Advances in Concrete Construction, *Vol. 6, No. 2 (2018) 159-175*
DOI: https://doi.org/10.12989/acc.2018.6.2.159

Durability properties of concrete containing metakaolin

Memduh Nas* and Şirin Kurbetci[a]

Department of Civil Engineering, Karadeniz Technical University, 61080, Trabzon, Turkey

(Received February 16, 2018, Revised March 10, 2018, Accepted March 12, 2018)

Abstract. The main aim of this study is to investigate the possible effects of metakaolin on strength and durability properties of concrete. For this purpose, concrete mixtures are produced by substituting cement with metakaolin 0, 5, 10 and 20% by weight. The amount of binder for the concrete mixtures are 300 and 400 kg/m^3 with a constant water to cement ratio of 0.6. Compressive and bending strengths, freeze-thaw and high-temperature resistances, capillary coefficients and rapid chloride permeability properties were determined and compared each other. Because of all the experiments conducted, it has been found that the use of metakaolin as a pozzolanic additive in concrete have positive effects especially on compressive and bending strengths, capillary, rapid chloride permeability, freeze-thaw resistance, and high temperatures, up to 800^{o}C. The results indicated that the performance of concrete can be enhanced by metakaolin. Particularly, compressive strength and durability properties have found to be improved with increasing metakaolin content which is attributed to pozzolanic activity and filler effect. Furthermore, metakaolin has relatively positive impacts under elevated temperatures and freeze-thaw effects. However, almost all the strengths of entire concrete specimens are lost at 800°C. Consequently, the optimum metakaolin substitution ratio can be suggested to be 20% as per this study.

Keywords: metakaolin; strength; durability; freeze-thaw; elevated temperature; rapid chloride permeability

1. Introduction

As general agreement, concrete is one of the most versatile composite materials in construction industry. During the production process of Portland cement large amounts of CO_2, a quite harmful greenhouse gas (GHG), is released. Cement production is thought to be responsible for about 7% of total worldwide GHG emissions amongst all industrial discharges (Choate 2003). In order to reduce the GHG and preserve the natural resources consumed for cement industry, supplementary materials such as silica fume, metakaolin (MK), limestone and fly ash have widely been used for several decades (Sabir *et al.* 2001, Taylor 1997). Of all supplementary materials, MK, which is white in color with a high pozzolanic activity, is obtained from calcined kaolinitic clays at 500-900°C (Sun *et al.* 2005, Siddique 2008).

MK was first used in concrete production as a sort of cement substitution in the construction of

*Corresponding author, Ph.D. Student, E-mail: memduhnas@ktu.edu.tr
[a]Assistant Professor, E-mail: skurbetci@ktu.edu.tr

http://www.techno-press.org/?journal=acc&subpage=7 ISSN: 2287-5301 (Print), 2287-531X (Online)

Jupia Dam/Brazil in 1962. The lesson learned from that project by using MK is that an increased durability of the concrete used in the body of the dam. Later, the use of MK in the concrete industry has been gained great interest, and it is still being in use in construction sector (Li *et al.* 2015).

MK is affecting the performance of concrete by three fundamental mechanisms. These are filler effect, acceleration effect on hydration rate of Portland cement, and pozzolanic activity. A work of the stress-strain relationship of high-performance concrete (Qian and Li 2001) indicated that MK reacts with calcium hydroxide to form extra binding gels in the paste. It is indicated that the use of MK in concrete and mortars improves the durability properties such as sorptivity, permeability, and durability (Siddique 2008). MK accelerates the hydration process of cement due to its pozzolanic reaction with the calcium hydroxide to provide extra C-S-H gel formation (Li *et al.* 2010, Cassagnabère *et al.* 2010, Kadri *et al.* 2011). MK-substituted concretes may impart a series of significant physical properties with respect to conventional concrete such as higher compressive strength; lower porosity, capillarity, permeability and improved pore structure (Frias *et al.* 2000, Gonçalves *et al.* 2009, Aquino *et al.* 2001, Bai *et al.* 2002, Abdul Razak *et al.* 2004, Ramezanianpour *et al.* 2012).

It is reported that compressive strength of concrete produced with metakaolin at ratios of 5% and 10% were found to be increased for 365 days. Concrete mixtures containing silica fume at the same ratios, a slight increase in compressive strength was obtained compared to those with MK (Caldarone *et al*. 1994).

It is pointed out that the performance of concrete, mortar, and paste increased by the filler effect of MK and its accelerating ability of cement hydration. They also found that the optimum MK substitution ratio was 20% for the same study (Wild *et al.* 1996, Wild *et al.* 1997).

In a study carried out for examining the microstructure and diffusion properties of concrete and cement pastes containing MK, it was concluded that the average pore size of concretes decreased significantly with 20% MK substitution with cement (Breddy *et al.* 1989, Kostuch *et al.* 1993).

Akcay *et al.* investigated the effects of MK on the fracture properties and mechanical behavior of high-performance concrete. As a result, they found that the compressive and three-point bending strength of concretes increased and pore structure improved by using MK (Akcay *et al.* 2017). Some others researchers pointed out that the MK replacement improved the mechanical properties of steel fiber reinforced high strength concrete (Sarıdemir *et al.* 2017).

Researchers reported that the use of MK improved the strength, carbonation depth and water absorption of concrete and the optimum replacement rate was found to be 10% (Lenka and Panda 2017). Joshaghani *et al.*, stated out that the water absorption, freeze-thaw resistance, rapid chloride permeation properties of MK-substituted concrete is found to be superior to concrete without MK (Joshaghani *et al.* 2017). Poon *et al.* indicated that the use of MK up to 20% significantly reduced the chloride permeation of concrete as per ASTM C1202 rapid chloride permeability test and increased the compressive strength (Poon *et al.* 2006). Morsy *et al.* studied the durability of mortars containing MK at high temperatures. Based on the results that they obtained, MK improved the compressive strength before and after the exposure to elevated temperatures and the 20% cement replacement of MK is the optimum percentage (Morsy *et al.* 2009). A study made by Morsy *et al.* on the resistance of MK-containing mortars to high temperatures suggested that after an initial increase in compressive strength at 250℃, the strength decreases considerably at temperatures beyond 250℃ (Morsy *et al.* 2012). Whereas in a study on concrete, the results were found to be parallel to this Moreover, residual compressive strengths of concretes were affected more than the plain mixtures (Poon *et al.* 2003).

