Available online at www.sciencedirect.com
ScienceDirect
Construction and Building Materials 22 (2008) 127–134
Construction and Building MATERIALS
www.elsevier.com/locate/conbuildmat

Study on strength and corrosion performance for steel embedded in metakaolin blended concrete/mortar

Anand Kuber Parande *, B. Ramesh Babu, M. Aswin Karthik, Deepak Kumaar K.K., Palaniswamy N.

Central Electrochemical Research Institute, Karaikudi 630 006, Tamilnadu, India

Received 24 October 2005; received in revised form 4 October 2006; accepted 14 October 2006
Available online 28 November 2006

Abstract

It is an undeniable fact that concrete is the most widely used man-made construction material in the world today, and will remain so for decades to come. The popularity of concrete is largely due to the abundance of raw material, low manufacturing and maintenance cost, excellence in compression, and corrosion aspects, durability to weathering and fire hazards, versatility in forming various shapes and its unlimited structural applications in combination with steel reinforcement. However, the cement industry is also highly energy intensive, and the emission of carbon dioxide during cement manufacturing has created enormous environmental concerns. There has also been an increase in the number of incidents where concrete structures experienced severe deterioration in extreme environments. All these factors have contributed pressures from various quarters to reduce cement consumption, and to intensify research in exploring the possibilities of enhancing strength, durability and corrosion reduction through the use of pozzolans as supplementary cementing materials. The utilization of calcined clay in the form of metakaolin as a pozzolan for concrete has received considerable interest in recent years. The use of metakaolin as a mineral admixture for concrete is a well documented practice. Metakaolin is a quality enhancing pozzolan for concrete. It is manufactured from kaolin which is abundance in India and other parts of the country.

In the present investigation mechanical property and corrosion behavior of carbon steel using metakaolin (5–20%) as partial replacement in ordinary Portland cement (OPC). Compressive strength, resistivity, ultra pulse velocity, open circuit potential, studies on water absorption, weight loss were studied. It was found that up to 15% replacement of metakaolin in OPC improves the mechanical properties of concrete. Corrosion of carbon steel improved by the addition of metakaolin up to 15%.

Keywords: Corrosion; Metakaolin; Strength; Concrete; Mortar; Carbon steel

1. Introduction

The latest advance in concrete technology shows that the use of mineral admixtures such as silica fume (SF) and fly ash (FA) is essential for producing high-performance concrete. In recent years, there has been a growing interest in the use of metakaolin (MK) for this purpose [1–5]. Metakaolin is a valuable pozzolanic material, it is a thermally activated alumino-silicate material obtained by calcining kaolin clay within the temperature range of 700–850 °C [1,3,6]. Kaolin from natural sources may be notably impure, even after beneficiation. During heating, it is essential to convert unreactive kaolin to reactive metakaolin. The impurities present in the precursor kaolin may become activated with respect to dissolution in alkaline cement pore fluid. The most important impurities in this context are muscovite and potassium-rich felspar. Potassium felspar and muscovite, heated and unheated were mixed with $Ca(OH)_2$ and water at ~22 °C for up to 28 days. Significant alkali releases were obtained even from unheated minerals. However, the extent of release is increased with increasing calcining temperature in the range of 500–700 °C. The results indicate that supposedly

* Corresponding author. Tel.: +91 4565227550; fax: +91 4565227556.
E-mail address: corrparande@yahoo.co.in (A.K. Parande).

0950-0618/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conbuildmat.2006.10.003

'inert' aggregate minerals may become reactive towards cement. In cement–metakaolin mixes, much of the alkali liberated from mineral impurities is probably incorporated into cement solids but the overall effectiveness of metakaolin in decreasing the alkali content of cement pore fluid is reduced. However, alkali release may also be beneficial: metakaolin may release sufficient alkali to enhance slag hydration in slag–$Ca(OH)_2$–metakaolin blends.

