Research Article

Experimental investigation on the effect of silica fume and zeolite on mechanical and durability properties of concrete at high temperatures

Mehrdad Abdi Moghadam[1] · **Ramezan Ali Izadifard**[1]

Abstract

Fire assessment of structures is an important area of concern. When the knowledge of concrete structures behavior at high temperatures is insufficient, there will be irreparable damage and financial losses. In this study, the mechanical and durability properties of concrete, aiming to overcome the adverse effects of high temperature by substituting a portion of cement with pozzolans is presented. The mechanical properties at the hot condition and the durability characteristics were tested when they reach the ambient temperature. The mechanical properties including compressive, tensile and shear strength, and the durability were evaluated based on the surface water absorption, water penetration depth, electrical resistance, and weight loss tests. Tests were conducted at different temperatures ranging from 28 to 800 °C. The results show that by increasing the temperature, the mechanical properties of the concrete decreased, with further increase in temperature they recovered and then started to decrease. Application of silica fume improved the compressive and tensile strength in a range of 1.35–26.74%, and 0.37–234.58% at the tested temperatures. However, pozzolans have not a significant impact on the shear strength. The study of the durability of concrete has shown that the heat reduced the durability of concrete while the addition of zeolite and silica fume compensated this reduction. In tests based on capillary properties and in the electrical resistivity test, samples containing zeolite had better durability properties. Meanwhile, in samples containing zeolite, those with a higher content of zeolite were better in terms of durability properties.

Keywords Mechanical characteristics · Durability characteristics · Zeolite · Silica fume · High temperature

1 Introduction

Concrete is one of the most widely used construction materials, due to its strength and low-cost, averagely 20 billion tons of concrete are produced each year [1]. One of the main components of concrete is cement. Production of cement causes problems like high energy consumption, carbon dioxide production and global warming. The cement industry contributes about 5–7% of carbon dioxide emissions in the world and is growing every second [1–3]. Reduction of pollution can be achieved by limiting cement consumption in concrete production; In other words, replacing a portion of cement with pozzolanic materials is a good solution. A wide range of pozzolanic materials are available throughout the world and are being used in various industries. Most pozzolanic materials are water-friendly and reduce concrete workability significantly [4]. Because cement has a great impact on concrete strength, engineers are allowed to replace a limited portion of cement with pozzolan. The optimal replacement of cement with pozzolan depends on the type of the pozzolan. Vailpoor et al. [5] tested several dosages of zeolite, silica fume, and metakaolin, concluding that the optimal percentage of cement replacement with mentioned pozzolans is about 10–15%, 7.5–10%, and 10% respectively. The optimal replacement of cement

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✉ Mehrdad Abdi Moghadam, m.abdimoghadam@edu.ikiu.ac.ir | [1]Department of Civil Engineering, Imam Khomeini International University, Qazvin, Iran.

SN Applied Sciences (2019) 1:682 | https://doi.org/10.1007/s42452-019-0739-2

Received: 31 March 2019 / Accepted: 4 June 2019 / Published online: 8 June 2019

with zeolite is recommended by 10% and 15% by other authors [6–8]. Although zeolite is superior to silica fume for its low-cost and eco-friendly nature, earlier studies have shown a higher effect of silica fume in the enhancement of compressive strength [9]. One source of natural zeolite is in Iran–Semnan, which is rich in Al_2O_3 and SiO_2, the reaction with $Ca(OH)_2$ leads to the production of C–S–H gel and aluminates in concrete [10]. This is the pozzolanic reaction. Analysis of concrete microstructure at ambient temperature has shown that C–S–H gel production improves the quality of the transition zone the quality of the concrete [11, 12]. Depending on the zeolite content, the ratio of water to the binder, chemical characteristics and sources of zeolite, the 28-day compressive strength of concrete may increase [9, 13, 14] or decrease [7, 8, 12]. However, the compressive strength of concrete containing zeolite at late-age is higher than that of normal concrete [8]. Chan and Ji stated that another influential factor on the effect of the substitution of cement with zeolite on the concrete properties is the ratio of water to water to binder (cement + pozollans). The results showed that for water to binder ratios lower than 0.45, the compressive strength of concrete with 10% zeolite was higher than that of normal concrete. Whereas in contrast for water to binder ratio of 0.45, the compressive strength of concrete decreased by 2.4 Mpa [9]. Nagrockiene and Girskas reported a 13.3% increase in compressive strength due to the 10% replacement of cement weight with zeolite for water to binder ratio of 0.45 [14]. In another study done by Madandoust et al. [10], a 5% decrease in the 28-day compressive strength of concrete containing 20% zeolite was reported. Tensile strength is another indicator of the mechanical properties of concrete. Due to the ratio of water to the binder and the content of the used pozzolan, the zeolite may increase or decrease the tensile strength [12, 15]. Based on the member position, the shear strength may be critical in the design of reinforced concrete structures. This parameter has a vital role in the overall behavior and the failure mode of the reinforced concrete members.

Studies on the durability properties of concretes containing pozzolans have shown a desirable effect of pozzolans at ambient temperature [10]. Different methods are available to measure the durability of concrete. Surface water absorption, primary and secondary water absorption, penetration depth and electrical resistivity tests have been attracted more attention of researchers. In the case of the sorptivity coefficient, zeolite has improved this parameter at ambient temperature. For example, 10% replacement of cement with zeolite reduced the sorptivity coefficient by 25% [12]. Earlier studies have shown that silica fume was effective in improving water absorption, electrical resistance and water penetration depth specifications of normal concrete at ambient temperature [5, 13, 16]. Water penetration depth is one of the important factors for determining the durability of concrete, reducing by increasing the zeolite content at ambient temperature [8]. Few studies have been carried out on the effects of high temperature on the durability specifications of the concretes containing pozzolans. In this regard, Khan and Abbas examined the compressive and tensile strength of concrete samples containing fly ash at temperatures ranging from 100 to 900 °C [17]. In another study, the undesirable effects of high temperatures on the flexural strength and tensile strength of concretes containing silica fume and metakaolin have been investigated [18]. In a recently published article by Abdi Moghadam and Izidifard, an equation for prediction of plain and fibrous concrete at ambient and high temperatures was proposed [19]. A comprehensive review of earlier studies has shown that few studies have focused on the mechanical properties of concrete at hot state. Meanwhile no design codes [20–22] has covered the mechanical properties of concrete containing pozzolans. Therefore, the effect of pozzolans on the enhancement of concrete specifications remained unclear. In this study, the mechanical properties of concrete, including compressive, tensile and shear strength and the durability properties using tests such as surface water absorption, water penetration depth, electrical resistance, and weight loss were assessed. Meanwhile, the effect of replacement a portion of cement weight with zeolite or silica fume on these specifications at temperatures of 28, 100, 200, 300, 350, 400, 450, 500, 650 and 800 °C were examined. Therefore, not only these results clarify the effect of pozzolans in improving concrete specification at high temperatures but also can be used in the concrete structural design with the risk of fire accidents. In addition, these precious data improve the knowledge of pozzolanic concrete in the hot condition.

