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Effect of pozzolans on mechanical behavior of recycled refractory brick concrete in fire

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Abstract. Reusing building materials and concrete of old buildings can be a promising strategy for sustained development. In buildings, the performance of materials under elevated temperatures is of particular interest for determining fire resistance. In this study, the effect of pozzolan and aggregate type on properties of concrete exposed to fire was investigated. In doing so, nanosilica with cement-replacement levels of 0, 2, and 4% as well as silica fume and ultrafine fly ash with cement-replacement levels of 0, 7.5, and 15% were used to study effect of pozzolan type, and recycled refractory brick (RRB) fine aggregate replacing natural fine aggregate by 0 and 100% was utilized to explore effect of aggregate type. A total of 126 cubic concrete specimens were manufactured and then investigated in terms of compressive strength, ultrasonic pulse velocity, and weight loss at 23°C and immediately after exposure to 400 and 800°C. Results show that replacing 100% of natural fine aggregate with recycled refectory brick fine aggregate in the concretes exposed to heat was desirable, in that it led to a mean compressive strength increase of above 25% at 800°C. In general, among the pozzolans used here, silica fume demonstrated the best performance in terms of retaining the compressive strength of heated concretes. The higher replacement level of silica fume and ultrafine fly ash pozzolans in the mixes containing RRB fine aggregate led to a greater weight loss rate, while the higher replacement level of nanosilica reduced the weight loss rate.

Keywords: recycled refractory brick; concrete; pozzolan; elevated temperatures; ultrasonic pulse velocity; weight loss; silica fume; nanosilica; ultrafine fly ash

1. Introduction

In the modern world of today, an important approach for sustained development is to reuse waste building materials such as recycled concrete aggregate (RCA) as a partial or total replacement of natural aggregate to produce new concretes through an economic and practical method (Sagoe-Crentsil *et al*. 2001). In this regard, with the ever-expanding urban areas and the reduction of landfill sites especially in large cities, it has become a major challenge to manage industrial waste and, in particular, recycle non-biodegradable wastes including ceramics (and bricks as a subgroup) that have a very long decomposition period (over 4000 years). With respect to the literature, the first recorded case of crushed brick application with Portland cement occurred in 1860 Germany to produce concrete materials; however, the first significant use of crushed brick as an aggregate in fresh concrete dates back to post-World War II reconstruction era (Hansen 2004).

The main advantages of using crushed refractory brick as an alternative aggregate in concrete include improved post-fire properties, reduced usage of natural aggregate, and lowered environmental damage (Baradaran-Nasiri and Nematzadeh 2017). Baradaran-Nasiri and Nematzadeh (2017) investigated the effect of using refractory brick aggregate on the post-heating mechanical properties of concrete. They studied the compressive strength and modulus of elasticity of concrete specimens containing refractory brick fine aggregate replacing 0 and 100% of natural fine aggregate, and the results showed that using refractory brick fine aggregate especially in combination with calcium aluminate cement improved the compressive strength values relative to conventional concrete at temperatures above 800°C. Furthermore, in the case of the refractory brick aggregate usages, a higher area under the stress-strain curve was obtained (Xiao *et al*. 2005). It is observed in the study of Liu *et al.* (2016) that in the replacement range of 0-100%, the compressive strength and modulus of elasticity of the recycled concretes see a considerable decrease with increasing temperature, and also, when the concrete containing recycled aggregate is exposed to heat, the effect of the content of the recycled aggregate on the concrete ultimate strain parameter is significant, with a higher concrete strain for a higher content.

Pozzolan is a name assigned to siliceous and siliceous-aluminous materials that have a low or zero content of cementitious materials and, in the presence of moisture, react with calcium hydroxide to form compounds having cementitious properties (Hasan-Nattaj and Nematzadeh

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2017). Utilizing pozzolans as a partial or total cement replacement is beneficial for concrete, in that it can reduce the concrete porosity especially in the long term (Rashiddadash *et al.* 2014, Nematzadeh and Fallah-Valukolaee 2017). Silica fume is a type of pozzolan capable of improving the bond strength between the cement paste and aggregate grains. It reacts with calcium hydroxide produced by a weak cement hydration to form a higher amount of cementitious materials in the mix and decrease permeability (Hasan-Nattaj and Nematzadeh 2017). Recently, researchers and engineers in the field of concrete technology have considered nanosilica as an attractive new additive. It is able to increase the compressive strength of the hardened cement paste especially at early ages. In addition, it can significantly reduce the concrete pores. Research has shown that the pozzolanic activity of nanosilica is much higher than that of silica fume, and regarding the ultrafine size of nanosilica particles, it can achieve a more uniform distribution throughout the cement paste and thus increase the hydration rate (Li *et al.* 2004, Jalal 2014, Zhang *et al.* 2016).

Also, using pozzolan can lead to a reduced cement production which in turn leads to a lower CO_2 emission level. Fly ash (FA) is another recycled material obtained as a byproduct of burning coal and provides benefits including an improved long-term compressive strength and a reduced amount of water required for concrete mixing (Kurda *et al.* 2017, Mahdavi et al. 2018), and it also leads to an improved workability and reduced permeability, hydration heat, creep, and thermal expansion of concrete (Wang *et al.* 2017).

It is generally believed that the degradation mechanism of concrete under elevated temperatures is controlled by two main factors (Peng *et al.* 2006): (i) an increased vapor pressure due to moisture evaporation and (ii) the formation and propagation of cracks developed due to thermal stresses appeared as a result of temperature differences between different locations in concrete (e.g. surface and core). Since the moisture levels and aggregate constituents are completely different between conventional concrete and recycled aggregate concrete, the effects of these two factors must also be different between the two concrete types. Therefore, the performance of recycled aggregate concrete during and after exposure to heat is of particular interest and requires further research (Cree *et al.* 2013).

When a concrete structure experience extreme fire for a prolonged period of time, severe concrete degradation occurs followed by structural damage. This damage also affects the structural steel, which may ultimately lead to structural collapse that has clear consequences from the loss of life to significant economic costs. The cement paste plays a key role in the structural stability after a fire.