Metakaolin contains typically 50–55% SiO_2 and 40–45% Al_2O_3 and is highly reactive. It has been reported that the replacement of cement by 5–20% MK results in significant increases in compressive strength for high-performance concretes and mortars up to 28 days, particularly at early ages [2–5]. The replacement also results in improved concrete durability properties, including the resistance to chloride penetration, freezing and thawing, and deicing salting scaling [2,4]. While a number of studies have been conducted on high-performance MK concrete or mortars [2–5], there have been no reports concerning the study of corrosion behavior of steel in concrete. In the present investigation, corrosion behavior of steel reinforcement in cement has been studies with partial replacement of cement by metakaolin (from 5% to 20%).

In most of the cases, mortars and concrete containing material with pozzolanic characteristics have (in normal condition), porosity values equal or superior to that of OPC concrete [7]. This evolution of the porosity depends on the characteristics of pozzolanic materials, such as fineness, mineralogy, loss of ignition, chemical composition and an important aspect to point out is the water/binder used [8]. It is well known that the critical factor affecting the performance and durability of concrete structure is the pore size distribution, rather than the total porosity. MK is being studied because of its high pozzolanic properties [6,9–12]. Owing to its fineness and chemical composition, MK shows a closer resemblance to silica fume than to porosity in fly ash [13]. Partial replacement of metakaolin by the weight of cement (5–20%) thus affects pore size. Due to this variation in pore size, there is much variation in micro-structural properties, mechanical properties and corrosion behavior studies. The results of various tests such as compressive strength, open circuit potential, resistivity, weight loss, determination of ultra pulse velocity (UPV), impressed voltage test, water absorption studies are tabulated for different weight (%) of metakaolin. The chemical and physical properties of the Portland cement, MK is given in Table 1.

2. Experimental procedure

2.1. Materials used

The following materials were used for the present study:

Ordinary Portland cement: conforming to IS 456-2000.

Table 1
Chemical and physical properties of the Portland cement, MK

Parameters	Cement	Metakaolin
SiO_2 (%)	21.0	53.2
Al_2O_3 (%)	5.9	43.9
Fe_2O (%)	3.4	0.38
CaO (%)	64.7	0.02
MgO (%)	0.9	0.05
Na_2O (%)	–	0.17
K_2O (%)	–	0.10
TiO_2 (%)	–	1.68
SO_3 (%)	2.6	–
Loss on ignition (%)	1.2	0.50
Specific gravity	3.15	2.62
Fineness (>45 μm, %)	–	–
Specific surface (cm/g)	3520	12.680

Graded fine aggregates: local clean river sand (fineness modulus of medium sand equal to 2.6) conforming to grading zone III of IS-383-1970 was used as fine aggregates.

Graded coarse aggregates: locally available well graded aggregates of normal size greater than 4.75 mm and less than 10 mm having a fineness modulus of 2.72 was used as coarse aggregates.

2.2. Sample preparation and compression tests

The cement mortars and concrete samples were prepared in this study. Commercially available metakaolin was used in the present study. MK-blended with OPC was of contents with different ratios namely 5%, 10%, 15%, and 20%.

3. Methodology

The mixed cements were prepared in a high-speed powder mixer to ensure homogeneity and dispersion. Mixtures were made up by weight of cement.

3.1. Compressive strength measurements

Concrete and Mortar cube specimens of size $10 \times 10 \times 10$ cm were cast using OPC with partial replacement of metakaolin by the weight of cement at 5%, 10%, 15% and 20%. Mortar specimens were prepared using 1:3 mixes with a water cement ratio of 0.40. Similarly concrete cubes were prepared using mix ratio 1:3.3:6.9 with a w/c ratio of 0.45. The specimens were vibrated mechanically to assist compaction. After 24 h of setting the specimens were demoulded and cured for 28 days in distilled water in order to avoid any contamination. After the curing period was over, the compressive strength was measured at the age of 3, 7, 28 and 90 days by using AIMIL compressive strength testing machine. Triplicate specimens were cast and the average compressive strengths were reported.

3.2. Open circuit potential

The OCPs for the different systems were periodically monitored using a voltmeter with a high input impedance of 10 MΩ. A saturated calomel electrode (SCE) was used as the reference. The positive terminal of the voltmeter was connected to the working electrode i.e., CTD rods. The common terminal was connected to the reference electrode. The corresponding potentials were recorded. Bimonthly readings were recorded for potential till 270 days of exposure period. In this study, triplicate specimens were used for each system and the average of these values were reported and interpreted based on ASTM C-876-1997.