2 Preparation of sample and heat regime

In this investigation, four different mix proportions namely samples without pozzolan (N), samples with 10% Zeolite (Ze10), 20% Zeolite (Ze20), and 10% Silica fume (SF10) cement replacement were investigated. The coarse aggregate was crushed limestone with a maximum size of 19 mm, the fine aggregate was river sand and ordinary Portland cement type 2 was used in the mix designs. Chemical properties of cement, natural zeolite, and silica fume are listed in Table 1. Natural pozzolan, as mineral additives, must have special specifications. The total amount of SiO_2, Al_2O_3, and Fe_2O_3 in zeolite is 81.06%, which meets the chemical requirements according to C 618-05 ASTM [22].

Table 1 Chemical properties of the cement, natural zeolite and silica fume

Chemical composition (% by mass)	Cement	Natural zeolite	Silica fume
Silica (SiO_2)	20.24	68.95	93.6
Alumina (Al_2O_3)	5.28	11.14	1.32
Iron oxide (Fe_2O_3)	3.72	0.97	0.37
Calcium oxide (CaO)	63.24	4.83	0.49
Magnesium oxide (MgO)	2.69	0.79	0.97
Sodium oxide (Na_2O)	0.258	0.95	0.31
Potassium oxide (K_2O)	0.533	0.9	1.01
Sulfur trioxide (SO_3)	2.54	0.068	0.1
Other	1.499	11.402	1.83
Total	100	100	100

Table 2 Mixing Plan

Mixture	Concrete component (kg/m^3)					
	Portland cement	Water	Coarse aggregate	Fine aggregate	Zeolite	Silica fume
Normal concrete (N)	400	200	935	765	–	–
Ze10	360	200	935	765	40	–
Ze20	320	200	935	765	80	–
SF10	360	200	935	765	–	40

Table 2 gives the details of the mix proportions. The mixing plan and curing condition for the samples were constant. In the first stage of mixing concrete components, dry materials (aggregate, cement, and pozzolan) were mixed for 1 min. Then water was added, and the batch was mixed for 4 min. Finally, concrete was poured into the mould. Samples were demoulded after 24 h of casting and were cured for 28 days in a water tank. To reduce the risk of concrete spalling during the heating process, the samples were moved to the laboratory and cured at laboratory environment for 14 days until 42 days' age when they were tested at the high-temperature condition. The temperatures studied were ambient temperature (28 °C), 100, 200, 300, 350, 400, 450, 500, 650, and 800 °C. Mechanical and durability tests were performed on three and two replicates, respectively. The average of the test results is presented in this investigation. In this study, the mechanical specification tests were carried by a 3000 kN testing machine and the heat source was an electric furnace with a heat capacity of 1200 °C. The concrete samples were kept in the furnace as long as enough to ensure that the samples are under a steady-state thermal condition. In order to prevent spalling, the samples were heated at a 1.66–3.61 °C/min rate until the desired temperature was achieved. After removing samples from the oven, the mechanical specification of specimens was tested immediately. The heating-time curves of tests are drawn in Fig. 1.

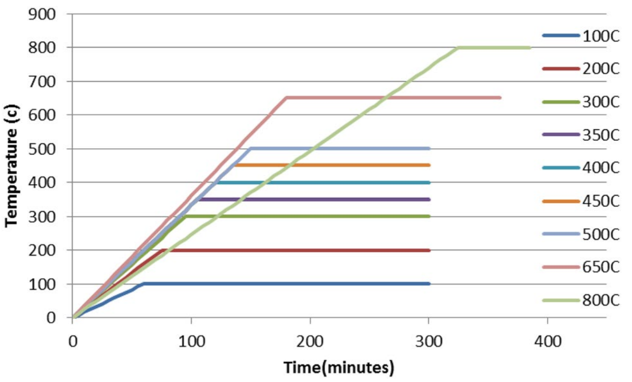

Fig. 1 Heating regime inside the electric furnace

3 Tests

3.1 Mechanical specifications of concrete

3.1.1 Compressive strength test

The compressive strength test was carried out in accordance to BS-En [23] standard using 100 mm concrete cubic specimens. Figure 2 presents the variation of compressive strength with increasing temperature. The compressive strength at ambient temperature was 53.38 MPa. The replacement of 10% and 20% of cement

