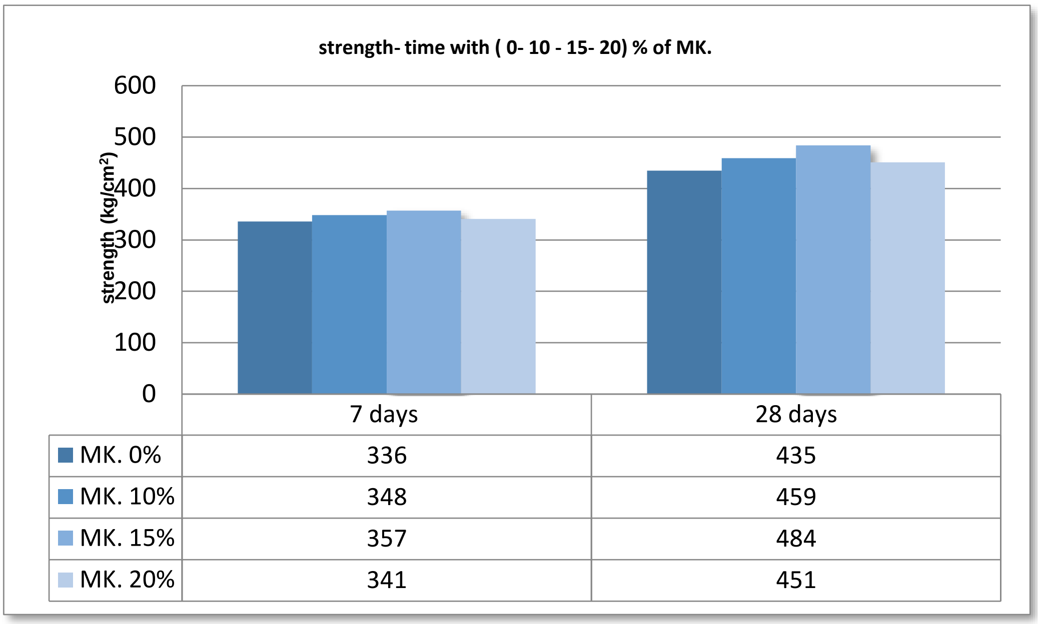


Figure 15. Average compressive strength of concrete with (0-10-15-20%) MK

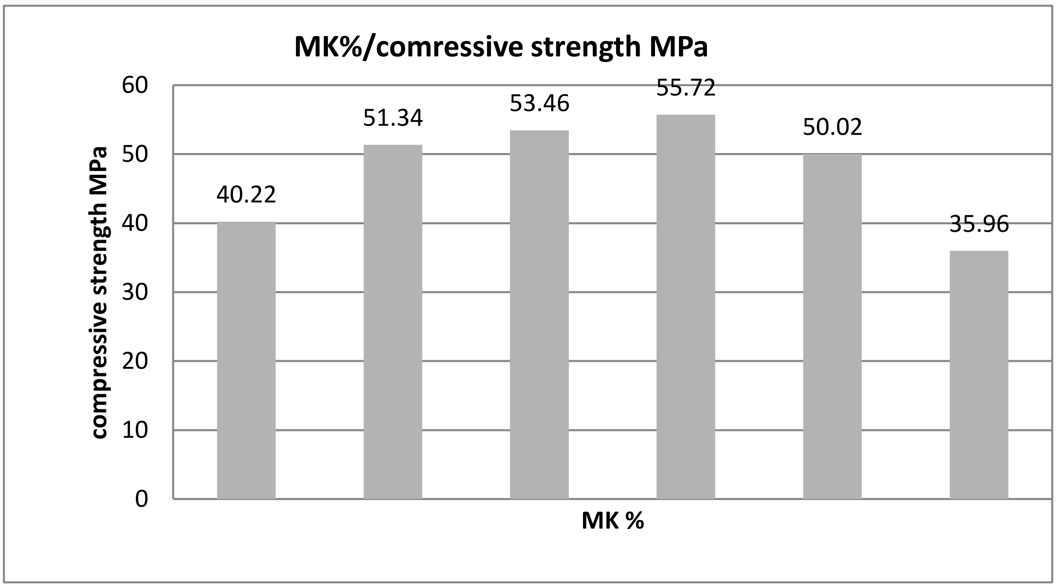


Figure 16. Representing compressive strength versus replacement of metakaolin (age = 28 days) [4].

The results of the compressive strength tests of the design mix, as can be seen from Fig. 15, show the improvement and growth rate of compressive strength in all Pozzolanic designs (up to 15% MK replacement) compared to the control concrete, which increased in the short term (7 days) that shows little enhancement in comparison to the control concrete and is more intuitive in the long run (28 days). Increasing the percentage of MK replacement to cement increases the compressive strength of concrete to 15%. Therefore, the highest increase in compressive strength was related to the 15% MK replacement plan with 6% growth at 7 days and 44% growth at 28 days concerning control concrete. It was also observed that replacement 20% of MK to cement consumed concrete decreased the compressive strength of concrete, but this decrease was more than the compressive strength obtained from control concrete. Thus, it can be said that in all the pozzolanic designs of MK, there is an improvement in the compressive strength of concrete. The replacement of 15% MK of cement is considered as the optimum percentage. The results obtained of this work shows higher compressive strength at 28 days (i.e. 484kg/cm^2) compared by other research [4] which gives (557.2 kg/cm^2) both at 15% MK replacement cement.