3.3. Weight loss

Concrete cubes of size $10 \times 10 \times 10$ cm were cast using OPC and MK with partial replacement of metakaolin by the weight of cement at 5%, 10%, 15% and 20%. Carbon steel rod of 1.2 cm diameter and 6 cm long was embedded at a cover of 25 mm in the cube. Initially the carbon steel rebars were cleaned in the following acid solution: HCl: 100%, $SnCl_2$: 35 g, Sb_2O_3: 25 g, degreased with acetone and washed with double distilled water and dried. The initial weight of the rebar was taken before casting using Metler balance for gravimetric weight loss measurements.

Concrete cube specimens were prepared using 1:3.3:6.9 mix with a w/c ratio of 0.45. The specimens were mechanically vibrated. After 24 h of curing, the specimens were removed and cured for 28 days in distilled water in order to avoid any contamination. The end of 270 days of exposure, the concrete specimens was split open. Then they subjected to visual observation. The carbon steel was separated out from the concrete and the losses in weight were determined with MK with partial replacement of metakaolin by the weight of cement at 5%, 10%, 15% and 20% and expressed in millimeter per year (mmpy) [16]. These studies were compared with OPC. The data were presented in Tables 4 and 5, mortar and concrete, respectively. Figs. 3 and 4 depict the weight loss of mortar and concrete samples.

The corrosion rate is calculated using the following equation:

$$\text{Corrosion rate} = \frac{87.6 \times W}{D \times A \times T}$$

where, W is the weight loss in g, D, density of the material used, A, area of the specimen (cm^2), T is the time duration in h.

3.4. Resistivity

Electrical resistivity of concrete is an important parameter, which can be related to various aspects such as strength, porosity, and deterioration. The resistivity of concrete has been found to vary considerably depending on the moisture content and the soluble salts present in the concrete. Concrete resistivity is generally measured by a Wenner four-probe method.

3.5. Ultrasonic pulse velocity (UPV)

The technique is more helpful in locating defects and cracks in concrete structures. The interpretation of data is very difficult as a large number of factors affect the pulse velocity.

The same specimens used for resistivity were subjected to quality control test using ultrasonic tester (Model MIN-020-1-00), Marut and Co. Ltd., Japan.

3.6. Impressed voltage

This test has been conducted as accelerated short-term test for evaluating the corrosion performance of OPC with partial replacement of metakaolin by the weight of cement at 5%, 10%, 15%, and 20%. This test has been conducted in the laboratory as an accelerated corrosion, testing technique for comparing different characteristics of concrete. In this technique the concrete specimen is immersed in 3.5% sodium chloride solution and embedded steel in concrete in made anode with respect to external stainless steel electrode serving as cathode by applying a constant positive potential of 12 V to the system from a DC source. The variation of current is recorded with time. A sharp rise in current indicates the onset of corrosion of cracking and cracking of concrete is usually visible thereafter. The time taken for initiation of first crack can be considered as measure of their relative resistance against chloride permeability and reinforcement corrosion.

Cylindrical concrete specimen of size 75 mm diameter 150 mm height were cast using 1:3.3:6.9 mix ratio (w/c ratio = 0.45) with centrally embedded rebar with OPC (control) with partial replacement of metakaolin by the weight of cement at 5%, 10%, 15% and 20%. During casting, the moulds were mechanically vibrated. After 24 h the cylindrical specimen were demoulded and subjected to water curing for seven days. After curing the specimen were subjected to impressed voltage tests.

For each specimen the time taken for the initial crack and corresponding maximum anodic current flowed were recorded.

4. Results and discussion

4.1. Compressive strength

The compressive strength data for mortar and concrete system is represented in Tables 2 and 3. Mortar specimens were blended with different ratio of metakaolin in cement by weight bases ranging from 5% to 20%. Compression strength for plain OPC after 3, 7, 28 and 90 days were

Table 2
Compressive strength of mortar

System	Compressive strength (MPa)			
	Days			
	3	7	28	90
OPC	22	32.5	40	48
OPC + 5% MK	31.5	40	52	52
OPC + 10% MK	30	43.5	56	64
OPC + 15% MK	29	42.1	60	67
OPC + 20% MK	27	44	58	65