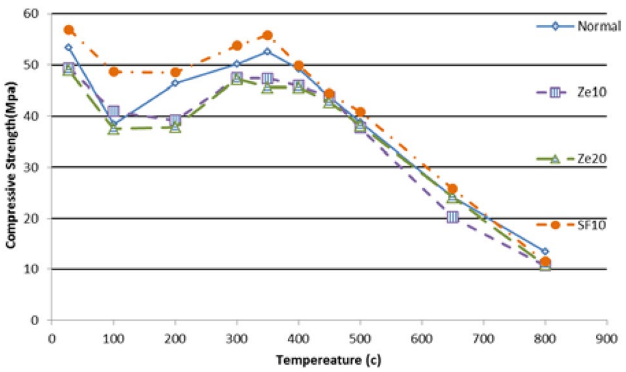

Fig. 2 The variation of compressive strength of concrete with temperature

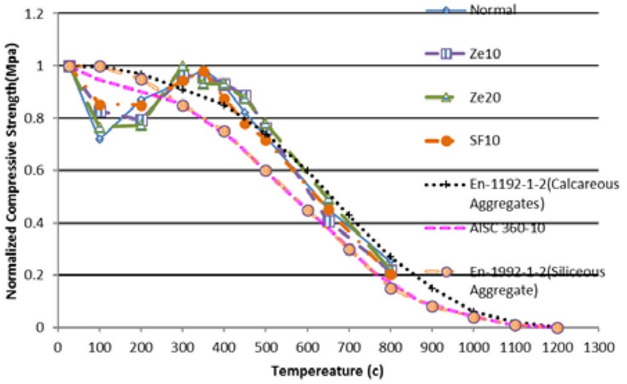

Fig. 3 Normalized compressive strength variations and comparison with existing regulations

weight by zeolite has reduced compressive strength by 7.41 and 8.33% to 49.42 and 48.93 MPa, respectively. On the other hand, the replacement of 10% of cement by silica fume, increased the compressive strength of normal concrete by 6.8% to 57 MPa. The maximum compressive strength was at ambient temperature and reduced by increasing temperature. The compressive strength variations of normal and pozzolanic concrete with increasing temperatures are similar. Initially, as the temperature increased to 100 °C, the compressive strength decreased sharply. In this temperature range, vapor pressure inside the concrete pores is responsible for the loss of resistance. With further increase in temperature, concrete recovered its strength. Where a second peak appears in the compressive strength-temperature curve, then the compressive strength decreases with increasing temperature and reaches its least value at 800 °C. For N and SF10, the second peak appears at 400 °C and for Ze10 and Ze20, appears at 350 °C. Earlier studies showed that the increase in resistance at these temperatures attributed to the stiffening of the cement gel due to cement layers contraction and an increase of surface forces between cement gel layers resulting from the removal of water from concrete [24]. The replacement of cement with silica fume increased the compressive strength by about 1.35–26.74% except for 800 °C, which resulted in a slight reduction in compressive strength. The greatest effect of silica fume on compressive strength improvement occurred at the temperature below 350 °C. This improvement is contributed to the pozzolanic reaction and formation of additional C–S–H [25]. The replacement of cement with zeolite has generally reduced compressive strength, reducing the compressive strength of normal concrete slightly at temperatures higher than 400 °C. Therefore, it can be a good alternative for cement in the case of fire accident risk.

The ratio of compressive strength at the target temperature to the compressive strength at ambient temperature is the normalized compressive strength (NCS). NCS of experimental results and suggested data by AISC 360-10 [26] and EN-1192-1-2 [22] standards are shown in Fig. 3. At 100 °C, the compressive strength of N, Ze10, Ze20, and SF10 decreased by 28.11, 17.19, 23.45 and 14.68%, respectively. It is observed that at 100 and 200 °C existing standards are overestimated and at the temperatures ranging from 300 to 400 °C are conservative. 450 °C onward, although the experimental results are slightly lower than those in the Eurocode standard, this standard is most consistent with test data. It is noted that although at the temperatures lower than 300 °C the EN-1192-1-2 for siliceous aggregates is higher than the AISC 360-10 standard, at higher temperatures they are similar. Finally, concluded that the EN-1192-1-2 standard has the most compatible with the experimental results. In addition, during the first 400 °C silica fume and 400 °C onward, zeolite specimens had higher normalized compressive strength. 400 °C onwards, specimens containing a higher dosage of zeolite have had higher normalized compressive strength. Meanwhile, although the replacement of zeolite with cement has reduced compressive strength, it has improved the NCS.

3.1.2 Tensile strength test

Splitting tensile test was carried out on 150 × 300 mm cylindrical samples in accordance with ASTM C 496/C 496M-04 standard [27]. Figure 4 shows the tensile behavior of the tested concrete at various temperature levels. The tensile strength of normal concrete at ambient temperature was 3.03 MPa. The replacement of 10% and 20% of cement weight with zeolite has reduced the tensile strength by 15.56 and 16.48% to 2.56 and 2.53 MPa, respectively. The replacement 10% of cement weight with

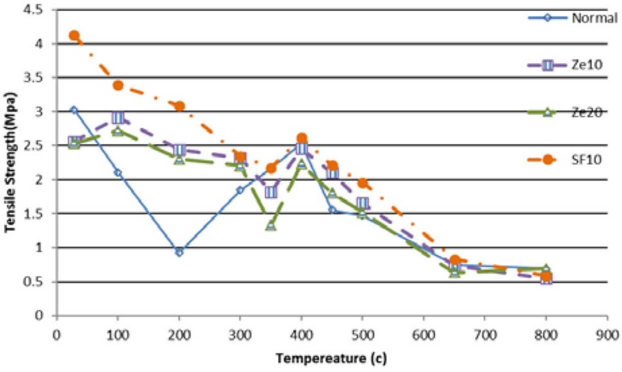

Fig. 4 Tensile strength variation with temperature

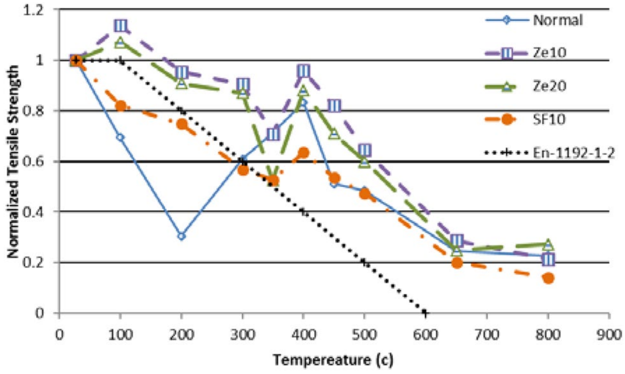

Fig. 5 Normalized tensile strength at different temperature and comparison with En-1992-1-2