Güneyisi and Gesoğlu stated out that MK reduced the shrinkage and water absorption of concrete; increased compressive and splitting tensile strengths (Güneyisi and Gesoğlu 2008). Güneyisi and Mermerdaş, indicated that the inclusion of MK greatly reduced sorptivity and chloride permeability of concrete (Güneyisi and Mermerdaş 2007a). On the other hand, Güneyisi *et al.* found that 15% MK substitution gave very good results when they compared the performance of concrete containing metakaolin and silica fume (Güneyisi *et al.* 2012).

The main aim of this study is to determine and compare the strength and durability properties of concretes containing MK. For this purpose, concrete mixtures were produced by substituting cement with MK 0, 5, 10 and 20% by weight. The amount of binder material for the concrete mixtures were 300 and 400 kg/m^3 with a constant water to cement ratio of 0.6. Compressive and bending strengths, freeze-thaw and high-temperature resistance, capillarity coefficients and rapid chloride permeability properties were determined on the concrete mixtures.

2. Experimental program

2.1 Materials

Ordinary Portland Cement CEM I 42.5 R, ASTM C-150 Type I which corresponds to TS EN 197-1 was used. As pozzolanic material metakaolin (MK) which is provided from a private industrial company was used in the production of concrete mixtures. The physical and chemical properties of the Portland cement and MK used in the mixtures are given in Table 1.

X-ray diffraction (XRD) analysis was performed on the MK and the diffraction pattern of MK is shown in Fig. 1. The crystalline phases of MK are composed of quartz (Q), micas (M) and anatase (An). A dome-like region between 2θ=20-30^o shows the amorphous phase resulting from

Table 1 Chemical composition and physical properties of Portland cement and MK.

Chemical Components	Amount (% by mass)		Physical and Mechanical Properties of Cement		
	Cement	*MK*	Retained on sieve 45 μm (%)		9.8
SiO_2	19.46	54.93	Retained on sieve 90 μm (%)		1.0
Al_2O_3	5.11	41	Specific surface (Blaine) (m^2/kg)		412.6
Fe_2O_3	3.31	1.38	Specific gravity (g/cm^3)		3.12
CaO	60.23	2	Setting Times (Vicat) (min.)	Initial	140
MgO	2.08	0.79		Final	200
SO_3	3.05	0.06	Water Demand (%)		29.2
Na_2O	0.27	0	Soundness (mm)		1.0
K_2O	0.69	0.21	Compressive Strength (MPa)	2 days	28.0
Cl^-	0.02	-		7 days	40.4
				28 days	51.5
Specific surface (m^2/kg)	413	2397			
Specific gravity (gr/cm^3)	3.12	2.79			
Loss on ignition (%)	3.00	0.21			

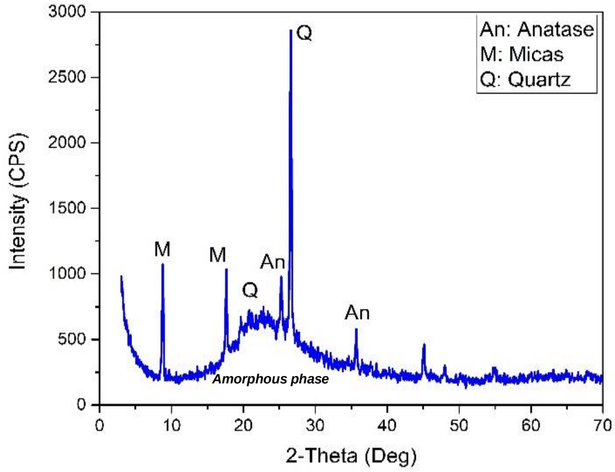

Fig. 1 X-ray diffraction of MK

Table 2 The physical properties of the aggregates used

Property	Coarse Aggregate	Fine Aggregate
Specific Gravity (kg/m^3)	2730	2590
Water Absorption Capacity (%)	1.13	3.23
Water Content (%)	0.155	1.306

the applied heat treatment of kaolinite. This dome-shaped amorphous structure is a clear indication that MK reaches a glassy structure and results in a pozzolanic character.

Local crushed calcareous aggregate with a maximum size of 16 mm and 4mm sand were used for mixtures. Specific gravity, water absorption and moisture content values of the aggregates are given in Table 2. Polycarboxylic ether-based superplasticizer admixture was used to obtain the desired workability in the mixtures. Fig. 2 shows the aggregate mixing curve along with the reference curves.

2.2 Specimens preparation

2.2.1 Mix design

The total binder amounts were 300 and 400 kg/m^3 in the concrete mixtures produced. Metakaolin (MK) replacement ratios were adopted as 5, 10 and 20%. Reference samples without MK were also produced for comparisons. In the literature, it has been stated that concretes containing MK reduces workability of fresh concrete significantly and increases the need for superplasticizer chemical admixture. For this reason, in this study, w/cm (water/cementitious materials ratio) was adopted as 0.6 to investigate the properties of normal strength conventional concretes. Slump values of mixtures were kept between 10-15 cm by using superplasticizer. Concrete specimens produced were stored and kept in a standard curing pool for 28 days. The material quantities used in concrete production are given in Table 3.

2.3 Test methods

Table 3 Composition of the concrete mixtures

Total Binder Material (kg/m³)	Mixture Code (kg/m³)	Cement (kg/m³)	MK (kg/m³)	Water (kg/m³)	Sand (kg/m³)	Gravel (kg/m³)	Plasticiser (kg/m³)
300	300-R	300	-	180	1201	646.9	8.1
	300-5M	285	15		1206	649.3	9.5
	300-10M	270	30		1205	648.8	10.8
	300-20M	240	60		1203	647.8	11.5
400	400-R	400	-	240	1050	565.8	7.3
	400-5M	380	20		1049	565.0	7.5
	400-10M	360	40		1048	564.4	6.7
	400-20M	320	80		1046	563.12	8.3

Table 4 Rapid Chloride ion permeability classification according to ASTM C1202

Charge Passing (Coulomb)	Chloride Ion Permeability
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very low
<100	Negligible

2.3.1 Compressive strength

For the compression strength test, three 15-cm cubes were used for each mixture, and the average strength values of these samples were determined as compressive strengths for the mixtures. The test was performed in accordance with TS EN 12390-3.

2.3.2 Flexural strength

For the three-point flexural strength test, two 10x10x40 cm prismatic samples were used for each mixture. Mean values were taken to determine flexural strength of the mixtures. This test was performed in accordance with TS EN 12390-5.

2.3.3 Capillarity

Capillarity coefficients of the mixtures were determined according to ASTM C 1585. For this test, two 10-cm cube samples were used and the mean values of these samples are taken.