Table 3
Compressive strength of concrete:

System	Compressive strength (MPa)			
	Days			
	3	7	28	90
	3	7	28	90
OPC	31	41.6	54	65
OPC + 5% MK	34.1	48.1	59.1	68
OPC + 10% MK	35.2	53.7	63.4	72
OPC + 15% MK	28	59	70	80
OPC + 20% MK	26.1	43.2	57	67

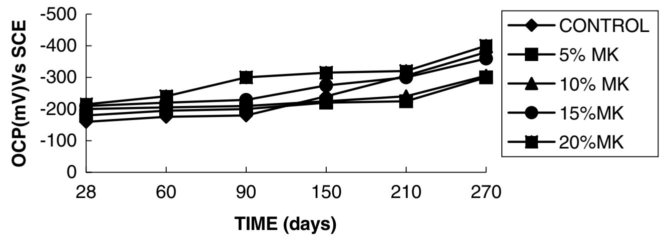

Fig. 1. Potential time behaviour of carbon steel embedded in mortar with MK.

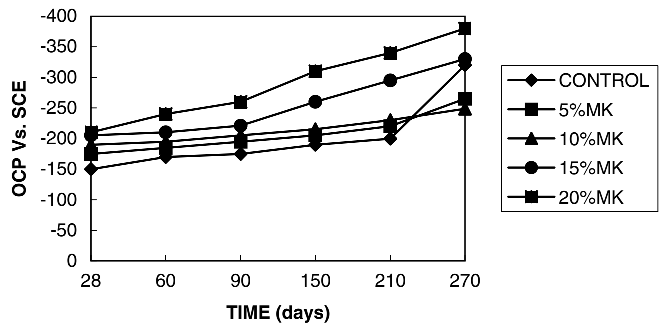

Fig. 2. Potential time behaviour of carbon steel embedded in concrete with MK.

found to be 22, 32.5, 40 and 48 N/mm^2, respectively. The compressive strength increased with the addition of metakaolin till the end of 90 days. The addition of 15% of MK gives the best result when compared to other replacement levels. It shows that MK has a function in enhancing of strength and it was found to be increased about 10 MPa higher in cement mortar study. The addition of more than 15% of MK with cement decreases the compressive strength. MK belongs to mineral admixture; it can improve the macro structural and mechanical properties of blended cement. The improvement in physical and chemical properties by the addition of MK has been explained as follows: ultra-fine particles fill the voids on cement, which makes the microstructure of cement paste denser and the reaction of MK with cement hydrates, respectively. The chemically bonded water with kaolin was driven out at a higher temperature. The reaction of MK with cement hydrates is faster and it is due to the reason that MK absorbs water easily.

Results indicate that MK blended with cement improves the strength of mortar and concrete to larger extent in the first 28 days. This phenomenon is a synergetic effect of mineral admixture and also called compounding effect [14].

A similar trend was observed in concrete specimen and showed increase in compressive strength when compared to mortar specimens.

4.2. Open circuit potential

4.2.1. Potential time behaviour of carbon steel

Figs. 1 and 2 show the potential time behaviour of carbon steel embedded in mortar and concrete with partial replacement of MK. The potential time behavior of carbon steel embedded at 25 mm cover in concrete/mortar in different ratios of MK replacement with cement. The open circuit potential (OCP) was monitored periodically for a period of 270 days of exposure. In 20% MK replacement the shift of potential towards negative direction crossing the threshold limit of −275 mV was observed in 80 days. Whereas in 15% it reached in 150 days, whereas in case of 5% MK and 10% MK threshold value of −275 mV vs. SCE is reached at the end of exposure period. An interesting result from that of 5% and 10% MK showed that OCP values were lesser than the control values at the end of exposure. This may be due to the pore filling effect in the mortar. The addition of 5% and 10% MK minimizes the chloride penetration into the mortar specimens which shows clearly that MK has a capability of reducing chloride permeability.