silica fume has increased tensile strength by 35.92% to 4.12 MPa. The addition of silica fume in concrete increased tensile strength by 0.37–234.58% at the studied temperatures, except at 800 °C, with reducing slightly. The increase in tensile strength is attributed to the improvement of the interfacial layer of the cement matrix and aggregate due to the pozzolanic reaction. As shown in Fig. 4 the splitting tensile strength decreases with increasing temperature until 200 °C. From then onward it increases until the 400 °C when it starts to decrease sharply. This trend is in line with the results reported in references [28, 29] using fewer temperatures. At 100 and 200 °C, the tensile strength of normal concrete decreased by 30.44 and 69.56% to 2.11 and 0.92 MPa, respectively. Replacement of cement with pozzolanic materials has considerably improved tensile strength at these temperatures. For example, at 100 °C, the tensile strength of Ze10, Ze20 and SF10 was improved by 38.16, 28.95 and 60.85% respectively, and at 200 °C the tensile strength of the mentioned samples was improved by 165.70, 149.62 and 234.58%, respectively. Furthermore, It was observed that the tensile strength of both Ze10 and Ze20 have a similar trend by increasing temperature and the level of improvement decreased with an increase in the zeolite content, except at 800 °C. At this temperature, the tensile strengths of N, Ze10, Ze20, and SF10 are 0.69, 0.55, 0.69 and 0.58 MPa, respectively.

The ratio of tensile strength at the target temperature to the tensile strength at ambient temperature (NTS) is shown in Fig. 5 and compared to the results of EN-1192-1-2 code. At 100 °C, the NTS is similar to the NCS (approximately 0.7). The descending trend of normal concrete continued until 200 °C. At this temperature, the NTS of N, Ze10, Ze20, and SF10 are 0.3, 0.95, 0.91 and 0.75, respectively. By comparing the experimental results with the Eurocode, it is observed that before 300 °C the experimental results are lower than that of given by Eurocode. 300 °C onward, the values of the Eurocode are conservative. Although at higher temperatures the Eurocode has assumed a zero value for the tensile strength, the experimental results indicate that at 650 and 800 °C the NTS of N is 0.25 and 0.23. At the same temperatures, the tensile strength of Ze10 was 0.29 and 0.21 of that of normal concrete at ambient temperature. The corresponding values are 0.25 and 0.27 for Ze20 and 0.2 and 0.14 for SF10. The results of the normalized tensile strength show that silica fume had the highest effect on the tensile strength improvement. However, the highest effect of NTS improvement achieved by the replacement of cement with zeolite.

3.1.3 Shear strength test

There are different methods for determining the shear strength of concrete [30–32]. The Japanese Society of Civil Engineering (JSCE-SF6) method is commonly used in determining the shear strength of concrete due to its advantages such as the simplicity of the test machine and its high precision in determining the shear strength [33, 34]. Figure 6a, b shows the proposed dimension of the shear test equipment by JSCE-SF6 and schematic design of equipment used in this study.

A 100 × 100 × 350 mm sample is used for the direct shear test in this study. The ends of the samples are held by the belt to make sure that pure shear exists and the notches are created by a cutting machine with a width of 5 mm and a depth of 10 mm. The greatest shear strength (τ) is calculated as follows:

$$\tau = \frac{p_{peak}}{2A_{eff}} \quad (1)$$

where (p_{peak}) is the maximum load (N) and A_{eff} is the effective area of the cutting surface (mm^2). Figure 7 shows the shear strength of the specimens at different temperature levels. The shear strength of normal concrete at ambient temperature is 8.43 MPa. Substitution 10% and 20%

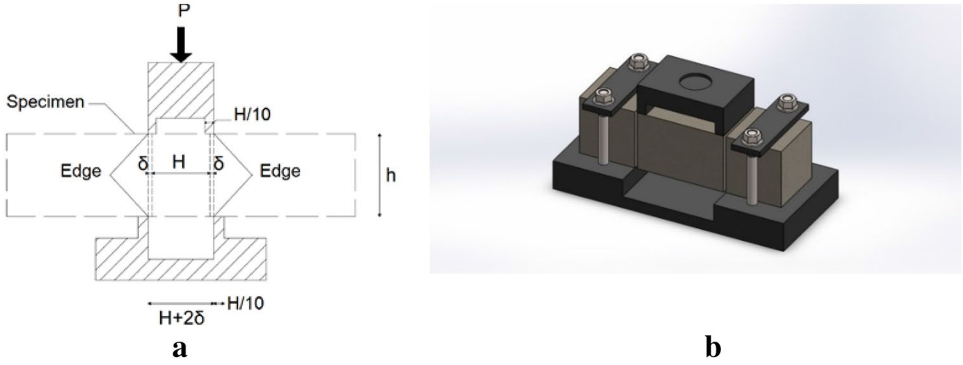

Fig. 6 Direct shear testing equipment: **a** direct shear test configuration according to JSCE [30], **b** schematic design