4. CONCLUSION

1. 10% MK replaced is more effective than other designs for the workability (slump) test.
2. Replacing MK reduces the temperature compared to the control concrete, which shows the highest decrease in the 15% MK replacement cement scheme by 2.5°C within one hour. Therefore, the use of controlled-release mineral replacement to cement allows for a decrease in temperature rise almost directly relative to Portland cement replaced

with MK. The reason is that under normal conditions, mineral materials do not react in large quantities for several days. Therefore,

3. Replacing 15% of MK in place of cement is considered to be the most optimal design for specific weight loss.
4. The lowest percentage of water absorption is related to concrete containing 20% of MK. Therefore, the replacement of 20% of MK with cement replacement is considered the optimal percentage.
5. 5- Concrete containing MK at both short and long ages has more compressive strength than the control sample. Subsequently, the use of MK improves the mechanical properties, including the compressive strength of concrete. However, limited and controlled, the optimal percentage to improve the mechanical properties is obtained using 15% cement substituted MK.
6. The results of this study show that with the addition of MK, electrical resistance in all designs mix increased in the early and late stages, which may be due to the decrease in porosity and permeability of concrete hence due to the relatively low hydration temperature, its use in bulk casting is recommended.
   more durability. The highest amount of electrical resistance has a design containing 20% of MK, which can be considered an optimal percentage.
7. MK can certainly improve the properties of concrete, but they should not be expected to offset the poor quality of the concrete material or the inadequate mixing ratio.
8. The effect of MK index on concrete is observed in its stability so that it can be considered as a suitable replacement for pozzolans used in corrosive environments exposed to aggressive agents.
9. Microscopic analysis indicates that the 15% MK replaced cement presented superior pozzolanic activity, consistent with the compressive strength test results and SEM observation.
10. Comparison of the results of compression strength from this research and other research shows that 15% MK replacement cement gives higher compression strength.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

5. REFRENCES

[1] Li Zongjin, Advanced Concrete Technology, John Wiley & Sons, 1st Edition, 4 February 2011. [View at Publisher]

[2] Behforouz B, Balkanlou VS, Naseri F, Kasehchi E, Mohseni E, Ozbakkaloglu T. Investigation of eco-friendly fiber-reinforced geopolymer composites incorporating recycled coarse aggregates. International Journal of Environmental Science and Technology. 2020 Jun;17(6):3251-60. [View at Google Scholar] ; [View at Publisher]

[3] Shakarchizadeh M, Mirdamadi A, Banakdar, A, Bakhshi, M, Improving the Properties of Powerful Concrete Using Meta-kaolin, Journal of Concrete Research, Issue 2, Winter 2008, pages 55-63. [View at Google Scholar] ; [View at Publisher]

[4] Weng TL, Lin WT, Cheng A. Effect of metakaolin on strength and efflorescence quantity of cement-based composites. The Scientific World Journal. 2013 Jan 1;2013. [View at Google Scholar] ; [View at Publisher]

[5] Paiva H, Velosa A, Cachim P, Ferreira VM. Effect of metakaolin dispersion on the fresh and hardened state properties of concrete. Cement and Concrete Research. 2012 Apr 1;42(4):607-12. [View at Google Scholar] ; [View at Publisher]

[6] Güneyisi E, Gesoğlu M, Karaoğlu S, Mermerdaş K. Strength, permeability and shrinkage cracking of silica fume and metakaolin concretes. Construction and Building Materials. 2012 Sep 1;34:120-30. [View at Google Scholar] ; [View at Publisher]

[7] Khatib JM, Baalbaki O, ElKordi AA. Metakaolin. InWaste and Supplementary Cementitious Materials in Concrete 2018 Jan 1 (pp. 493-511). Woodhead Publishing. [View at Google Scholar] ; [View at Publisher]

[8] Şahin F, Uysal M, Canpolat O. Systematic evaluation of the aggregate types and properties on metakaolin based geopolymer composites. Construction and Building Materials. 2021 Apr 5;278:122414. [View at Google Scholar] ; [View at Publisher]

[9] Abdelmelek N, Lubloy E. Evaluation of the mechanical properties of high-strength cement paste at elevated temperatures using metakaolin. Journal of Thermal Analysis and Calorimetry. 2020 Jul 8:1-5. [View at Google Scholar] ; [View at Publisher]

[10] Thankam GL, Thurvas Renganathan N. Ideal supplementary cementing material–Metakaolin: A review. International Review of Applied Sciences and Engineering. 2020 Apr;11(1):58-65. [View at Google Scholar] ; [View at Publisher]

[11] Chandak MA, Pawade PY. Influence of metakaolin in concrete mixture: a review. The IJES. 2018:37-41. [View at Google Scholar] ; [View at Publisher]