Fig. 2 depicts that the potential time behavior of carbon steel embedded in concrete. There was a shift of value of OCP towards negative direction for 20% and 15% MK addition. The threshold potential −275 mV was reached at the end of 100 days and 190 days for 20% and 15% MK, respectively. In the case of 5% and 10% MK the threshold potential did not reach till the end of exposure period. It is due to the fact that the rebars were in passive condition throughout the exposure period. The replacement level at 5% and 10% MK showed lesser potential values when compared to control system. This shows the influence of MK on the micro-structural diffusion properties of blended cemented mortars/concrete and also the pore size distribution may be the reasons for the concrete/mortars has significantly reduced the potential, which acts as filler material [15].

4.3. Corrosion rate by gravimetric measurements

The results of gravimetric weight loss measurements are shown in Tables 4 and 5. The corrosion rate in mortars/concrete systems is represented in Figs. 3 and 4. The addition of metakaolin above 15% showed higher corrosion rate when compared to other systems. In 5% MK addition, corrosion rate was found to be slightly higher than the control system. But at the end of exposure period the corrosion rate for 5% was found to be lesser than that of control system. In case of 10% and 15% MK showed lesser corrosion rate till the end of exposure period.

But 20% MK addition showed higher corrosion rate from initial to final. This observation was due to the fact of pore refinement in cement. This may be the reason for the decrease in weight loss; the same observation was noticed in potential time behavior studies. It is important to note that, although the rate of metakaolin reaction after a prolonged curing was still considerable.

In case of concrete the corrosion rate is lesser when compared to mortar systems. An interesting observation made was due to the fact that, in case of 5% 10% and 15% metakaolin replacement the corrosion rate was lesser than control. But whereas in 20% metakaolin corrosion rate was higher at 90 days till 270 days of exposure period. From these data it is inferred that 15% of MK gives the best performance among other ratios for corrosion of steel embedded in concrete.

4.3.1. Resistivity and UPV

The data collected from resistivity and UPV measured in K-Ω-cm are reported in Tables 6 and 7. The compression

Table 4
Corrosion rate measurements for steel embedded in mortars specimen

System	Corrosion rate (mmpy)			
	90 days	150 days	210 days	270 days
Control	0.0014	0.0015	0.0016	0.00165
5% MK	0.0015	0.0016	0.0015	0.0013
10% MK	0.0013	0.0014	0.0012	0.0011
15% MK	0.0012	0.00135	0.0013	0.0012
20% MK	0.0017	0.0018	0.00185	0.0019

Table 5
Corrosion rate measurements for steel embedded in concrete specimen

System	Corrosion rate (mmpy)			
	90 days	150 days	210 days	270 days
Control	0.0015	0.0016	0.00165	0.0017
5% MK	0.0013	0.0015	0.0013	0.0014
10% MK	0.0011	0.0013	0.0010	0.0012
15% MK	0.0010	0.0012	0.0011	0.0011
20% MK	0.0016	0.0017	0.0018	0.0019

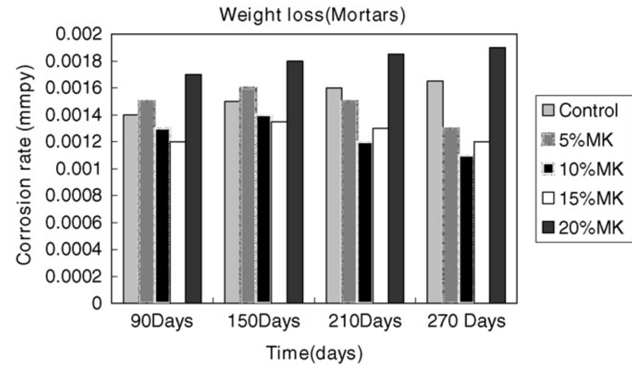

Fig. 3. Weight loss measurement for mortar specimens with MK.

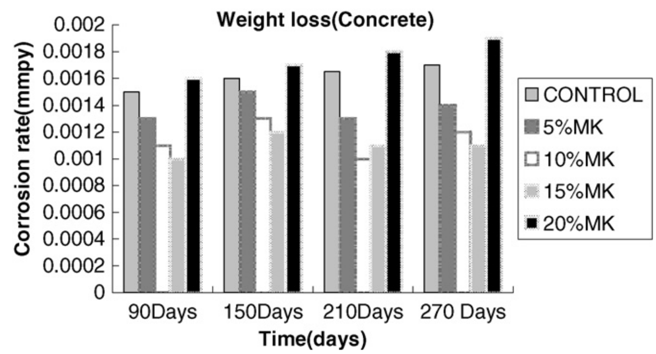

Fig. 4. Weight loss measurement for concrete specimens with MK.