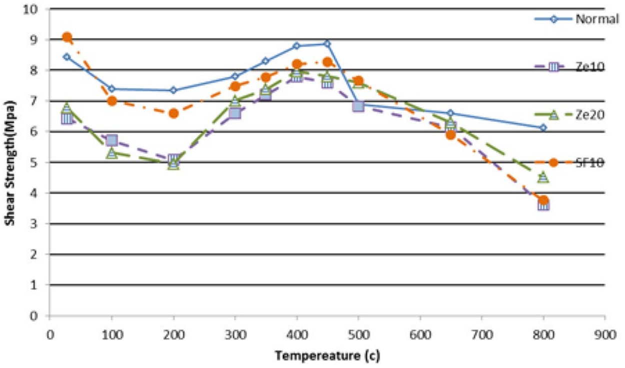

Fig. 7 Shear strength variation with temperature

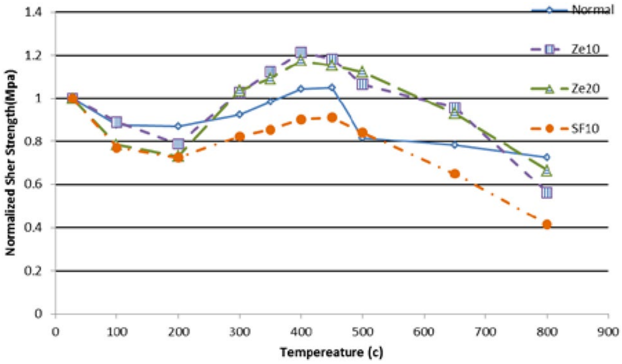

Fig. 8 Normalized shear variation of concrete with heat changes

of cement weight with zeolite have reduced the shear strength by 23.82 and 19.7% to 6.42 and 6.77 MPa, respectively. On the other hand, the replacement 10% of cement weight with silica fume, has increased the shear strength of concrete by 7.82% to 9.09 MPa. The shear strength decreases dramatically throughout the first 200 °C. From then onward, the shear strength grows to its maximum value. The peak of N and SF10 samples occurred at 450 °C. The corresponding peak of the Ze10 and Ze20 samples occurred at 400 °C. The shear strength of N, Ze10, Ze20 and SF10 samples at these temperatures are 8.85, 7.8, 7.96 and 8.27 MPa, respectively. After the peak point, the shear strength reduced again and the lowest shear strength occurred at 800 °C. At this temperature, the shear strength of N, Ze10, Ze20, and SF10 is 6.13, 3.61, 4.51 and 3.8 MPa, respectively. The study of the effect of cement replacement with pozzolan has shown that at 500 °C replacement of 20% zeolite and 10% silica fume with cement improved the shear strength of normal concrete by about 10%. However, at other temperatures replacement of zeolite and silica fume with cement reduced shear strength on average by 17.4 and 10.9%, respectively. Contrary to the compressive and tensile strength, which addition of pozzolans improved the mechanical properties at the tested temperatures, the shear strength is not improved by the pozzolans. The reason for the improvement of the compressive and tensile strength is the pozzolan's nature properties for reducing concrete internal pores and improving the structure of the transition zone between the cement paste and aggregates. In the direct shear test, however, the size and shape of the coarse aggregates play a significant role. The employment of these pozzolans has decreased the shear strength at tested temperatures. However, owing to a slight decline, zeolite and silica fume can be a good alternative of cement for the construction of concrete with the risk of fire accidents. Furthermore, it was observed that the shear strength of the Ze10 and Ze20 followed a similar trend and the level of shear strength improvement increased with increasing zeolite content, except at 100 and 200 °C.

The normalized shear strength (NSS) is presented in Fig. 8. An extensive review of standard design codes shows that the shear strength of concrete at high temperatures was not considered. The NSS like the NCS has fallen at 100 °C. At this temperature, the NSS of N, Ze10, Ze20, and SF10 decreased by 12.26, 11.02, 21.54 and 22.92%, respectively. Meanwhile, The lowest normalized shear strength at all tested temperatures was related to the sample containing silica fume. This is due to the high shear strength of the specimen with silica fume at ambient temperature. The results show that replacement of cement with zeolite has improved the normalized shear strength about 11–37% at temperatures higher than 200 °C. Furthermore, it is observed that for most of the studied temperatures, the NSS of the ZE10 is 5% higher than that of Ze20 on average. However, at the temperature of 800 °C, the NSS of the ZE20 is about 18.6% higher than ZE10.

3.2 Durability properties

In this study, concrete durability evaluation was studied by examining the sorptivity coefficient, water penetration depth and electrical resistance tests on the heated samples after cooling as well as weight loss due to exposure at different temperatures. The proposed results are the average of two replicates for each test.

3.2.1 Sorptivity test

Sulfates and carbonates are compositions that are responsible for the destruction of concrete during its lifetime. The penetration of these harmful substances through the pores is due to capillary properties of concrete. Various methods are available to estimate the permeability properties of concrete. Some of them are based on the gas and others are based on the water penetration [35]. In this study, for the surface water absorption test, 100 × 100 × 100 mm cube samples were used. The lateral surfaces of the samples were sealed with the sealing materials up to the height of 30 mm from the bottom of the samples. In this test, the bottom surface of the sample contributes to the water absorption. To provide the free movement of water from the bottom of the samples, 10 mm diameter bars were placed on the tray and the samples have been placed on bars (Fig. 9). The specimens were weighted before setting in the tray and at intervals of 3, 6, 24, 48, and 72 h after they were in the tray. During the test duration, the water evaporates causes the variation of the pressure gradient. So the water level in the tray should be kept at a constant level by adding water at regular intervals. The sorptivity coefficient is calculated using Eq. 2.

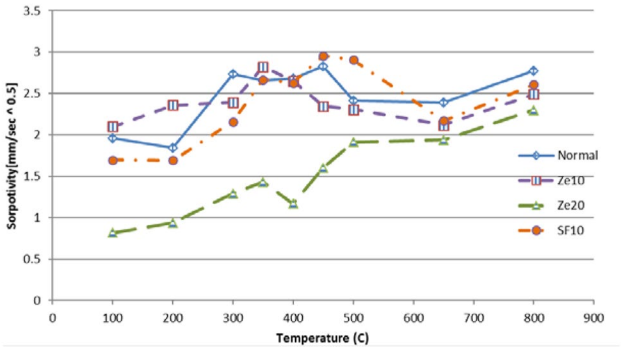

Fig. 10 Variation of sorptivity coefficient with temperature

$$i = S \times \sqrt{t} + C \tag{2}$$

where $i = \frac{m_i - m_0}{A \times \gamma_{water}}$. In this equation S is the sorptivity coefficient, A is the sectional area of the concrete exposed to water $\left(\mathrm{mm}^2\right)$, m_i is the sample weight after the different period they were put in the tray (gr), m_0 is the weight of the sample before they were put in the tray (gr). The sorptivity coefficient of the tested samples at various temperature levels is shown in Fig. 10. The sorpotivity coefficient of normal concrete at 100 °C was 1.96 $\frac{\mathrm{mm}}{\mathrm{s}^{0.5}}$. The increase in the test temperature increased this coefficient which at 800 °C was 2.77 $\frac{\mathrm{mm}}{\mathrm{s}^{0.5}}$. Addition of zeolite and silica fume reduced this coefficient at 800 °C. At this temperature, the sorpotivity coefficient of Ze10, Ze20 and SF10 is 2.47, 1.509 and 2.61 $\frac{\mathrm{mm}}{\mathrm{s}^{0.5}}$, respectively. Because of the fineness size of zeolite and silica fume, they have a filler property. By forming silica gel they reduce the number and volume of concrete pores which reduce the sorptivity coefficient and improve durability properties. The replacement 20% of cement weight with zeolite has the most effect on the sorptivity coefficient reduction. Because substitution higher percentage of cement with zeolite, fills more pores, resulting in a greater improvement of the sorptivity coefficient. In the case of samples containing the same zeolite