[12] Rong-rong Z, Dong-dong M. Effects of curing time on the mechanical property and microstructure characteristics of Metakaolin-based geopolymer cement-stabilized silty clay. Advances in Materials Science and Engineering. 2020 Feb 14;2020. [View at Google Scholar] ; [View at Publisher]

[13] Shinde PB, Pawade PY, Chandak MA. Mixed influence of metakaolin (MK) and steel fiber on mechanical properties of concrete. InSmart Technologies for Energy, Environment and Sustainable Development 2019 (pp. 381-390). Springer, Singapore. [View at Google Scholar] ; [View at Publisher]

[14] Building and Housing Research Center, National Concrete Mix Design Methodology Guide, Tehran, Building and Housing Research Center Publication, Second Edition, 2009, p. 15. [View at Publisher]

[15] Hahladakis JN, Purnell P, Aljabri HM. Assessing the role and use of recycled aggregates in the sustainable management of construction and demolition waste via a mini-review and a case study. Waste Management & Research. 2020 Apr;38(4):460-71. [View at Google Scholar] ; [View at Publisher]

[16] Salimi J, Ramezanianpour AM, Moradi MJ. Studying the effect of low reactivity metakaolin on free and restrained shrinkage of high performance concrete. Journal of Building Engineering. 2020 Mar 1;28:101053. [View at Google Scholar] ; [View at Publisher]

[17] Shekarchizadeh M, Valipour M, Parger, F, Investigation of the effect of using silica, MK , zeolite and propylene fibers on resistance to chlorine ion diffusion in concrete under environmental conditions of Qeshm Island, Journal of Civil Engineering Mashhad, 22, No. 1, 2010, Pages 83 to 96. [View at Google Scholar] ; [View at Publisher]

[18] Homayoonmehr R, Ramezanianpour AA, Mirdarsoltany M. Influence of metakaolin on fresh properties, mechanical properties and corrosion resistance of concrete and its sustainability issues: A review. Journal of Building Engineering. 2021 Jul 24:103011. [View at Google Scholar] ; [View at Publisher]

[19] Mo Z, Gao X, Su A. Mechanical performances and microstructures of metakaolin contained UHPC matrix under steam curing conditions. Construction and Building Materials. 2021 Jan 25;268:121112. [View at Google Scholar] ; [View at Publisher]

[20] Sinenko S, Zhadanovskiy B, Pakhomova L. Assessment of complex technological processes of concrete mixes preparation with on-site automated concrete mixing plants. InIOP Conference Series: Materials Science and Engineering 2018 Dec 1 (Vol. 463, No. 3, p. 032032). IOP Publishing. [View at Google Scholar] ; [View at Publisher]

[21] BSI (2011) BS 1881: Part 122: Method for determination of water absorption. BSI, London, UK. [View at Publisher]

[22] Office of National Building Regulations, National Building Regulations No. 9, Tehran, Iranian Development Publication, Ninth Edition, 2015, p. 49. [View at Publisher]

[23] Erdis E, Ozdemir SA. Analysis of technical specification-based disputes in construction industry. KSCE Journal of Civil Engineering. 2013 Nov 1;17(7):1541-50. [View at Google Scholar] ; [View at Publisher]

[24] Kessler RJ, Powers RG, Vivas E, Paredes MA, Virmani YP. Surface resistivity as an indicator of concrete chloride penetration resistance. In2008 Concrete Bridge ConferenceFederal Highway AdministrationNational Concrete Bridge CouncilMissouri Department of TransportationAmerican Concrete Institute (ACI) 2008. [View at Google Scholar] ; [View at Publisher]

[25] Neville A.M, Properties of Concrete, Pearson Education Limited 2006. [View at Google Scholar] ; [View at Publisher]

[26] American Society for Testing and Materials. Committee C-9 on Concrete and Concrete Aggregates. Standard test method for electrical indication of concrete's ability to resist chloride ion penetration. ASTM International; 2012. [View at Google Scholar] ; [View at Publisher]

[27] Güneyisi E, Gesoğlu M, Karaboğa F, Mermerdaş K. Corrosion behavior of reinforcing steel embedded in chloride contaminated concretes with and without metakaolin. Composites Part B: Engineering. 2013 Feb 1;45(1):1288-95. [View at Google Scholar] ; [View at Publisher]

[28] Nadeem A, Memon SA, Lo TY. Mechanical performance, durability, qualitative and quantitative analysis of microstructure of fly ash and Metakaolin mortar at elevated temperatures. Construction and Building Materials. 2013 Jan 1;38:338-47. [View at Google Scholar] ; [View at Publisher]

[29] Gao Y, Chen SB, Liya EY. Efflorescence relative humidity of airborne sodium chloride particles: A theoretical investigation. Atmospheric Environment. 2007 Mar 1;41(9):2019-23. [View at Google Scholar] ; [View at Publisher]

[30] BSI (1983a) BS 1881: Part 116: Method of determination of compressive strength of concrete cubes. BSI, London, UK. [View at Publisher]