2.3.4 Rapid chloride permeability test (RCPT)

The rapid chloride permeability test was performed according to ASTM C 1202. For this test, a 5 cm sliced specimen was taken from a 10 cm cylinder sample. Before testing, the sliced specimen was initially saturated with water. Then the specimen was placed in the test setup shown in Fig. 3. Sides of the test cell were filled with 3%NaCl and 0.3 N NaOH solutions. The cylindrical faces of the specimen were isolated by using silicone agent to prevent leakage. The total charge passed through the concrete specimen within 6 hours under 60 V potential difference was measured in Coulombs (C). The permeability classification according to the relevant standard is given in Table 4.

Fig. 3 Set up for rapid chloride permeability test

2.3.5 Ultrasonic pulse velocity (UPV)

Ultrasonic pulse velocity values (UPV) of cube samples were measured before and after the experiments in order to determine the level of deterioration caused by freeze-thaw effect on the internal structure of concrete.

2.3.6 Elevated temperature resistance

In order to examine the effect of high temperature, three 10 cm cube specimens were placed in an oven at 70°C for 48 hours and then placed in a furnace with 6-10°C/min heating rate and kept under the target temperature for 1 hour according to TS EN 1363-1. At the end of 1 hour, the samples were removed from the furnace and left to cool down in the laboratory. The temperatures employed were 200℃, 500℃ and 800℃ respectively.

2.3.7 Freeze-thaw resistance

The Freeze-thaw experiment was performed according to ASTM C 666. Three 15 cm cubes were used for this test. Before the freeze-thaw test, the weights and the UPV values of samples were determined. In order to determine the damage due to freeze-thaw, UPV, weight and compressive strength changes were measured before and after the freeze-thaw cycles. The change in the weight is an indication of the level of the damage due to scaling. UPV measurement is an indication of the level of internal damage to the concrete due to freeze-thaw. Each freeze-thaw cycle took 12 hours and temperature limits were between -20 and +20℃. A total number of 100 cycles were performed for each sample.

3. Results and discussion

3.1 Compressive strength

The 28-day mean compressive strength values are demonstrated in Fig. 4. As the metakaolin (MK) content increased, there was a steady increase in the compressive strength over both dosages. An increase of 47% and 52% in the compressive strengths of the 300 and 400 dosage mixtures with 20% MK substitution was observed. This result is clearly compatible with some studies in the literature (Poon *et al.* 2003, Güneyisi and Mermerdaş 2007, Wild *et al.* 1996). This is explained by the fact that the very fine MK grains acts as a physical filler and fill the fine gaps. This is also explained by the pozzolanic property of MK (Khatib *at al.*1996).

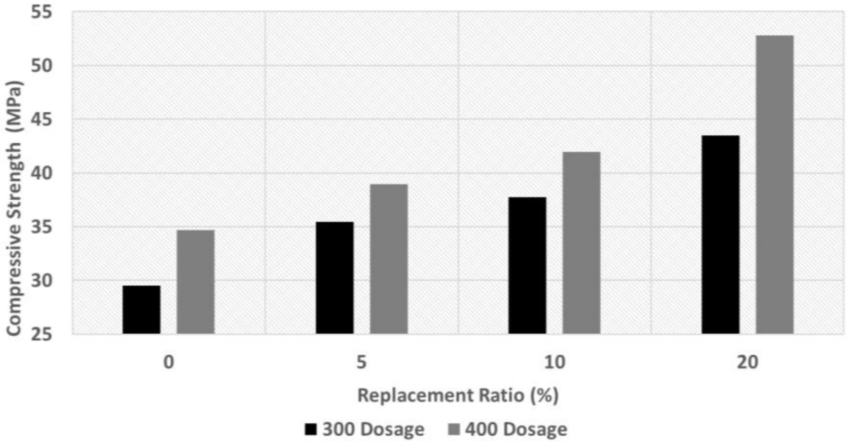

Fig. 4 28 days compressive strengths of the mixtures

Table 5 ANOVA results of compressive strength

Mixtures	300 Dosage				400 Dosage			
	OPC	MK5	MK10	MK20	OPC	MK5	MK10	MK20
Std. Dev.	1.902	1.421	1.219	1.221	1.641	1.221	1.204	1.983
Sig.*	-	0.005	0.001	0.000	-	0.038	0.002	0.000

*The mean difference is significant at the 0.05 level

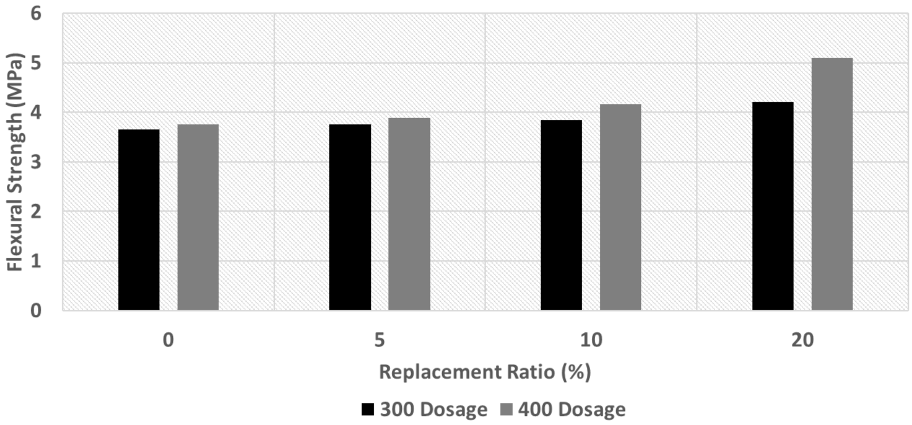

Fig. 5 28 days flexural strength values of the mixtures

The values of ANOVA (analysis of variance) are depicted in Table 5 which signify whether or not the differences in compressive strength between all samples containing MK and the control sample are statistically significant. As a rule of thumb according to the significance level (0.05), when the *p*-value of samples with MK is less than or equal to 0.05, it is accepted that there is a meaningful difference between the compressive strength against control samples. On the other hand, samples with a p-value greater than 0.05 have a negligible difference with the control sample (Tabatabaeian *et al.* 2017). Accordingly, for all MK substitution ratios, the compressive strength of mixtures increased meaningfully for both dosages.