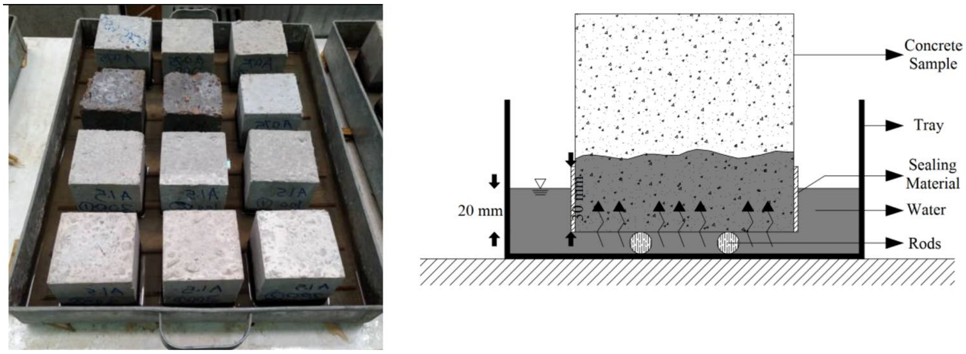

Fig. 9 Surface water absorption test

Fig. 11 Split Ze10 samples at 400 and 500 °C

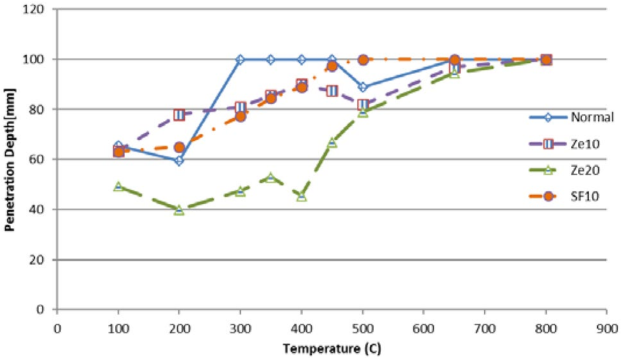

Fig. 12 Variation of water penetration depth with temperature

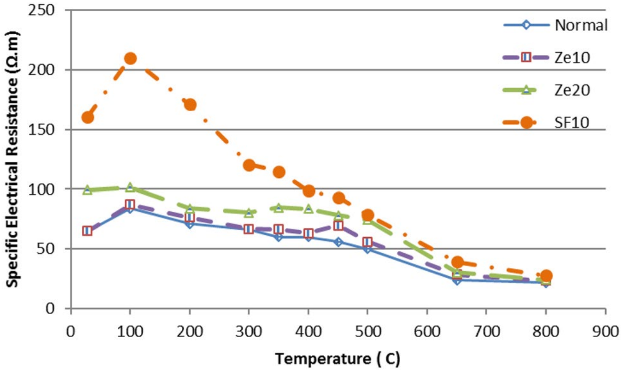

Fig. 13 Variation of specific electrical resistance of samples with temperature

and silica fume content (Ze10 and SF10 samples), it is observed that SF10 have lower sorptivity coefficients until 400 °C. 400 °C onward, the Ze10 have lower surface water absorption coefficients. This proves a better performance of zeolite on improvement of the durability properties of concrete at high temperatures.

3.2.2 Water penetration depth test

At the end of the surface water absorption test, the samples were split in half to determine the water penetration depth. The spilt sample and the penetration depth of water profile due to the capillary suction after 72 h at different temperature are given in Figs. 11 and 12, respectively. At 100 °C, the water penetration depth of N, Ze10, Ze20, and SF10 are 65.5, 63.4, 49.3 and 63.2 mm, respectively. Samples containing pozzolan have lower pore due to the pozzolanic activity which consume $Ca(OH)_2$ and produce excessive C_S_H gel, resulting in lower penetration depth. In the diagram of N, Ze10, and Ze20 a fracture occurred at temperatures of 450, 400 and 350 °C, respectively. At these temperatures, the penetration depth decreased and then increased with the further increase of temperature. Although the amount of absorbed water at lower temperatures is lower than that of higher temperatures, the penetration depth of water is higher. This may be due to the enlargement of the pores and, subsequently, the reduction of capillary properties at a higher temperature. The larger pores cause higher absorbed water and the lower suction property. Visual inspection shows that the penetration depth of water was saturated at higher temperatures. This is illustrated in Fig. 12 for the Ze10 sample which experienced a temperature of 400 and 500 °C. Meanwhile, observed that by increasing the temperature, the penetration depth of concrete has increased. Replacement 20% of cement weight with zeolite had the greatest effect on reducing the penetration depth of water at all test temperatures. Which the highest reduction was 57% and occurred at 450 °C. In the case of samples containing the similar content of zeolite and silica fume (Ze10 and SF10 samples), it is observed that SF10 samples have lower water penetration depth until 400 °C. Beyond 400 °C, the Ze10 samples were better in the reduction of water penetration.