strength specimens were used for the measurement for this test. For mortar specimen as the percentage of addition of metakaolin in cement is increased, it behaves to be good soundness properties when compared to control system. This observation is found in 5–15% metakaolin only whereas in 20% metakaolin system, which showed lesser resistivity and UPV measurements. From this data it is inferred that up to15% the concrete shows to be in a good soundness manner. The experiments were carried out for different curing periods namely 3, 7, 28, and 90 days. The same observation was made in concrete inferred that up to 15% of MK replaced concrete showed good resistivity and soundness when compared to control system.

4.4. Water absorption studies

Water absorption studies tests on the specimen were conducted after 28 days of standard curing. First the specimen is kept in an oven at 105 °C (less than 0.1% mass change in 24 h). After 24 h weight of specimen is noted. After weighing, the specimens are immersed in a container at 20 ± 2°C. Each specimen is removed from water, wiped off with a dry cloth and weighed (wet mass). The immersion continues until there is no variation in mass greater than 0.1% after 24 h. Water absorption studies results are reported in Tables 8 and 9.

From Table 8, it is inferred that the coefficient of water absorption for 5%, 10%, and 15% of metakaolin replace-

Table 6
UPV and resistivity values of mortars

Days	Control		5% MK		10% MK		15% MK		20% MK	
	Res	Upv	Res	Upv	Res	Upv	Res	Upv	Res	Upv
3	12.5	4.65	14.38	4.2	15.5	4.1	13.8	4	11.3	3.8
7	13.8	4.7	15.5	4.15	16.1	4.0	14.2	3.9	11.5	3.7
28	18.8	4.9	17.5	4.5	18.3	4.25	18.1	4.15	16	3.9
90	36	10.5	40	11	42	8.5	38.5	7.8	34	6.5

Table 7
UPV and resistivity values of concrete

Days	Control		5% MK		10% MK		15% MK		20% MK	
	Res	Upv	Res	Upv	Res	Upv	Res	Upv	Res	Upv
3	11.25	4.55	13.35	4.1	14.5	4.0	12.8	3.9	10.3	3.7
7	12.7	4.6	14.5	4.05	15.1	3.9	13.2	3.8	10.5	3.6
28	17.6	4.8	16.5	4.4	17.3	4.1	17.2	4.10	15	3.8
90	35	9.5	39	10	40	8.0	37.1	7.5	33	6

Res, resistivity and UPV, ultrasonic pulse velocity.

Table 8
Water absorption studies

System	Area of suction (a) (cm^2)	Initial mass (g)	Final mass (g)	Mass of water absorbed	Volume of water absorbed	Coefficient of water absorption $ka = (Q/A)^2 \times 1/t\ m^2/s \times 10^{-4}$
Control	55.6536	473.54	482.04	8.5	8.5	8.2972
5% MK	55.1787	469.85	479.73	9.88	9.88	8.2551
10% MK	55.7594	466.16	475.68	9.52	9.52	8.2272
15% MK	55.9421	465.26	475.88	10.62	10.62	8.2689
20% MK	56.5029	447.32	457.87	10.55	10.55	8.3384

ment showed lesser amount of water absorption when compared to control system. But in 20% metakaolin the coefficient of water absorption was found to be slightly higher than the other replacement, and also higher than control specimen. The coefficient of water absorption for 5% and 10% was found to be lesser when compared to other system. This can be due to lack of homogeneity in the mortar caused by inadequate blending. This can also be due to the fact that the pozzolanic effect has insufficient time to proceed because these tests were carried out after 28 days of hydration.

Test result for dry and wet bulk density, water absorption and apparent porosity of metakaolin replacement with cement are tabulated in Table 9. Fig. 5 shows the results of the water adsorption studies. The decrease in water absorption on metakaolin-modified mortars was lesser than cement mortar. But this was not in the case of 20% MK.