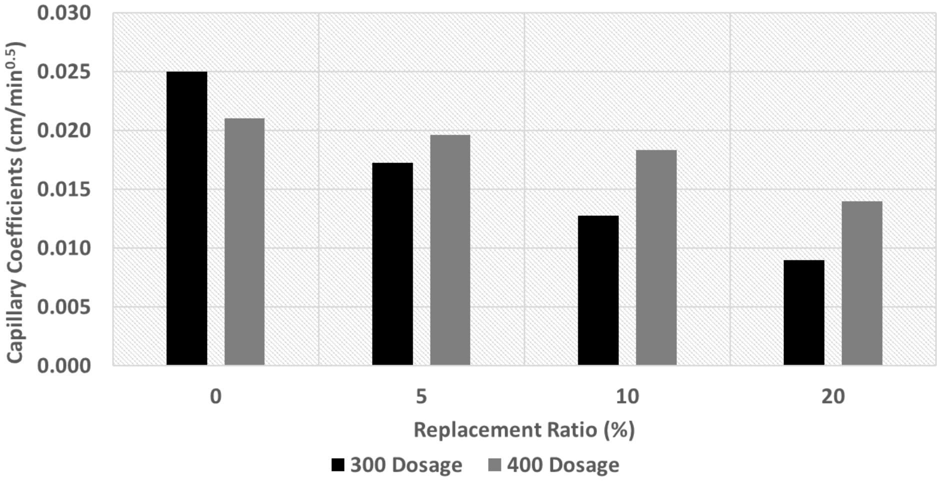

Fig. 6 Capillary coefficients of the mixtures

3.2 Flexural strength

The 28-day flexural strengths are given in Fig. 5 and it denotes that no significant change was observed in the substitution ratios of 5% and 10%. With 20% MK substitution, increments of 15% and 36% in the flexural strengths obtained in the 300 and 400 dosage mixtures respectively. These results are matching with the literature (Qian and Li 2001, Akcay *et al.* 2016).

3.3 Sorptivity

Capillary coefficients of all samples obtained from the capillarity test according to ASTM C1585 on 10 cm cubes are illustrated in Fig. 6. The results of this experiment show that while the amount of MK increases, the capillary coefficient of the mixtures decreases. The lowest capillarity coefficients were obtained with %20 MK replacement. This phenomena can be explained by the filler effect of the MK and making the paste phase more intense by forming an extra gel (Siddique 2008).

The capillary coefficient of the reference mixture with total binder of 300kg/m^3 was found to be 0.025 cm/min$^{0.5}$. With 5, 10, and 20% MK substitutions, this value decreased by 31, 49 and 61% respectively. The capillary coefficient was determined to be 0.02 cm/min$^{0.5}$ for the reference mixture containing 400 kg/m^3 binder. With 5, 10, and 20% MK substitutions, this value decreased by 1, 13 and 23% respectively. These results are found to be consistent with some studies in the literature. It was stated by Güneyisi and Mermerdaş that replacement of MK had a clearly positive effect on capillarity. The capillary coefficients of 28-day standard cured MK concrete with 0.55 w/cm and 350 kg/m^3 binder dosage were found to be significantly reduced in that study (Güneyisi and Mermerdaş 2007b). The capillary coefficients of concretes containing MK were recorded as 2-36% less than the reference concrete. This decreasing in the capillarity coefficients signify that the pore structure of the cement paste is small and it prevents entering the pore system of concrete from harmful substances (Bai *et al.* 2002). In another study, it was reported that the sort and fineness of mineral admixture greatly influences the pore structure of the concrete and provides a significant reduction in the capillarity coefficients of proper-cured concrete (Taşdemir 2003).

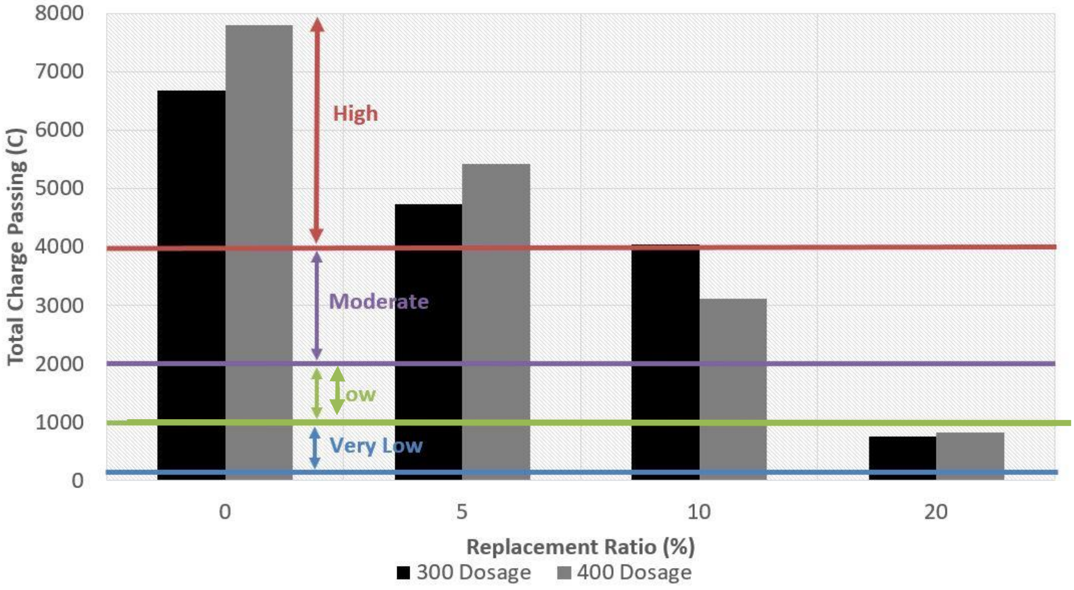

Fig. 7 Total charge passing from the mixtures

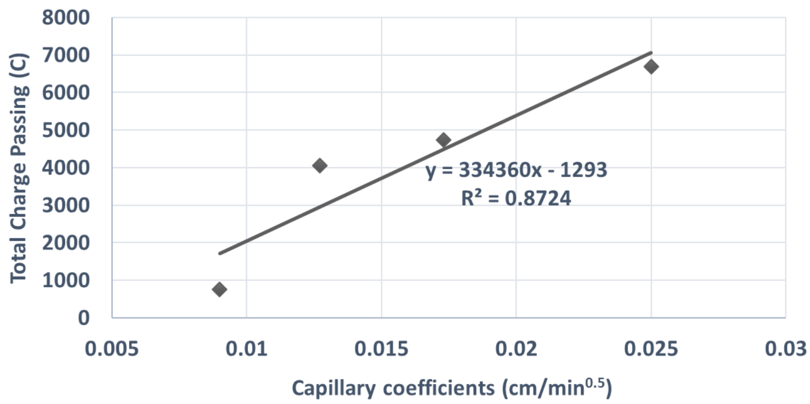

Fig. 8 Relationship between capillary coefficients and charge passing values of 300 dosage mixtures