Concrete damage in a fire is due to the degradation of Portland cement hydrates, affecting the concrete properties. Contrary to the Portland cement concrete, it has been claimed that in the concrete containing active alkali materials (e.g. concretes containing active pozzolans), elevated temperatures can lead to a partial melting of the concrete constituents, which may have a significant effect on the compressive strength (Bakharev 2006, Fernández-Jiménez *et al.* 2008, Fernández-Jiménez *et al.* 2010, Martin *et al.* 2015, Saavedra and de Gutiérrez 2017, Nematzadeh and Baradaran-Nasiri 2017, Nematzadeh and Mousavimehr 2019). Martin *et al.* (2015) studied the behavior of alkaline cements based on fly ash activated by sodium silicate and sodium hydroxide solutions in comparison with the behavior of ordinary Portland cement (OPC). The researchers reported that the strength loss of active alkaline specimens at temperatures above 600°C was significantly lower than that of the OPC specimens. Saavedra and de Gutiérrez (2017) investigated the performance of geopolymer concrete containing fly ash after exposure to elevated temperatures, and showed that the active alkaline concrete specimens containing fly ash and granulated blast furnace slag had the lowest compressive strength reduction at 700°C, confirming a higher stability of these specimens. Mousa (2015) addressed the effect of elevated temperatures on the properties of high-strength concrete containing silica fume and recycled tire rubber. Their results indicated that the residual strength of the concrete specimens with 20% silica fume at 800°C was around five times that of the specimen lacking silica fume. Moreover, using silica fume led to a reduced thermal expansion of the concrete specimens, which in turn led to a decreased trend of crack development. Bastami et al. (2014) studied the mechanical properties of high-strength concrete modified with nanosilica exposure to elevated temperatures. Their results demonstrated that nanosilica used in high-strength concrete can improve its mechanical properties at elevated temperatures so that the presence of nanosilica increased residual compressive and tensile strengths while spalling and mass loss decreased. Khan and Abbas (2015) examined the behavior of high volume fly ash concrete at varying peak temperatures ranging from 100 to 900°C. Their findings showed that the loss of weight of the concrete increased with increase in the temperature as well as the fly ash content. Moreover, for a given temperature, the compressive strength of concrete decreased more for concrete containing higher fly ash content.

Based on the above discussion, the present work was aimed at investigating the effect of the type and content of cement-replacing pozzolans as well as the effect of aggregate type (natural or recycled refractory brick) used in the concrete on its behavior under elevated temperatures. Here, 126 cubic specimens were made using 14 different mix designs to examine the compressive strength, ultrasonic pulse velocity, and weight loss of the concrete specimens at temperatures of 23, 400, and 800°C. The pozzolans employed in this study include nanosilica, silica fume, and ultrafine fly ash, with the cement-replacement levels of 0, 7.5, and 15% for the silica fume and ultrafine fly ash and 0, 2, and 4% for the nanosilica in the concrete mixes under study.

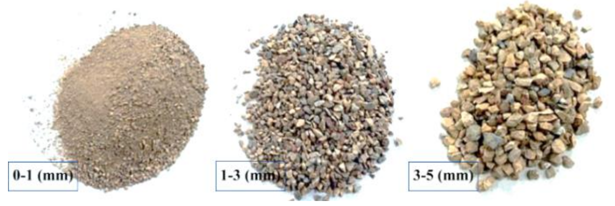

Fig. 1 Different grain sizes of refractory brick aggregate

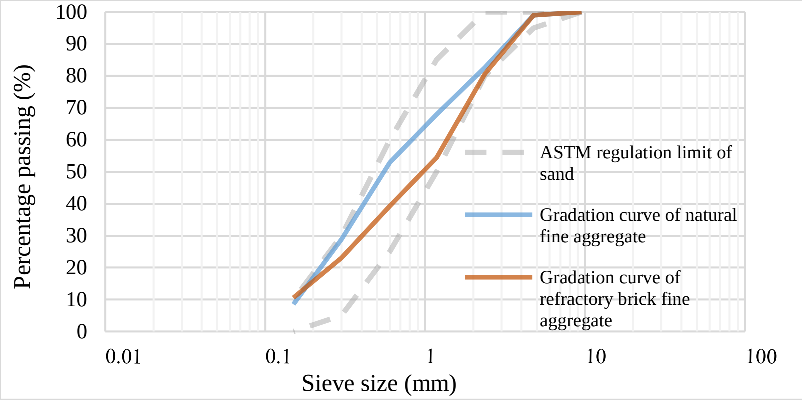

Fig. 2 Grading curves of natural and recycled refractory brick fine aggregates

Table 1 Characteristics of cementitious materials and recycled refractory brick fine aggregate

Composition	Portland cement (CEM-I 42.5N)	Silica fume	Nano-silica	Ultrafine fly ash	Recycled Refractory brick
SiO_2 (%)	20.6	93	≥98	65.8	52
Al_2O_3 (%)	4.86	1.7	0.076	23.9	40
Fe_2O_3 (%)	3.37	1.2	0.293	4.4	1.5
CaO (%)	63.56	0.3	0.392	1.6	0.5
MgO (%)	2.18	1	0.05	0.8	0.3
Loss on Ignition (%)	2.2	0.4-3	-	0.3	-
Refractoriness (°C)	-	-	-	-	1700

Table 2 Carboxal HF5000 superplasticizer properties

Form	Aqueous solution of modified Poly-carboxylates
Appearance	Viscous liquid
color	Transparent or milky
Subsidiary effect	Hardening accelerator and high range water reducer
Solid value (%)	40 ± 0.02
pH	6-8

2. Experimental study

2.1 Materials

In this study, the materials used to prepare the mix designs included Type I Portland cement, recycled refractory brick (RRB) fine aggregate, natural fine aggregate, and the pozzolans of nanosilica (NS), silica fume (SF), and ultrafine fly ash (UFA). The nanosilica used in this study was the grade F-110 amorphous type, provided from Fadak Group, Isfahan, Iran. The silica fume was of MK.A102 type with an amorphous structure, provided from Mokamelkaran Co., Tehran, Iran, with the super fly ash provided from Clinicbeton Co., Tehran, Iran. Moreover, the superplasticizer used here had been provided from Capco Co. Tehran, Iran.

Type I Portland cement (CEM-I 42.5N) supplied from a local source was used for all the mix designs of this work. This cement type has a setting time similar to ordinary Portland cement (ASTM Type-I). Table 1 presents the properties of this cement type.

The concrete prepared here lacked coarse aggregate, and the fine aggregates used included natural sand and RRB fine aggregate, with the fineness modulus of 2.60, water absorption of 1.73%, specific gravity of 2.63, and maximum grain size of 4.75 mm for the natural sand. In addition, RRB fine aggregate was added in the mixes with different grades ranging from 0.15 to 4.75 mm with the grading in compliance with the ASTM C33 standard (2003). With respect to the tests performed on the crushed bricks, the specific gravity and water absorption were obtained as 2.61 and 2.18%, respectively. Moreover, the properties of crushed refractory brick aggregate are given in Table 1, with photos of different grades of the RRB fine aggregate shown in Fig. 1. Furthermore, the grading curve of the natural sand and RRB fine aggregate is plotted in Fig. 2.

The SF and UFA pozzolans were added in the concrete mixes with cement-replacement levels of 0, 7.5, and 15%, and NS with cement-replacement levels of 0, 2, and 4%. Fly ash consists of spherical particles with a smooth surface, which improve workability and reduce water demand (Chindaprasirt *et al.* 2010). In general, the size of fly ash particles varies in the 1-10 μm range, and in the current work, fly ash with a 3 μm particle size was selected. However, the size of SF and NS particles was 0.23 and 0.025 μm, respectively. Additionally, the fly ash used here is an F class type under the commercial name “pozzocrete 100”. The chemical constituents of the cement, SF, NS, provided by the manufacturers, and UFA, determined using an X-ray analysis, are shown in Table 1.