3.2.3 Electrical resistance test

The electrical resistance test carried out on 100 mm cubic concrete specimens. Samples were immersed in a water tank 24 h before the test. They tested after removing the water. Specific electrical resistance is calculated using Eq. (3).

$$r = \frac{R \times A}{L} \tag{3}$$

where R is the electrical resistance (Ω), A is the concrete surface area (m^2), L is the sample length and r is the specific electrical resistance (Ω m). In this test, the electrical resistance of the concrete was measured in two perpendicular directions of specimens and, the average of the results was presented in Fig. 13. The results show that the electrical resistance of the samples at 28 °C is lower than that of at 100 °C, it can be attributed to the presence of free water inside the concrete which is not evaporated. Beyond 100 °C, the specific electrical resistance of normal and pozzolan concrete decreased by increasing temperature. This can be attributed to the increase of pores and cracks in size and numbers. Substitution a portion of cement weight with pozzolans has increased the electrical resistance of concrete which, silica fume has the greatest effect. The results showed that the electrical resistance of Ze10, Ze20 and SF10 at the tested temperatures averagely was 89.22, 7.7 and 32.02% higher than that of normal concrete. Due to the fine distribution of particles and cationic properties, zeolites have reduced the concentration of ions, resulting an increase of electrical resistance [36]. Substitution a higher portion of cement with pozzolan fills more pores and enhance the rate of the electrical resistance improvement at high temperatures. Before 450 °C, silica fume has a significant effect on the electrical resistance improvement. With a further increase in temperature, this positive effect has decreased, where 450 °C onwards, the differences between the electrical resistance of samples containing zeolites and silica fume is negligible.

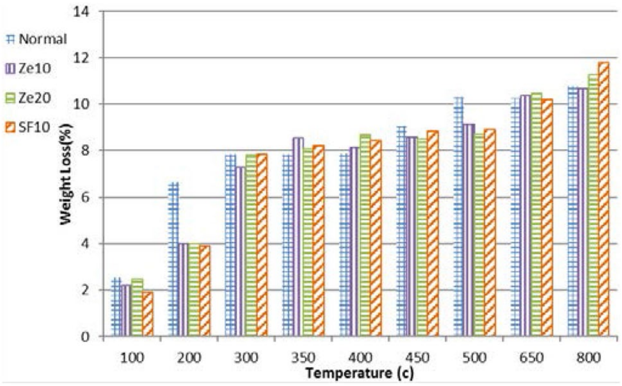

Fig. 14 Variation of weight loss with temperature

3.2.4 Weight loss of concrete

In order to find the weight loss of concrete at various temperatures, 100 mm cubic samples were weighed before and after being placed in the furnace. Figure 14 shows the variations of weight loss of samples with a change in the temperature. It is observed that the increase in the test temperature has led to an increase in the weight loss of the samples. The main cause of the weight loss in the temperature range of 100–200 °C is due to the evaporation of free water in capillary pores, in this range the weight loss rate is higher than other temperatures. The addition of zeolite and silica fume has improved the permeability properties of concrete. Therefore, the application of these pozzolans at these temperatures prevent the release of free water and eventually decreases its weight loss. At higher temperature, the main cause of weight loss is evaporation of water in C–S–H gel and degradation of aggregates and cement due to expansion. In addition, the weight loss of pozzolanic concrete is slightly lower than that of normal concrete, except at 350, 400, and 800 °C. Which the greatest effect of pozzolan in reducing the weight loss of concrete was at temperatures of 200 and 500 °C. Meanwhile, there is no significant difference in the weight loss of pozzolanic concrete due to exposure to different temperatures.

4 Conclusions

In this study, the effect of zeolite and silica fume on mechanical and durability properties of concrete at different temperatures was investigated. This experimental study allows us to obtain the following:

The overall trend of compressive, tensile and shear strength graph is similar. The temperature of the relative extremum, however, varies depending on the test. The greatest improvement on the compressive and tensile strength of normal concrete was achieved by replacement of 10% cement weight with silica fume. The mentioned strengths were improved by 1.35–26.74% and 3.84–234.58%, respectively at the tested temperatures. However, the shear strength is not improved by the silica fume, except at 28 and 500 °C. At these temperatures 10% replacement of cement weight by silica fume has improved the shear strength by 7.8 and 10%, respectively. In the direct shear test, the size and shape of the coarse aggregates play a significant role. However, in associated with the compressive and tensile strength, pozzolans by reducing concrete internal pores and improving the structure of the transition zone between the cement paste and aggregates increase the strength of concrete. Due to the high compressive strength achieved by adding silica fume to concrete at ambient temperature, the ratio of compressive strength at each temperature to that of at ambient temperature for specimens contains silica fume was low. However, silica fume improved the NTS significantly at temperatures of 100 and 200 °C, having a slight difference with the NTS of normal concrete at temperatures above 450 °C.

The replacement of 10% and 20% of cement weight with zeolite reduced the compressive strength at the tested temperatures. Concerning the tensile strength, at temperatures ranging from 100 to 300 °C, it was increased significantly by substitution of cement weight with zeolite. However, samples containing higher zeolite content have lower tensile strength. In terms of shear strength test, it was observed that the addition of zeolite to concrete reduced the shear strength at high temperatures and the level of shear strength improvement increased with increasing zeolite content, except at 100 and 200 °C. The replacement of cement with zeolite have improved the normalized strength and in comparison with silica fume has had the greatest impact on the normalized strength.

By examining the provisions of design codes, it was observed that the shear strength of concrete at high temperatures was not taken into account. In addition, the experimental results obtained in this study can help to improve previous design codes and introduce considerations for the fire design of concrete structures containing pozzolans.

About the durability of concrete, it was observed that the high temperature reduced the durability properties of concrete. The most effective solution for improving the surface water absorption specifications in concrete that experienced high temperatures was the replacement of 20% cement weight with zeolite. In the case of samples containing the same zeolite and silica fume content, it was seen that at temperatures until 400 °C, SF10 and at temperatures higher than 400 °C, Ze10 was better in tests based on the capillary properties. The replacement of cement with zeolite, due to the fine distribution of particles and reducing the concentration of ions, improved the specific electrical resistance of concrete at all temperatures. However, the electrical resistance of samples containing silica fume was higher than samples containing zeolite. Meanwhile, samples containing a higher content of zeolite were better in terms of durability properties.