3.4 Rapid Chloride Permeability Test (RCPT)

Total charge passing obtained from the rapid chloride permeability test according to ASTM C1202 are given in Fig. 7 including the limit values of the relevant standard. As the MK substitution ratio increases, the charge values passing through the mixtures decreases regularly. In the 300-dose mixtures, 6685 coulombs passed through the control sample while the mixtures containing %5, 10 and 20 MK were passed through 4737, 4050, 755 coulombs, respectively. In the 400-dose mixtures, 7796 passed through the control sample while the mixtures containing %5, 10 and 20 MK were passed through 5418, 3110, 824 coulombs, respectively. Reductions observed in both dosages were up to 90% starting from 30%. Mixtures with high permeability could be moved up to very low permeability class (according to ASTM C1202) with MK substitution This can be

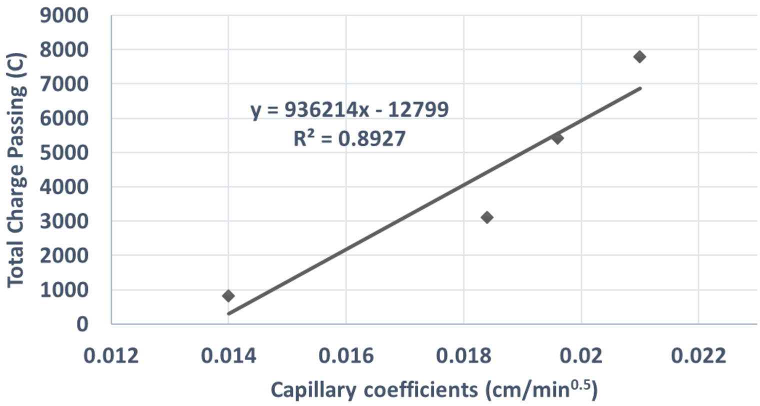

Fig. 9 Relationship between capillary coefficients and charge passing values of 400 dosage mixtures

explained by three main actions, which are speeding up cement hydration, pozzolanic reaction, and the filing effect. It was reported elsewhere (Dhinakaran *et al.* 2012), total charge passing through the concretes decreased with MK substitution up to 10%. In the case of 15% MK replacement, a slight increase was observed in the total charge passing value of the concrete compared to the 10% MK. However, according to the ASTM C1202 standard, this concrete could be involved in a very low permeable concrete class. As a result, the chloride permeability of all concrete mixtures containing MK were much lower than that the reference mixture. These developments are quite close to this study.

The relationship between total charge passing and capillary coefficient values of the concrete mixtures are plotted in Figs. 8 and 9, indicating that there is a strong relationship between total charge passing and capillary values of the concrete mixtures. The coefficient of determination (R^2) values (app.0.9) are found to be very close to 1.0.

3.5 Elevated temperature resistance

3.5.1 Effect of high temperature on compressive strength

The compressive strengths of the mixtures exposed to high temperature are demonstrated in Figs. 10-11. At 200℃, an increase in the strength of reference mixtures was observed for both dosages. One reason for the increase in strength at 200℃ is that unhydrated cement grains are hydrated by the effect of steam called internal autoclaving (Baradan *et al.* 2010, Saad *et al.* 1996). Similarly, Hager reported that the capillary water is completely disappeared at 200℃ (Hager 2013). After 500℃, there was a sharp decrease in compressive strength, and the cracks were observed in samples. Fares *et al.*, ascribed this observed loss of strength to decomposition of portlandite into free lime and loss of water from the micropores of hydrates (Fares *et al.*2010). Furthermore, Peng and Huang reported that CSH, which is the most important gel for concrete strength, begins to decompose at about 560℃ (Peng and Huang 2008). In our case, at 500℃, the highest compressive strength was obtained in the reference mixtures while the closest result among the other mixtures obtained from 20% MK. Significant physical distortions and cracks occurred in the concrete specimens right after the exposure to 500℃ are demonstrated in Fig. 12(a), (b).

At 800℃ the compressive strengths of 300 dosage mixtures were reduced to 15 MPa as an

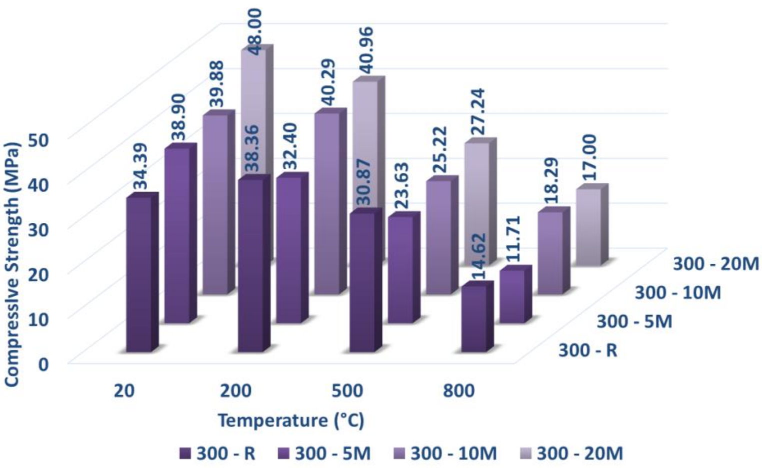

Fig. 10 Compressive strength-temperature relation of 300 dosage mixtures

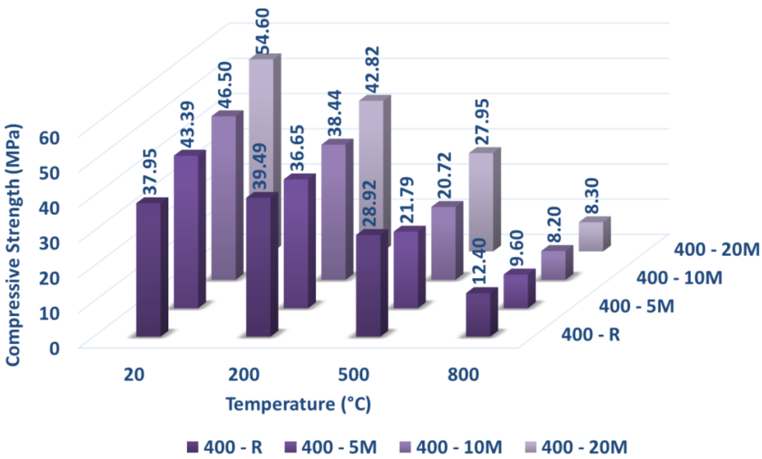

Fig. 11 Compressive strength-temperature relation of 400 dosage mixtures

average. Compressive strengths of 300 dosage-mixtures containing 0, 5, 10 and 20% MK were reduced by 58, 70, 54 and 65%, respectively, compared to those not exposed to high-temperature effect. The compressive strengths of the 400-dosage mixtures decreased to an average of 9.6 MPa at this temperature. Compressive strengths of 400-dosage mixtures containing 0, 5,10 and 20% MK were reduced by 67, 70, 82 and 85. Similar reduction percentages were noted in other studies. Chan *et al.* denoted that the strength loss of normal strength concrete exposed to 800℃ was approximately %20 and elevated temperature resistance declined due to deterioration of binder phase (Chan *et al.* 1999).