To preserve concrete workability in most of the mix designs used here, a polycarboxylate ether-based superplasticizer with a trade name of Carboxal HF5000 having a 40% solid content and specific gravity of 1.1 g/cm^3 was used as a fraction of all cementitious materials. Based on ASTM C494 (2016), it is a Type F superplasticizer with properties shown in Table 2.

2.2 Determining mix proportions

Here, a total of 126 specimens were made using 14 concrete mixes. Half of the mixes were prepared with RRB

Table 3 Concrete mix proportions

Mix no.	Specimen ID	Water -Binder ratio (W/B)	SP* (%)	Mix proportions (kg/m^3) Cement	Silica fume	Nano silica	Ultra-fine fly ash	Water	Fine aggregate (SSD) Natural	Fine aggregate (SSD) Recycled
1	Plain-N	0.55	0.0	500	0	0	0	275	1400	0
2	NS 2-N	0.55	1.5	490	0	10	0	275	1400	0
3	NS 4-N	0.55	3.2	480	0	20	0	275	1400	0
4	SF 7.5-N	0.55	1.5	462.5	37.5	0	0	275	1400	0
5	SF 15-N	0.55	3.5	425	75	0	0	275	1400	0
6	UFA 7.5-N	0.55	0.0	462.5	0	0	37.5	275	1400	0
7	UFA 15-N	0.55	0.0	425	0	0	75	275	1400	0
8	Plain-R	0.55	3.0	500	0	0	0	275	0	1415
9	NS 2-R	0.55	4.5	490	0	10	0	275	0	1415
10	NS 4-R	0.55	7.0	480	0	20	0	275	0	1415
11	SF 7.5-R	0.55	4.5	462.5	37.5	0	0	275	0	1415
12	SF 15-R	0.55	6.5	425	75	0	0	275	0	1415
13	UFA 7.5-R	0.55	3.0	462.5	0	0	37.5	275	0	1415
14	UFA 15-R	0.55	3.0	425	0	0	75	275	0	1415

*Superplasticizer as a percent of binder weight

fine aggregate (100% of the fine aggregate content) and different cement-replacement levels of NS, SF and UFA pozzolans, while the other half were prepared with natural fine aggregate (100% of the fine aggregate content) and different levels of the pozzolans. The levels at which the pozzolans replaced cement in the mixes were considered to be 0, 2, and 4% by the cement weight for NS and 0, 7.5, and 15% for SF and UFA in the present work.

The water-to-cementitious materials (binder) ratio was 0.55, and the fine aggregate content was the same for all the mix designs; thus they were excluded from the analysis of results as factors affecting data variations, which in turn led to a more accurate comparison of the effect of pozzolans on concrete parameters after exposure of elevated temperatures. Table 3 provides details on all the concrete mix designs. The slight difference seen between the fine aggregate contents of the refractory and normal (with natural sand) concrete mixes is due to different specific gravities of RRB aggregate and natural sand.

Since the workability of concrete specimens containing crushed refractory brick is affected by the water absorption level of RRB aggregate, the RRB aggregate used in this study was soaked to reach its water absorption level, and thus its grains achieved the saturated surface dry (SSD) condition 24 h prior to making the concrete. In addition, since contrary to coarse aggregate grains, it is not feasible to dry the surface of fine aggregate grains after soaking them in water, the RRB fine aggregate was put in plastic sheets and then kept there for 24 h, according to the method first proposed by Khalaf *et al.* (2004, 2005).

The mix proportions of concrete are given in Table 3, where the names assigned to each mix design group, except for the pozzolan-lacking one, are consisted of three parts; the first two letters represent the pozzolan type, with the following number indicating the replacement level of the used pozzolan. For example, NS 4 is a specimen containing 4% nanosilica. The pozzolan-lacking specimens are specified by "Plain." In the final part of the names, letters N and R represent natural and recycled refractory brick aggregates, respectively. In this manner, NS 4-R is a specimen containing 4% nanosilica and 100% RRB fine aggregate, and Plain-N is a pozzolan-lacking concrete specimen containing 100% natural fine aggregate.

2.3 Manufacturing specimens

To prepare the concrete mix, the aggregate and cement were first blended together in a dry state for 1 min, and in the mixes with a pozzolan, it was also blended with the cement and aggregate in this step. Then, water and the superplasticizer were added to the initial mix in a gradual manner, and the mixing continued for 5 more minutes. Finally, the fresh concrete mix was cast in 10×10 cm cubic molds. From each mix design, three identical specimens were made for each exposure temperature. The specimens were removed from the molds 24 h after casting the concrete and then cured in a water container at 23°C and moisture level of 100% for 28 days in accordance with the ASTM C192 (2002) specifications. The next step included the removal of the specimens from water and keeping them in the laboratory environment for 6 days to become air-dried. Subsequently, the air-dried specimens were exposed to 110°C in an oven for 24 h to become oven-dried before testing. The specimens were then heated up to 400 and 800°C in a furnace and then cooled to reach ambient

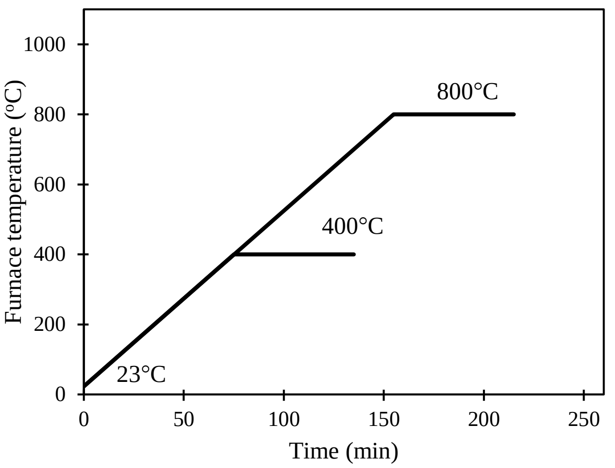

Fig. 3 Heating regimes inside electric furnace applied to concrete specimens

temperature. Finally, the specimens were put through some tests to determine the compressive strength, weight loss, and ultrasonic pulse velocity.

2.4 Thermal treatment

Each group of the concrete specimens was examined at three thermal levels of 23, 400, and 800°C; the former was considered as ambient (reference) temperature and the latter two were regarded as elevated temperatures to investigate the variation of the concrete parameters after exposure to these temperatures. The specimens intended for exposure to elevated temperatures were placed inside an 800×800×800 mm vertical electric furnace, and after reaching the target temperature, all groups (three specimens for each group for the averaging purpose) were kept at that temperature for one hour (Cheng *et al.* 2004, Arioz 2007, Sarhat and Sherwood 2012, Baradaran-Nasiri and Nematzadeh 2017). Internal thermocouples were responsible for recording the temperature inside the furnace, and the thermal load could be adjusted. In this work, the thermal loading rate was selected as 5°C/min, as shown in Fig. 3. After the thermal treatment completion, the specimens stayed in the furnace to reach ambient temperature. Immediately after reaching ambient temperature, the compression testing was conducted at this temperature. Note that all the specimens that experienced temperatures of 400 and 800°C had already experienced 23 and 110°C.