Table 9
Test result for dry and wet bulk density, water absorption and apparent porosity

System	Oven dry wt. A (g)	Sat. weight after immersion B (g)	Sat weight after boiling C (g)	Immersed wt. D (g)	% Of H_2O absorption after immersion $(B-A)/A \times 100$	% Of H_2O absorption after boiling $(C-A)/A \times 100$	Bulk Sp. gravity after drying $G_1 = A/(C-D)$	Bulk Sp. gravity after immersion $= B/(C-D)$	Bulk Sp. gravity after boiling $= C/(C-D)$	Apparent Sp. gravity $G_2 = A/(A-D) \times 100$	% Of Vol. of permeable voids $(G_2 - G_1)/G_2 \times 100$	Effective porosity $= (B-A)/V \times 100$
Control	464.66	494.6	501.0	278.7	6.45	7.83	2.089	2.2247	2.2535	2.499	19.58	13.19
5% MK	482.83	520.3	522.5	290.8	7.76	8.22	2.083	2.2453	2.2549	2.514	17.14	12.70
10% MK	465.98	508.3	513.0	282.2	9.03	10.09	2.019	2.2019	2.2234	2.536	16.38	11.85
15% MK	469.08	514.8	519.4	284.1	9.75	10.74	1.993	2.1877	2.2075	2.536	15.36	10.48
20% MK	459.85	507.9	512.8	277.3	10.2	11.27	1.957	2.1575	2.1782	2.511	14.06	9.25

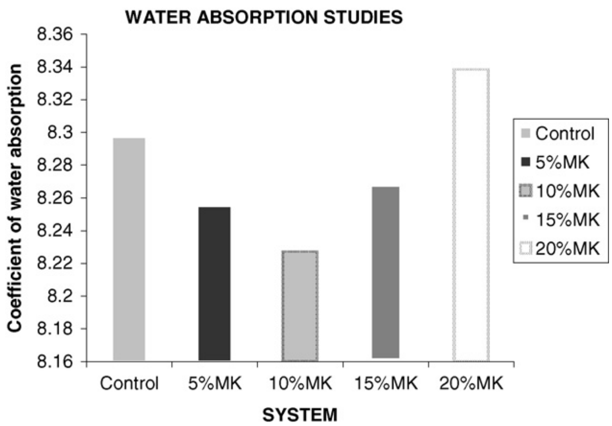

Fig. 5. Water absorption studies in MK replacement.

Samples after 28 days of curing were dried in oven 100 ± 5 °C. The size of the specimen was 80 cm in diameter and 50 cm height. The mass variation in a capillary was registered from 0 to 90 min. Capillary absorption studies in water has been also studied and reported in Table 10. Measurements of mass variation up to 90 min were carried out relatively constant value of mass variation in comparison with cement mix but light decrease for 20% replacement ratio. This is probably due to low grannulometry of metakaolin particles, which are able to compare the granular skeleton of the fine particles. This effect does not show clear observation, may be a modification of the dimension of the pore is produced by the pozzolanic reaction but the quantity of the total water that is absorbed still remains the same.

4.5. Impressed voltage test

The time taken for initiation of crack is reported in Table 11. Different ratio of MK was partially replaced with OPC was used in this test. Control, 5%, 10%, 15% and 20%, the time taken for initial crack was found to be 63, 92, 110, 140, 56 h and the maximum anodic current was 70, 42, 39, 30.5, 60 mA, respectively. From the result it was inferred that corrosion resistance was found to increase up to 15% MK replacement after which it decreases. In case of 15% MK replacement the time of initiation of crack was found to be higher than other systems studied. The impressed voltage directly correlates the permeability of concrete and hence the permeability for 15% MK replacement is lesser over other systems.

Table 11
Accelerated impressed voltage test content

System	Initial current (mA)	Final current (mA)	Time of initiation of crack (h)
Control	36	70	63
5% MK	10	42	92
10% MK	8	39	110
15% MK	7	30.5	140
20% MK	40	72	56

5. Conclusion

Metakaolin is a new active mineral admixture used in cement concrete product. It has a good effect on the mechanical properties of cement. By incorporating 5%, 10%, 15%, 20% metakaolin. It was found that the compressive strength increased up to 15% replacement. beyond which it decreased.