The external view and cross-sectional area of a sample exposed to 800℃ are presented in Figs. 12(c), (d). Severe cracks in the samples surface and the color changes to pink on the paste phase can be seen in same figures. It can be observed from the cross-sectional area of the broken specimen that paste-aggregate interface is almost lost and some aggregates are removed from the paste. It can be understood from this type fracture that paste-aggregate interface is almost lost. Cracking of concrete at this temperature can be explained by three factors: decompositions of

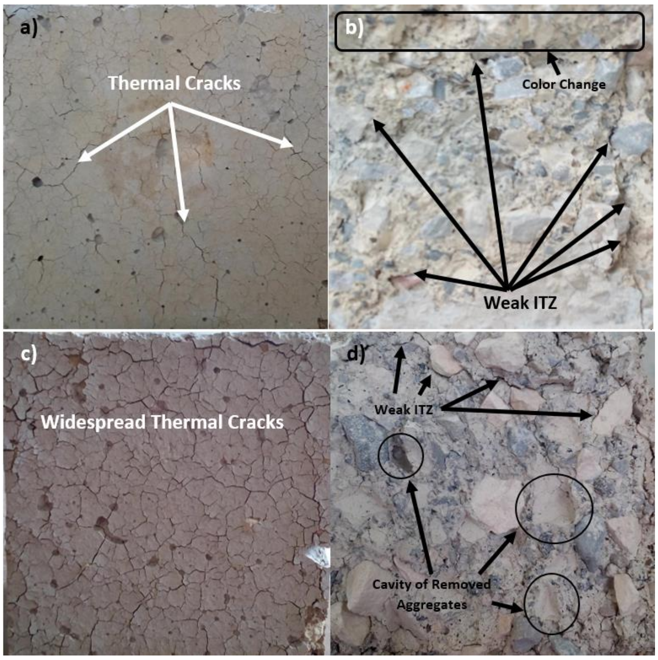

Fig. 12 Visual appearance of thermally damaged sample surface cracks and outer shell damage in cross section (a), (b) exposed to 500℃ and (c), (d) exposed to 800℃

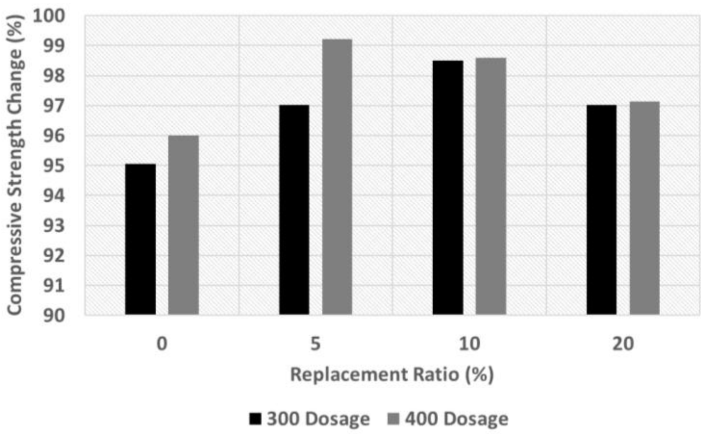

Fig. 13 Compressive strength change of the mixtures due to freeze-thaw

hydration products, shrinkage of cement matrix and different thermal behavior of aggregate-cement phases just as suggested by (Fu *et al.* 2006). This result is parallel with a scanning electron microscopy analysis study (Morsy *et. al.* 2009).

3.6 Freeze-thaw resistance

3.6.1 Effect of freeze-thaw on compressive strength

The changes in the compressive strengths of the mixtures according to the reference samples

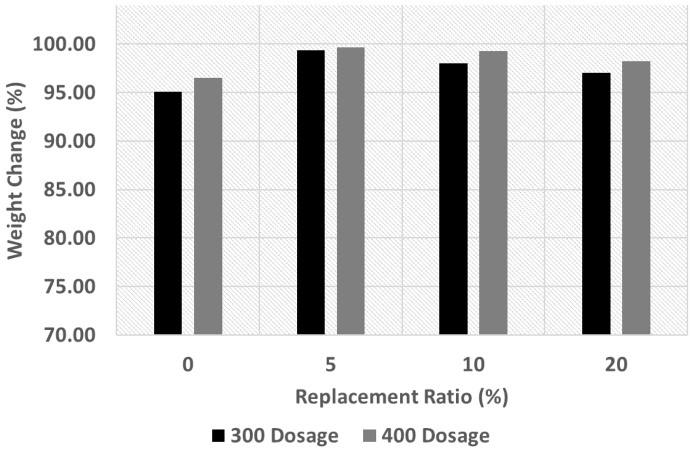

Fig. 14 The weight changes of the mixtures due to freeze-thaw effect

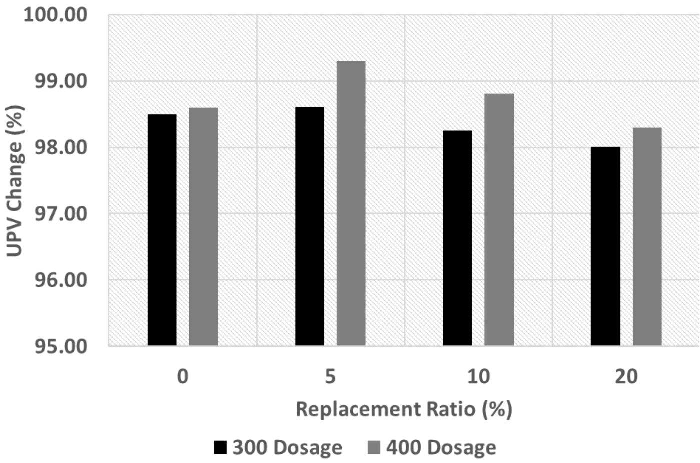

Fig. 15 The UPV changes of the mixtures due to freeze-thaw effect

are shown in Fig. 13. The use of MK has a positive effect on the freeze-thaw resistance of the mixtures. According to Fig. 13, the loss in the compressive strength of the reference mixtures was the maximum, while %10MK was the minimum. For 400-dose mixtures, the least strength loss was observed in 5% MK replacement. 20% MK replacement decreased strength loss to 3% for 300 and 400 dosage mixtures both.