2.5 Tests on hardened concrete

To evaluate and compare the concrete specimens after thermal treatment, their physico-mechanical properties including compressive strength, ultrasonic pulse velocity (UPV), and weight loss at different temperatures were determined. Moreover, changes in the surface appearance of the specimens after exposure to elevated temperatures were also examined visually.

The compression testing of the concrete specimens was conducted based on the specifications of the BS 1881-116 (1983) standard. Axial loading was applied on the concrete specimens using a 200-ton hydraulic jack immediately after the temperature of the thermally-treated specimens reached ambient temperature. A constant compressive loading rate of 0.25 MPa/s being within the associated standard range (0.2 ± 0.4 MPa/s) was considered for all the specimens.

Fig. 4 Ultrasonic pulse test apparatus and attachment of transducers to surface of specimens

The nondestructive ultrasonic pulse velocity (UPV) test was conducted on the cubic specimens according to ASTM C597 (2016) after a curing period of at least 28 days and before the compression testing. In this test, the transmission velocity of an ultrasonic pulse is obtained using the direct transmission method, being more precise than other two methods (indirect and semi-direct) specified in the ACI 228.2R (2004). The UPV experiment was conducted using a portable tester (PUNDIT, Model PC 1012) shown in Fig. 4, and the results of the identical specimens were averaged and reported. To ensure a proper attachment of the transducers to the specimen surface and also to facilitate the transfer of the ultrasonic energy from the transducer to the test specimen, a thin layer of refractory grease was applied on the specimen surface.

3. Results and discussion

The objective of this research was to examine the effect of RRB fine aggregate as well as the type and level of some cement-replacing pozzolans on the post-fire properties of hardened concrete. For this purpose, as discussed above, 14 mix designs were prepared, and the compressive strength, weight loss and UPV of all the specimens after their exposure to temperatures of 23, 400, and 800°C were determined, with the corresponding results discussed in the following sections. Here, from each of the 14 mix design groups, the specimens that only experienced 23°C were considered as the reference specimens, and the results obtained for other specimens were compared with those of the corresponding reference specimen.

3.1 Compressive strength

The mean compressive strength of the three identical specimens of each concrete mix made from RRB and natural fine aggregates and containing NS, SF, and UFA was obtained via the compression tests and presented in

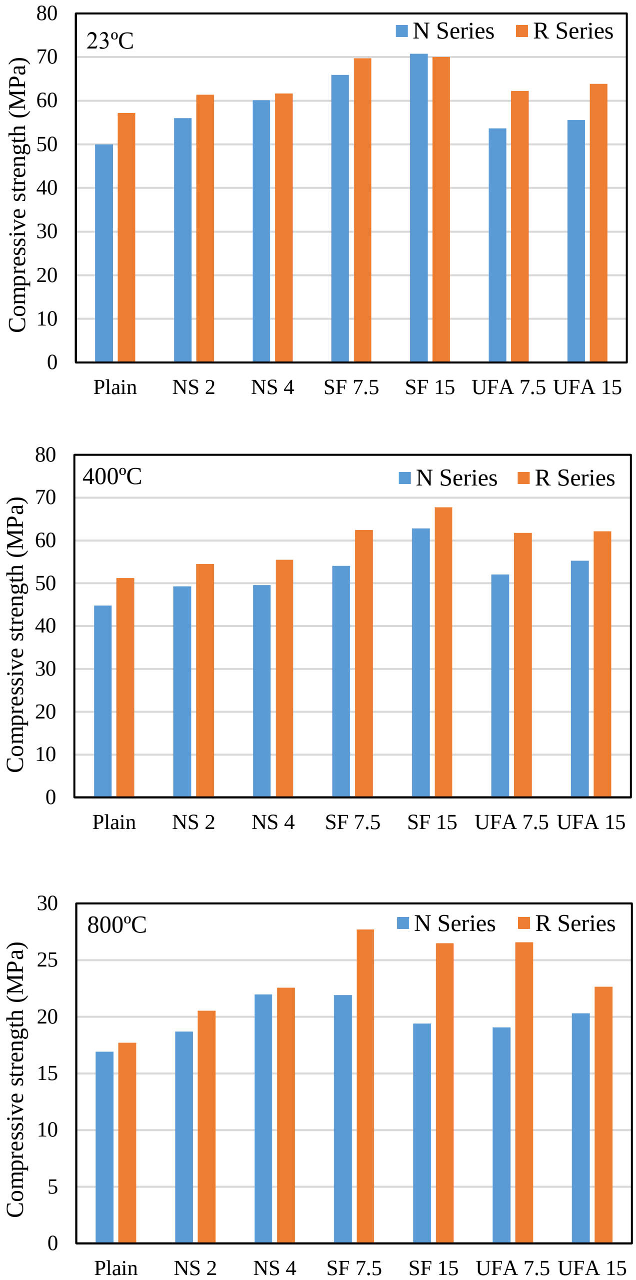

Fig. 5 Effect of different types of fine aggregate on compressive strength for each thermal group

Figs. 5 and 6. Furthermore, Table 4 lists the compressive strength values together with the coefficient of variation (COV) values for all the specimens. With respect to the results at ambient temperature, the highest and lowest mean compressive strength values pertain to the SF 15-N and Plain-N mixes as 70.7 and 50 MPa, respectively. As can be seen in Fig. 5, using 100% RRB fine aggregate led to an increased compressive strength, with the exception being the SF 15 mix for which the compressive strength of the RRB-containing specimen decreased relative to that of the natural fine aggregate-containing specimen by around 1%. In general, at ambient temperature, the highest strength improvement values due to RRB fine aggregate usage were obtained for the UFA 7.5 and UFA 15 specimens as 16 and 15%, respectively, suggesting a better behavior of the UFA pozzolan in combination with RRB fine aggregate. Inaddition, for the plain concrete mixes (lacking pozzolan), replacing natural sand with RRB led to a 14.4% enhancement of the mean compressive strength.

As the temperature raised to reach 400°C, the mean values of compressive strength saw a reduction for all the concrete mixes. With respect to the results reported in Table 4, the highest and lowest mean compressive strength values in the mixes containing RRB fine aggregate pertain to the SF 15 and Plain mixes as 67.7 and 51.2 MPa, respectively.