The results obtained related to corrosion behavior studies showed that as the replacement ratio increases the corrosion does not exists. Corrosion rate was found to be lesser up to 15% MK beyond 20% it showed slight higher values. The open circuit potential measurements showed that up to 20% replacement of MK with cement the threshold value of −275 mV was had reached up to 190 days in concrete. It is concluded that 15% addition with metakaolin replacement with cement showed to be good corrosion resistance property, water absorption, resistivity and UPV values with concrete. The carbon steel rebars behaves in passive condition up to 15% addition of MK, but the rebars behaves in active condition at 20% addition of MK.

References

[1] Kostuch JA, Walters V, Jones TR. High performance concretes incorporating metakaolin: a review. In: Dhir RK, Jones MR, editors. Concrete 2000. London, UK: E&FN Spon; 1993. p. 1799–811.
[2] Caldarone MA, Gruber KA, Burg RG. High-reactivity metakaolin: a new generation mineral admixture. Concr Int 1994;16(November):37–40.
[3] Sabir BB, Wild S, Khatib JM. on the workability and strength development of metakaolin concrete. In: Dhir RK, Dyer TD, editors. Concrete for Environmental Enhancement and Protection. London, UK: E&FN Spon; 1996. p. 651–6.

Table 10
Capillary properties of metakaolin mortars

System weight (g)	Minutes									
	0	10	20	30	40	50	60	70	80	90
Control	473.54	474.5	475.2	476.1	477.9	479.2	480.1	481.1	481.6	482.0
5% MK	469.85	470.8	471.5	472.4	474.2	475.5	476.7	477.7	478.2	479.7
10% MK	466.16	467.1	467.8	468.7	470.5	471.8	473.0	474.0	474.5	475.6
15% MK	465.26	466.2	466.9	467.8	469.6	470.9	472.1	473.1	473.6	475.8
20% MK	447.32	448.3	449.0	449.9	451.7	453.0	454.2	455.2	455.7	457.8

[4] Zhang MH, Malhotra VM. Characteristics of a thermally activated alumino-silicate pozzolanic material and its use in concrete. Cem Concr Res 1995;25(8):1713–25.

[5] Curcio F, Deangelis BA, Pagliolico S. Metakaolin as a pozzolanic microfiller for high-performance mortars. Cem Concr Res 1998;28(6):803–9.

[6] Ambroise J, Maximillen S, Pera J. Properties of metakaolin blended cements. Adv Cem Mater 1994;1(4):161–8.

[7] Massazza F, Oberti G. Durability of pozzolanic cements and Italian experience in mass concrete. In: Malhotra VM, editor. Second inter conference on durability and concrete, Montreal, Canada, vol. II. Montreal, Canada: American Concrete Institute; 1991. p. 1259–83.

[8] Gjorv O. High strength concrete. In: Malhotra VM, editor. Advances in concrete technology. Montreal, Canada: American Concrete Institute; 1992. p. 21–77.

[9] Silva PS, Glasser FP. Phase relation in the system $CaO–Al_2O_3–SiO_2–H_2O$ relevant to MK–lime hydration. Cem Concr Res 1993;23:627–39.

[10] Coleman NJ, Page CL. Aspects of the pore solution chemistry of hydrated cement pastes containing MK. Cem Concr Res 1997;27(1):147–54.

[11] Wild S, Khabit JM, Jones A. Relative strength pozzolanic activity and cement hydration in superplasticised MK concrete. Cem Concr Res 1996;26(10):1537–44.

[12] Bai J, Wild S, Sabir BB, Kinuthin JM. Workability of concrete in incorporating PFA and MK. Mag Concr Res 1999;51(3):207–26.

[13] Frías M, Sánchez de Rojas MI, Cabrera JG. The effect that the pozzolanic reaction of MK has on the heat evolution in MK–cement mortar. Cem Concr Res 2000;30(2):209–16.

[14] Ding Z, Zhang D, Yu R. High strength composite cement. China Build Mater Sci Technol 1999;1:14–7.

[15] Kostuch JA, Walters GV, Jones TR. High performance concrete incorporating metakaolin – a review, concrete 2000. University of Dundee; 1993. p. 1799–811.

[16] Saraswathy V, Muralidharan S, Thangaveland K, Srinivasan S. Adv Cem Res 2002;14:19.