3.6.2 Effect of freeze-thaw on weight change

As is known, mass loss is a factor in assessing the damage in concrete samples exposed to freeze-thaw effect. The weight change of samples due to the freeze-thaw effect is shown in Fig. 14.

As a result of this experiment, scaling and honeycomb voids were observed on the concrete surfaces. The Fig. 14 shows that the weight losses in the MK containing mixtures are lower than the reference mixtures. It can be seen that the most efficient MK substitution ratio is 5% for both dosages. The weight of the specimens was decreased by 5% and 4% approximately in the reference mixture for 300 and 400 dosages respectively. In an extensive study of Joshaghani *et al.* by using MK up to 15%, a relatively weight losses were reported for concretes including a total cementitious materials amount of 420 kg/m^3 with w/cm ratio 0.47 (Joshaghani *et al.* 2017). Although the level is not the same, this result is fairly parallel to our study.

3.6.3 Effect of freeze-thaw on UPV

The ultrasonic pulse velocity (UPV) changes of mixtures due to the freeze-thaw effect are shown in Fig. 15. The UPV values of the reference mixtures after the freeze-thaw cycles at both dosages were reduced by 1.5%. The reductions in UPV values were 1.4, 1.7 and 2% in the 300 dosage mixtures containing 5, 10 and 20% MK, respectively. The reductions in the UPV values were 0.7, 1.2 and 1.7% in the 400 dosage mixtures containing 5, 10 and 20% MK respectively. The slight changes in UPV values at the end of 100 cycles can be explained by facial scaling and absence of internal degradation.

4. Conclusions

The effects of metakaolin (MK) on the compressive and flexural strength, sorptivity, rapid chloride permeability, high temperature and freeze-thaw resistance of concrete were investigated. The main conclusions obtained in this study are as follows:

- The compressive strengths of concretes increased as the replacement ratio of MK were increased regardless of total binder content. The increment was more than 50% at %20 MK replacement.
- A slight increase in flexural strength was observed by MK replacement. 20% MK replacement provided 10 and 22% increase for 300 and 400 kg/m^3 dosage mixtures respectively.
- The rapid chloride ion permeability significantly decreased as the MK replacement ratio increased. With 20% MK, reference concrete which could be classified as a high permeable according to ASTM C1202 turned to be very low permeable class.
- The capillary coefficients decreased by increasing MK ratio for all mixtures. The decrease in the capillary coefficients were more significant for the concrete mixtures with a total binder of 300 kg/m^3.
- The strength of the mixtures containing MK increased at 200℃ and no positive effect was observed over that temperature. Concretes containing MK suffered more than the reference mixture at higher temperatures. It can be said that compressive strength of all mixtures got almost lost at 800℃.
- At the end of the freeze-thaw cycles, the compressive strength of mixtures containing MK suffered less than the reference mixtures.
- Consequently, the performance of concrete significantly improved as the substitution ratio of MK increased regardless of the total binder material amount. The optimum MK substitution ratio can be postulated to be 20% according to this study.

Acknowledgments

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Abdul Razak, H., Chai, H.K. and Wong, H.S. (2004), "Near surface characteristics of concrete containing supplementary cementing materials", *Cement. Concrete Compos*., **26**, 883-889.

Akcay, B., Sengul, C. and Tasdemir M.A. (2016), "Fracture behavior and pore structure of concrete with metakaolin", *Adv. Concrete. Constr.*, **4**(2), 71-88.

Aquino, W., Lange, D.A. and Olek, J. (2001), "The influence of metakaolin and silica fume on the chemistry of alkali-silica reaction products", *Cement. Concrete Comp*., **23**, 485-493.

ASTM C1202 (2012), Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration, American Society for Testing and Materials, Philadelphia, U.S.A.

ASTM C150 (2004), Standard Specification for Portland Cement, American Society of Testing and Materials, Philadelphia, U.S.A.

ASTM C1583 (2013), Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes, American Society for Testing and Materials, Philadelphia, U.S.A.

ASTM C666 (2015), Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, American Society for Testing and Materials, Philadelphia, U.S.A.

Bai, J., Wild, S. and Sabir, B.B. (2002), "Sorptivity and strength of air-cured and water-cured PC-PFA-MK concrete and the influence of binder composition on carbonation depth", *Cement Concrete. Res*., **32**, 1813-1821.

Baradan, B., Yazıcı, H. and ÜN, H. (2010), Beton ve Betonarme Yapılarda Kalıcılık(Durabilite), Turkey Ready Mixed Concrete Association, Istanbul.

Bredy, P., Chabannet, M. and Pera, J. (1989), "Microstructure and porosity of metakaolin blended cements", *Proc. Mater. Res. Soc. Symp.*, **137**, 431-436.

Caldarone, M.A., Gruber, K.A. and Burg, R.G. (1994), "High reactivity metakaolin: a new generation mineral admixture", *Mod. Steel Constr.*, **16**(11), 37-40.

Cassagnabère, F., Mouret, M., Escadeillas, G., Broilliard, P. and Bertrand, A. (2010), "Metakaolin, a solution for the precast industry to limit the clinker content in concrete: Mechanical aspects", *Constr. Build. Mater.*, **24**, 1109-1118.

Chan, Y.N., Peng, G.F. and Anson, M. (1999), "Residual strength and pore structure of high-strength concrete and normal strength concrete after exposure to high temperatures", *Cement Concrete Compos.*, **21**, 23-27.

Choate, W.T. (2003), "Energy and emission reduction opportunities for the cement industry. Department of energy", *Office of Energy Efficiency and Renew. Energy*, Columbia, MD, USA.

Dhinakaran, G., Thilgavathi, S. and Venkataramana, J. (2012), "Compressive strength and chloride resistance of metakaolin concrete", *KSCE J. Civil Eng*., **16**(7), 1209-12017.

Fares, H., Remond, S., Noumowe, A. and Cousture, A. (2010), "High temperature behaviour of self-consolidating concrete microstructure and physicochemical properties", *Cement Concrete Res.*, **40**, 488-96.

Frias, M. and Cabrera, J. (2000), "Pore size distribution and degree of hydration of metakaolin-cement pastes", *Cement Concrete Res*., **30**, 561-569.

Fu, Y., Wong, Y., Poon, C. and Tang, C. (2006), "Literature review of study on mechanism of explosive spalling in concrete at elevated temperatures", *Jianzhu Cailiao Xuebao/J. Build. Mater.*, **9**(3), 323-329.

Gonçalves, J.P., Tavares, L.M, Toledo Filho, R.D. and Fairbairn, E.M.R. (2009), "Performance evaluation of cement mortars modified with metakaolin or ground brick", *Constr. Build. Mater.*, **23**, 1971-1979.