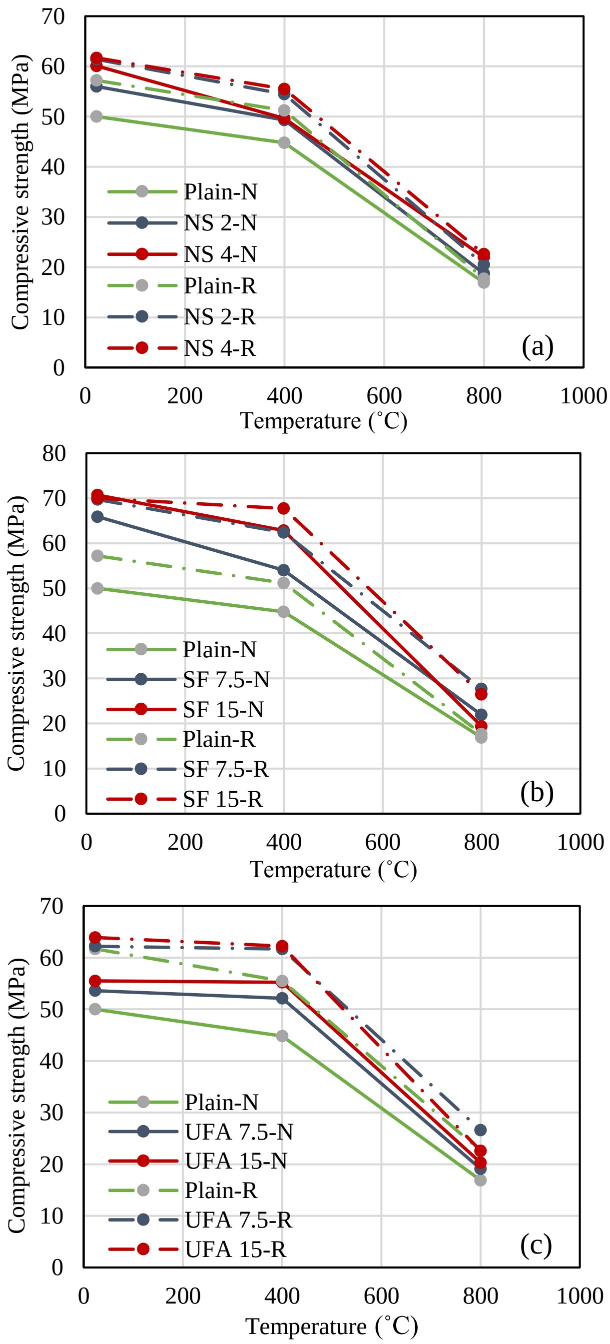

Fig. 6 Effect of different pozzolan types on compressive strength; (a) nanosilica, (b) silica fume, and (c) ultrafine fly ash

Table 4 Compressive strength results

Mix No.	Specimen ID	23ºC		400ºC		800ºC	
		Mean (MPa)	COV (%)	Mean (MPa)	COV (%)	Mean (MPa)	COV (%)
1	Plain-N	50	4.2	44.8	0.9	16.9	6.2
2	NS 2-N	56	0.9	49.3	1.6	18.7	4.8
3	NS 4-N	60.1	4.5	49.6	1.1	22	6.8
4	SF 7.5-N	65.9	5.3	54	6.5	21.9	4.7
5	SF 15-N	70.7	4.9	62.8	6.3	19.4	3.4
6	UFA 7.5-N	53.6	5.1	52.1	0.6	19.1	6.6
7	UFA 15-N	55.5	1.4	55.2	0.7	20.3	6.8
8	Plain-R	57.2	0.6	51.2	4.6	17.7	3.9
9	NS 2-R	61.4	3.0	54.5	6.1	20.5	7
10	NS 4-R	61.7	3.0	55.5	4.1	22.6	2.2
11	SF 7.5-R	69.7	4.7	62.4	3.2	27.7	3.8
12	SF 15-R	70	2.0	67.7	3.6	26.5	1.7
13	UFA 7.5-R	62.2	0.6	61.7	1.2	26.6	2.7
14	UFA 15-R	63.9	1.9	62.2	0.7	22.6	6.7

However, the corresponding values in the mixes containing natural fine aggregate also belong to the SF 15 and Plain mixes as 62.8 and 44.8 MPa, respectively. This indicates that for both fine aggregate types, using SF replacing 15% of the cement weight had the best performance relative to other mixes. At ambient temperature, this pozzolan also recorded the highest values with both fine aggregates. Furthermore, as shown in Fig. 5, using 100% RRB fine aggregate led to an improved compressive strength in all the mixes relative to using natural fine aggregate, contrary to what seen at ambient temperature.

In general, at 400°C, the greatest strength increase due to the usage of RRB fine aggregate was obtained for the SF 7.5 specimens with a mean increase of 18%, and UFA used in combination with RRB showed once again a better overall performance for this temperature; hence, a positive influence of brick fine aggregate on the thermal performance of this pozzolan is seen. Additionally, for the plain concrete mixes (without pozzolan), using RRB fine aggregate resulted in a 14% improvement in the mean compressive strength relative to using natural fine aggregate.

At 800°C and regarding further temperature increase, the mean compressive strength of all the concrete mixes saw a reduction, with a rate greater than that at 400°C. Regarding the results presented in Table 4, at this temperature, the highest and lowest mean compressive strength values in the RRB-containing groups belong to the SF 7.5 and Plain mixes as 27.7 and 17.7 MPa, respectively. In addition, in the groups containing natural fine aggregate, the NS 4 and Plain mixes show the highest and lowest mean strength values of 22 and 16.9 MPa, respectively. Moreover, as can be seen in Fig. 6, all the concrete mixes containing RRB fine aggregate demonstrated an improved compressive strength. In general, the highest strength improvement due to using RRB fine aggregate instead of natural fine aggregate occurred for the UFA 7.5 specimens as 39%,

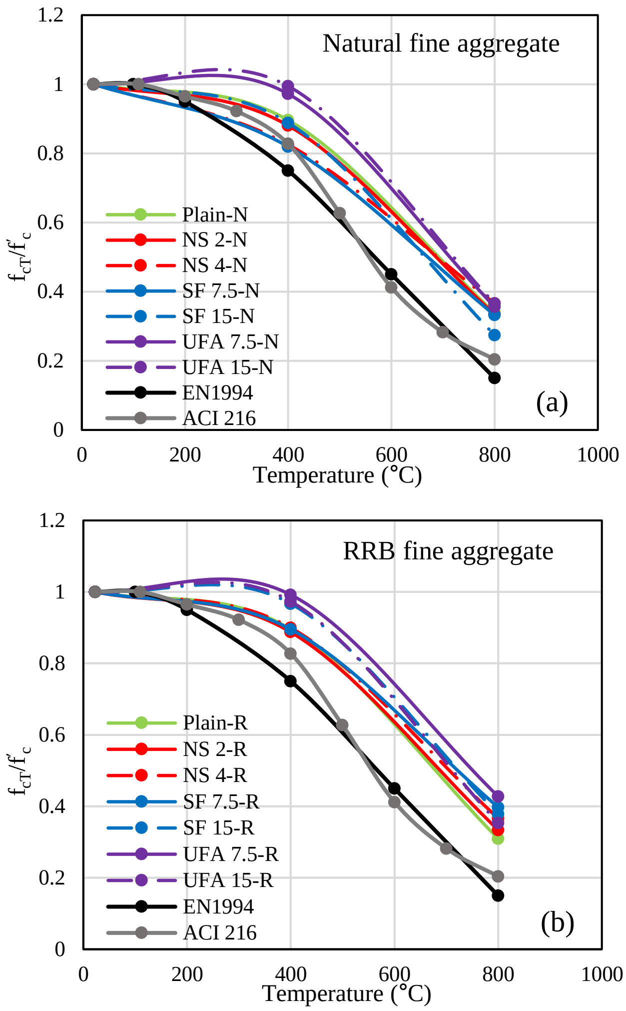

Fig. 7 Normalized compressive strength of concrete as a function of temperature; (a) mixtures containing natural fine aggregate and (b) mixtures containing RRB fine aggregate