The results presented in this paper were done for normal strength concrete. It is expected that the effect of substitution a portion of cement with pozzolan on the characteristic of high strength or lightweight concrete at high temperatures varies from the results of this study. Further research on these issues is warranted. Although the rate of increase in the test temperature in this study was in the range of 1.66–3.61 °C/min, in a real fire the target temperature achieved in a short time. Because of the low capacity of the furnace, the temperature rate was lower than an actual fire, it will be important that future research investigates the effect of higher rate on these results. About the examination of the durability characteristics of concrete, several methods are available. In this study, a few of these experiments were conducted to achieve a good view of concrete durability properties. Therefore, it is recommended that further durability tests be carried out in future studies to evaluate the porosity, pore-size distribution, sulfate resistance, and gas permeability.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Tošić N, Marinković S, Stojanović A (2017) Sustainability of the concrete industry: current trends and future outlook. Tehnika 72(1):38–44
2. Meyer C (2004) Concrete materials and sustainable development in the United States. Struct Eng Int 14(3):203–207
3. Crow JM (2008) The concrete conundrum. Chem World 5(3):62–66
4. Markiv T, Sobol K, Franus M, Franus W (2016) Mechanical and durability properties of concretes incorporating natural zeolite. Arch Civ Mech Eng 16(4):554–562
5. Valipour M, Pargar F, Shekarchi M, Khani S (2013) Comparing a natural pozzolan, zeolite, to metakaolin and silica fume in terms of their effect on the durability characteristics of concrete: a laboratory study. Constr Build Mater 41:879–888
6. Markiv T, Huniak O, Kh S (2014) Optimization of concrete composition with addition of zeolitic tuff. Theory Build Pract Lviv Polytech Natl Univ 781:116–120
7. Samimi K, Kamali-Bernard S, Maghsoudi AA, Maghsoudi M, Siad H (2017) Influence of pumice and zeolite on compressive strength, transport properties and resistance to chloride penetration of high strength self-compacting concretes. Constr Build Mater 151:292–311
8. Najimi M, Sobhani J, Ahmadi B, Shekarchi M (2012) An experimental study on durability properties of concrete containing zeolite as a highly reactive natural pozzolan. Constr Build Mater 35:1023–1033
9. Chan SYN, Ji X (1999) Comparative study of the initial surface absorption and chloride diffusion of high performance zeolite, silica fume and PFA concretes. Cem Concr Compos 21(4):293–300
10. Madandoust R, Sobhani J, Ashoori P (2013) Concrete made with zeolite and metakaolin: a comparison on the strength and durability properties. Asian J Civ Eng 14(4):533–544
11. Ikotun BD, Ekolu S (2010) Strength and durability effect of modified zeolite additive on concrete properties. Constr Build Mater 24(5):749–757

12. Ramezanianpour AA, Mousavi R, Kalhori M, Sobhani J, Najimi M (2015) Micro and macro level properties of natural zeolite contained concretes. Constr Build Mater 101:347–358
13. Ahmadi B, Shekarchi M (2010) Use of natural zeolite as a supplementary cementitious material. Cem Concr Compos 32(2):134–141
14. Nagrockiene D, Girskas G (2016) Research into the properties of concrete modified with natural zeolite addition. Constr Build Mater 113:964–969
15. Eskandari H, Vaghefi M, Kowsari K (2015) Investigation of mechanical and durability properties of concrete influenced by hybrid nano silica and micro zeolite. Procedia Mater Sci 11:594–599
16. Sabet FA, Libre NA, Shekarchi M (2013) Mechanical and durability properties of self consolidating high performance concrete incorporating natural zeolite, silica fume and fly ash. Constr Build Mater 44:175–184
17. Khan MS, Abbas H (2015) Effect of elevated temperature on the behavior of high volume fly ash concrete. KSCE J Civ Eng 19(6):1825–1831
18. Çiflikli M, Sarıdemir M, Soysat F (2018) Adverse effects of high temperatures and freeze-thaw cycles on properties of HFRHSCs containing silica fume and metakaolin. Constr Build Mater 174:507–519
19. Moghadam MA, Izadifard R (2019) Evaluation of shear strength of plain and steel fibrous concrete at high temperatures. Constr Build Mater 215:207–216
20. Bihr JE, Bletzacker RW (1994) Guide for determining the fire' endurance of concrete elements
21. Lie TT (1992) Structural fire protection, no. 78
22. B. S. EN (2004) 1-2: 2004 Eurocode 2: design of concrete structures-part 1–2: general rules-Structural fire design. European Standards, London
23. B. Standard (2009) Testing hardened concrete. Compressive Strength Test Specimens, BS EN, pp 12390–12393
24. Castillo C (1987) Effect of transient high temperature on high-strength concrete. Rice University, Houston
25. Hale WM, Freyne SF, Bush TD Jr, Russell BW (2008) Properties of concrete mixtures containing slag cement and fly ash for use in transportation structures. Constr Build Mater 22(9):1990–2000
26. A. ANSI (2010) AISC 360-10. Chicago, IL
27. C. ASTM (2004) 496/C 496M-04. Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
28. Faiyadh FI, Al-Ausi MA (1989) Effect of elevated temperature on splitting tensile strength of fibre concrete. Int J Cem Compos Light Concr 11(3):175–178
29. Novak J, Kohoutkova A (2018) Mechanical properties of concrete composites subject to elevated temperature. Fire Saf J 95:66–76
30. J. S. of C. Engineering (1990) JSCE-SF6: Method of test for shear strength of steel fiber reinforced concrete (SFRC). Tokyo
31. Hofbeck JA, Ibrahim IO, Mattock AH (1969) Shear transfer in reinforced concrete. J Proceedings 66(2):119–128
32. F. I. de la Precontrainte (1998) FIP guide of good practice. Compos Floor Struct FIP Lond
33. T. Soetens, S. Matthys (2011) A formula to predict the maximum direct shear load of SFRC. In: 7th Central European congress on concrete engineering: innovative materials and technologies for concrete structures (CCC-2011), pp 99–102
34. Boulekbache B, Hamrat M, Chemrouk M, Amziane S (2012) Influence of yield stress and compressive strength on direct shear behaviour of steel fibre-reinforced concrete. Constr Build Mater 27(1):6–14
35. Houaria MBA, Abdelkader M, Marta C, Abdelhafid K (2017) Comparison between the permeability water and gas permeability of the concretes under the effect of temperature. Energy Procedia 139:725–730
36. Naiqian F, Tingyu H (1998) Mechanism of natural zeolite powder in preventing alkali–silica reaction in concrete. Adv Cem Res 10(3):101–108