Güneyisi, E. and Gesoğlu, M. (2008), "Improving strength, drying shrinkage, and pore structure of concrete using metakaolin", *Mater. Struct.*, **41**, 937-949.

Güneyisi, E. and Mermerdaş, K. (2007a), "Effect of metakaolin and foundry sand on the near surface characteristics of concrete", *Constr. Build. Mater*., **25**(8), 3257-3266.

Güneyisi, E. and Mermerdaş, K. (2007b), "Comparative study on strength, sorptivity, and chloride ingress characteristics of air-cured and water-cured concretes modified with metakaolin", *Mater. Struct*, **40**(10),

1161-1171
Güneyisi, E., Gesoğlu, M., Karaoğlu, S. and Mermerdaş, K. (2012), "Strength, permeability and shrinkage cracking of silica füme and metakaolin concretes", *Constr. Build. Mater.*, **34**, 120-130.
Hager, I. (2013), "Behaviour of cement concrete at high temperature", *Bull. Pol. Acad. Sci.-Tech.*, **61**(1), 145-154.
Joshaghani, A., Moeini, M.A. and Balapour, M. (2017), "Evaluation of incorporating metakaolin to evaluate durability and mechanical properties of concrete", *Adv. Concrete Constr.*, **5**(3), 241-255.
Kadri, E., Kenai, S., Karim, E., Siddique, R. and De Schutter, G. (2011), "Influence of metakaolin and silica fume on the heat of hydration and compressive strength development of mortar", *Appl. Clay Sci.*, **53**, 704-708.
Khatib, J.M. and Wild, S. (1996), "Pore size distribution of metakaolin paste", *Cement Concrete Res.*, **26**(10), 1545-1533.
Kostuch, J.A., Walters, G.V. and Jones, T.R. (1993), "High performance concrete incorporating metakaolin - a review", Concrete 2000, University of Dundee.
Lenka, S. and Panda, K.C. (2017), "Effect of metakaolin on the properties of conventional and self compacting concrete", *Adv. Concrete Constr.*, **5**(1), 31-48.
Li, C., Sun, H. and Li, L. (2010), "A review: The comparison between alkali-activated slag (Si+Ca) and metakaolin (Si+Al) cements", *Cement Concrete Res*., **40**, 1341-1349.
Li, Q., Geng, H., Huang, Y. and Shui, Z. (2015), "Chloride resistance of concrete with metakaolin addition and seawater mixing: a comparative study", *Constr. Build. Mater.*, **101**, 184-192.
Morsy, M.S., Al-Salloum, Y.A., Abbas, H. and Alsayed, S.H. (2012), "Behavior of blended cement mortars containing nano-metakaolin at elevated temperatures", *Constr. Build. Mater.*, **35**, 900-905.
Morsy, M.S., Rashad, A.M. and El-Noughy, H.A. (2009), "Effect of elevated temperature on physico-mechanical properties of metakaolin blended cement mortar", *Struct. Eng. Mech.*, **31**(1), 1-10.
Peng, G. and Huang, Z. (2008), "Change in microstructure of hardened cement paste subjected to elevated temperatures", *Constr. Build. Mater.*, **22**(4), 593-599.
Poon, C.S., Azhar, S., Anson, M. and Wong, Y.S. (2003), "Performance of metakaolin concrete at elevated temperatures", *Cement Concrete Compos.*, **25**(1), 83-89.
Poon, C.S., Kou, S.C. and Lam, L. (2006), "Compressive strength, chloride diffusivity and pore structure of high performance metakaolin and silica fume concrete", *Constr. Build. Mater.*, **20**(10), 858-865.
Qian, X. and Li, Z. (2001), "The relationships between stress and strain for high-performance concrete with metakaolin", *Cement Concrete Res*., **31**, 1607-1611.
Ramezanianpour, A.A. and Jovein, H.B. (2012), "Influence of metakaolin as supplementary cementing material on strength and durability of concretes", *Constr. Build. Mater.*, **30** , 470-479.
Saad. M., Abo-El-Enein. S.A., Hanna, G.B. and Kotkata, M.F. (1996), "Effect of temperature on physical and mechanical properties of concrete containing silica fume", *Cement Concrete Res.*, **26**(5), 669-675.
Sabir, B.B., Wild, S. and Bai, J. (2001), "Metakaolin and calcined clays as Pozzolans for concrete: a review", *Cement Concrete Compos.*, **23**(6), 441-54.
Sarıdemir, M., Secercan, M.H. and Çelikten, S. (2017), "Mechanical properties of SFRHSC with metakaolin and ground pumice: Experimental and predictive study", *Steel Compos. Struct.*, **23**(5), 543-555.
Siddique, R. (2008), *Waste Materials and By-Products in Concrete*, Springer-Verlag Berlin Heidelberg, Berlin, Germany.
Sun, S.H., Ma, J.T., Pang, X.M., Sun, Y.T. and Wang, S.L. (2005), "Sulfur reduction additive prepared from acid - modified kaolin", *Bull. Catal. Soc. India*, **4**, 72-78.
Tabatabaeian, M., Khaloo, A., Joshaghani, A. and Hajibandeh, E. (2017), "Experimental investigation on effects of hybrid fibers on rheological, mechanical, and durability properties of high-strength SCC", *Constr. Build. Mater.*, **147**, 497-509.
Taşdemir, C. (2003), "Combined effects of mineral admix- tures and curing conditions on the sorptivity coefficient of concrete", *Cement Concrete Res.*, **33**, 1637-1642.
Taylor, H.F.W. (1997), *Cement Chemistry*, 2nd Edition, Thomas Telford Services Ltd., London.
TS EN 12390-3 (2010), Testing Hardened Concrete-Part 3: Compressive Strength of Test Specimens,

Ankara, Turkey.
TS EN 12390-5 (2010), Testing Hardened Concrete-Part 5: Flexural Strength of Test Specimens, Ankara, Turkey.
TS EN 1363-1 (2013), Fire resistance tests-Part 1. General requirements. Turkish Standards Institution, Ankara, Turkey.
TS EN-197-1 (2012), Cements-Part 1: Compositions and conformity criteria for common cements, Ankara, Turkey.
Wild, S. and Khatib, J.M. (1997), "Portlandite consumption in metakaolin cement pastes and mortars", *Cement Concrete Res*., **27**(1), 137-146.
Wild, S., Khatib, J.M. and Jones, A. (1996), "Relative strength, pozzolanic activity and cement hydration in superplasticised metakaolin concrete", *Cement Concrete Res*., **26**(10), 1537-1544.

CC