showing once again a better combined performance of UFA and RRB fine aggregate and suggesting a positive influence of brick fine aggregate on the thermal behavior of this pozzolan at all temperatures. In addition, in the plain (pozzolan-lacking) concrete mixes, the usage of RRB fine aggregate increased the mean compressive strength relative to using natural fine aggregate by 5%.

Altogether, the application of RRB fine aggregate instead of natural fine aggregate was desirable for the concretes exposed to heat, in that 3 out of 14 mixes showed a mean compressive strength improvement of over 25% at 800°C. The COV of the specimens was less than 7% for all the prepared mixes, with values varying from 0.6 to 7% for different thermal groups.

The individual effect of each pozzolan type on the concrete mixes is shown in Fig. 6. As can be observed in Fig. 6(a), using NS with a cement-replacement level of 4% together with RRB fine aggregate yielded a better thermal performance at all the temperatures compared with the replacement level of 2%. In addition, a similar trend was also seen for the case of using this pozzolan with natural fine aggregate, with a higher compressive strength for the higher level of cement-replacement. With increasing temperature up to 800°C, the compressive strength reduction of the mixes containing 2 and 4% NS for both fine aggregate types was 63 and 67%, respectively, indicating a similar performance of this pozzolan with both fine aggregates.

Regarding Fig. 6(b), using 15% SF led to a better thermal performance at all the temperatures relative to the replacement level of 7.5% for both fine aggregate types (except for the SF 15 mix at 800°C). It can be said that a higher cement-replacement level of SF leads to an improved compressive strength as temperature increases, and the usage of higher contents of this pozzolan is recommended for concrete specimens. It is also seen that for the SF-containing mixes, as temperature increases, the compressive strength shows a 6-10% lower reduction in the specimens with RRB fine aggregate relative to the ones with natural fine aggregate; this indicates that the employment of this pozzolan in combination with RRB fine aggregate gives higher compressive strength values while at the same time reducing the loss of compressive strength with temperature relative to the case with natural fine aggregate.

As can be seen in Fig. 6(c), using UFA at a replacement level of 15% showed a better thermal performance compared with the replacement level of 7.5% for both fine aggregate types at all the temperatures (except for the RRB fine aggregate at 800°C). This suggests that this pozzolan can be used at a higher replacement level for future works addressing the effect of elevated temperatures on concrete.

In order to present a general comparison among the mixes containing pozzolans, it can be said that as the temperature increased up to 400°C, the lowest mean strength loss (of four mixes containing the same pozzolan type) occurred for UFA as 1.7%, while the mean compressive strength loss value for SF at this temperature was greater. In addition, with temperature increase from 400 to 800°C, the mean loss values of the pozzolan-containing mixes became very close to one another such that their compressive strength loss values could not be clearly separated; however, considering the mean residual compressive strength values for the mixes containing SF at 800°C, the employment of this pozzolan especially in combination with RRB fine aggregate can be more appropriate. Hence, it is safe to say that among the pozzolans used in the present work, SF demonstrates the best performance in terms of retaining the compressive strength of concrete exposed to heat.

The normalized compressive strength of concretes with siliceous aggregate as a function of temperature as proposed by the EN 1994-1-2 (2004) and ACI 216 (1989) codes is presented in Fig. 7. It is worth noting that the curves presented by EN 1994-1-2 (2004) and shown in the figure pertain to heated concretes cooled at room temperature, and thus they are different from the curves proposed by EN 1992-1-2 for heated concretes without cooling.

It can be seen in Fig. 7 that the experimental results of the specimens containing natural fine aggregate are closer than those of the specimens containing RRB fine aggregate to the curves proposed by the two above codes prior to 400°C, beyond which, however, the test results of all the specimens move apart from the prediction curves. It is also seen that the equation proposed by EN 1994-1-2 provides a good estimation for the normalized compressive strength results of the mixes containing natural fine aggregate up to around 250°C (except for the mix containing UFA), while above which, the experimental results of all the mixes move apart from the EN 1994-1-2 values, and the values predicted by this code underestimate the experimental values for all the mixes (see Fig. 7(a)). Moreover, ACI 216 provides a proper estimation for the normalized experimental compressive strength results of the mixes containing natural fine aggregate below 400°C (except for the mix containing UFA). However, as the temperature increases above this limit, it is seen that the predictions of ACI 216 underestimate the normalized compressive strength results of the tests conducted on the specimens containing natural fine aggregate. For the specimens containing RRB fine aggregate, as can be is in Fig. 7(b), the predictions of the ACI 216 and EN 1994-1-2 codes are close to the experimental results below 200°C (except for the mix containing UFA), while above which the predictions become smaller than the experimental values.

Using the nonlinear regression analysis, the relationship of the normalized compressive strength (f_{cT} /f_c') with parameters of temperature (T) and the replacement level of pozzolan by the cement weight (R_P) for the mixes containing the pozzolans of NS, SF, and UFA together with natural and RRB fine aggregates is expressed as Eq. (1). Parameter a, being dependent on the cement weight-replacement level of pozzolan, is defined as a_N for the groups containing natural fine aggregate and a_R for the ones with RRB fine aggregate, as presented in the equation. In addition, parameter β being dependent on temperature is defined as β_N and β_R for the groups containing natural fine aggregate and RRB fine aggregate, as expressed in Eq. (1). The coefficient of determination (R^2) of the equation was obtained as 0.98 and 0.97 for the mixes containing natural and RRB fine aggregates, respectively, demonstrating a good regression of the experimental results.

$$\frac{f_{cT}}{f_c'} = a \Big/ 1+e^{\beta}$$
$$\begin{aligned} a_{N1} &= 5.01 R_P^{\ 2} - 0.52 R_P + 1.01 \\ \beta_{N1} &= -4.77 + 0.007T \\ a_{R1} &= -17.08\, R_P^{\ 2} + 2.85\, R_P + 1 \\ \beta_{R1} &= -4.87 + 0.0069T \\ & 23^\circ C \le T \le 800^\circ C \\ & 0 \le R_P \le 0.15 \end{aligned} \tag{1}$$

In the above equation, f_c' and f_{cT} are the compressive strength of each concrete mix at ambient and elevated temperatures, respectively.

3.2 Loss of weight

The weight of the specimens before and after exposure to heat was measured to evaluate the weight loss of each group

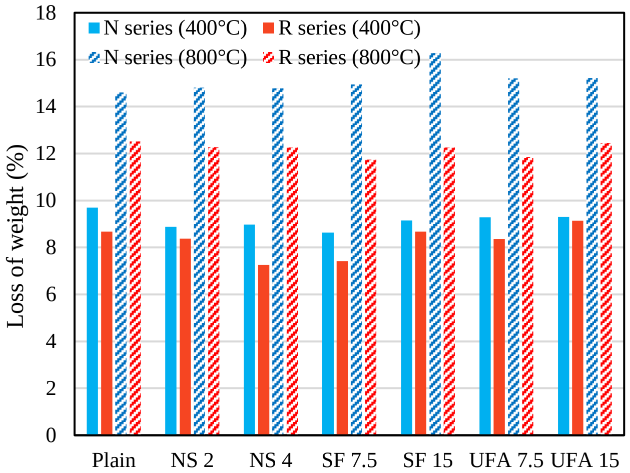

Fig. 8 Loss of weight of mixtures exposed to elevated temperatures

of concrete specimens. Fig. 8 shows the weight variation of different concrete specimens at temperatures of 400 and 800°C relative to that at ambient (reference) temperature. It is seen that as temperature increases, so does the weight loss, attributed to the loss of free water, chemical composition water, and other factors; therefore, an increase in the weight loss of all the concrete mixes with increasing temperature is seen. The experimental results of this study showed that at 400°C, using 100% RRB fine aggregate reduced the weight loss of the specimens for all the associated mixes and had a positive effect on the integrity of concrete, thus it can be said that by using RRB fine aggregate, concrete specimens record lower weight loss values relative to the case of using natural fine aggregate. Note that the weight loss extremes of the specimens containing natural fine aggregate were 8.6 and 9.7% for the SF 7.5 and Plain mixes, respectively, while these values for the specimens containing RRB fine aggregate were 7.3 and 9.1% for the NS 4 and UFA 15 mixes, respectively (see Fig. 8).

It is observed in Fig. 8 that at 800°C, using 100% RRB fine aggregate leads to a decrease in the weight loss trend of the concrete specimens, similar to the case at 400°C but with greater weight loss reduction values. In addition, it can be said that via the application of RRB, the concrete specimens record a smaller weight loss values at all the temperatures compared with natural fine aggregate. Note that the weight loss of the specimens containing natural fine aggregate varied in the 14.6-16.3% range, with the upper and lower values for the Plain and SF 15 mixes, respectively, while the loss for RRB fine aggregate varied in the 11.7-12.5% range, with the upper and lower values for the SF 7.5 and Plain mixes, respectively.

Fig. 8 also shows the effect of the pozzolan type used in the concrete mixes on the weight loss level of each mix. As can be seen, at 400°C, using NS with a replacement level of 4% leads to a weaker thermal performance in the mixes containing natural fine aggregate and a better performance in the mixes containing RRB fine aggregate relative to a replacement level of 2%. However, at 800%, the higher replacement level of this pozzolan (4%) has no particular effect on the weight variation.

In addition, the SF replacement level of 15% led to higher weight loss values relative to the replacement level of 7.5% for both fine aggregate types at 400°C. As temperature increased up to 800°C, a similar trend was seen, with a greater weight loss for the higher replacement level.

Furthermore, at 400°C, compared with the 7.5% replacement level of UFA, using the 15% replacement level led to an almost similar thermal performance in the mixes containing natural fine aggregate and a weaker (around 0.7%) thermal performance in the mixes containing RRB fine aggregate. However, the effect of the higher replacement level of this pozzolan at 800°C was almost similar to that at 400°C, with almost no difference in the mixes with natural fine aggregate and a weaker performance in the mixes containing RRB fine aggregate. At the end, it can be said that contrary to what previously seen for compressive strength, the performances of pozzolans, especially NS and SF, were similar in terms of the weight loss parameter, with SF showing a better mean performance at 400°C (0.25 difference relative to the mean of the NS mixes) and NS showing a better mean performance at 800°C (0.21 difference relative to the mean of the SF mixes).

3.3 Relationship between weight loss and compressive strength

The graphs in Fig. 9 show the relationship between the weight loss and compressive strength of the concrete mixes at different temperatures. As can be seen, there is a linear relationship between the losses of weight and compressive strength. By conducting the linear regression analysis on the experimental results of the two parameters, linear equations were obtained for the specimens without pozzolan and those with the NS, SF, and UFA pozzolans. Coefficients of determination for all the mixes together with relationships between the weight and compressive strength were determined and shown in the figure. The lines of best fits obtained in Fig. 9 indicate that the compressive strength loss percentage of these mixes is 3.05-4.19 times their weight loss percentage. It is found from the results that the slope of the relationship for the mixes containing NS replacing 4% of the cement weight in the natural fine aggregate groups is almost equal with the slope for the mixes containing 2% NS, while using 4% NS in the RRB fine aggregate groups leads to an increased slope for the weight loss-compressive strength loss relationship relative to using 2% NS. Moreover, a lower slope is seen for this pozzolan type when natural fine aggregate instead of RRB fine aggregate is used.

Considering Fig. 9(b), a similar trend for the weight loss-compressive strength loss relationship is observed for both fine aggregate types, with a greater replacement level leading to a smaller slope. Note that a decreased slope in this relationship is considered a desirable behavior indicating a mix with a greater compressive strength retention for its weight loss.

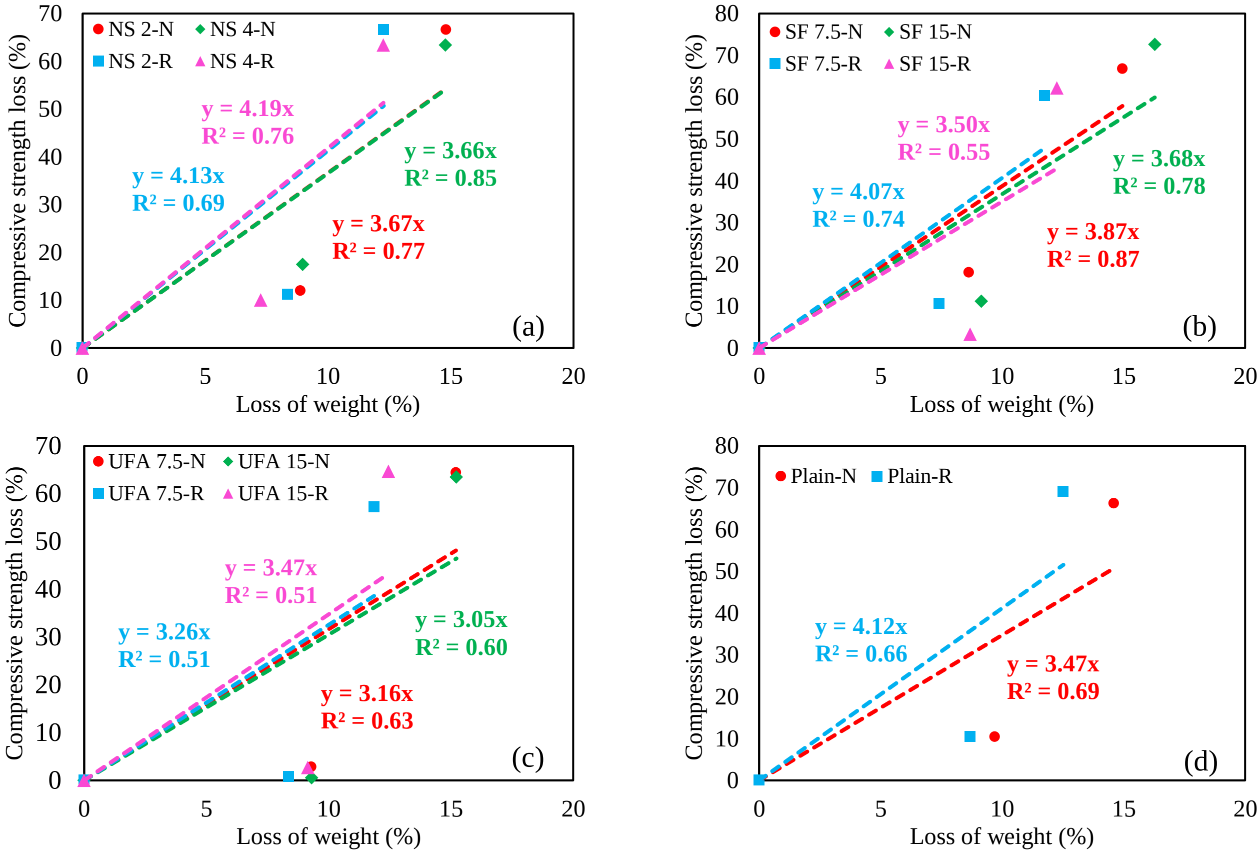

Fig. 9 Relationship between weight loss and compressive strength loss of different mixes; (a) nanosilica, (b) silica fume, (c) ultrafine fly ash, and (d) plain

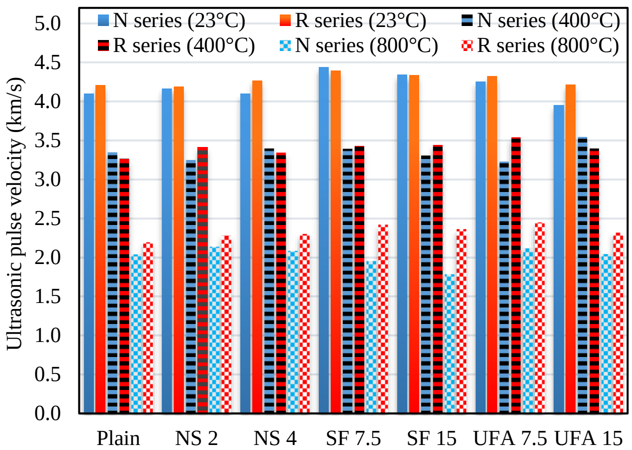

Fig. 10 Ultrasonic pulse velocity of mixes exposed to elevated temperatures

The relationship between weight loss and compressive strength loss for UFA is presented in Fig. 9(c) where it is seen that the greater pozzolan replacement level (15%) leads to a decreased slope in the mixes containing natural fine aggregate and an increased slope in those containing RRB fine aggregate. In addition, Fig. 9(d) indicates that in the pozzolan-lacking specimens, using natural fine aggregate reduces the slope of the weight loss-compressive strength loss relationship.

3.4. Ultrasonic pulse velocity

As a nondestructive test, the ultrasonic pulse velocity (UPV) test can indicate concrete defects such as non-homogeneities and cracks. In general, a higher UPV is seen in concretes with a higher quality. The mean UPV of the three identical specimens of each concrete mix made from natural fine aggregate and RRB fine aggregate and containing the pozzolans of NS, SF, and UFA was obtained and presented in Fig. 10 and Table 5. Additionally, The COV of the UPV values of all the specimens is given in the table. Since UPV is a function of the volumetric concentration of constituents (Albano *et al.* 2009), lower velocity values may indicate a smaller solid phase and a lower cementitious material production as well as more voids in a concrete specimen containing pozzolans due to inadequate mixing.

Furthermore, in grading the concrete quality (based on pulse velocity method) as proposed by the IS 13311-1 (1992) standard, four grades of excellent (E), good (G), medium (M), and poor (P) are presented, for which the UPV ranges are above 4.5, 3.5-4.5, 3.0-3.5, and below 3 km/s, respectively. Table 6 reports the quality grading of each concrete mix based on UPV at different temperatures.

Regarding the test results at ambient temperature, using 100% RRB fine aggregate to prepare pozzolan-lacking (plain) concrete led to an increase in the UPV by 2.68%, indicating a better quality of concrete containing RRB fine

Table 5 Ultrasonic pulse velocity test results

Mix no.	Specimen ID	23ºC			400ºC			800ºC		
		Mean (km/s)	COV (%)	Q*	Mean (km/s)	COV (%)	Q*	Mean (km/s)	COV (%)	Q*
1	Plain-N	4.10	1.03	G	3.35	1.09	M	2.04	2.63	P
2	NS 2-N	4.17	3.28	G	3.25	4.28	M	2.14	3.57	P
3	NS 4-N	4.10	2.77	G	3.40	4.64	M	2.08	2.71	P
4	SF 7.5-N	4.44	0.36	G	3.39	4.03	M	1.95	5.34	P
5	SF 15-N	4.34	0.90	G	3.31	3.80	M	1.78	4.72	P
6	UFA 7.5-N	4.26	0.89	G	3.23	4.27	M	2.12	4.77	P
7	UFA 15-N	3.95	3.47	G	3.54	5.58	G	2.04	3.31	P
8	Plain-R	4.21	0.70	G	3.27	3.55	M	2.19	1.60	P
9	NS 2-R	4.19	0.37	G	3.42	5.55	M	2.28	1.31	P
10	NS 4-R	4.27	0.87	G	3.35	2.98	M	2.30	5.60	P
11	SF 7.5-R	4.39	1.23	G	3.43	3.90	M	2.42	1.04	P
12	SF 15-R	4.34	2.28	G	3.44	3.93	M	2.36	2.13	P
13	UFA 7.5-R	4.32	1.03	G	3.54	4.66	G	2.45	4.17	P
14	UFA 15-R	4.22	1.63	G	3.40	2.99	M	2.32	5.21	P

*Quality of concrete based on UPV; excellent (E), good (G), medium, (M) and poor (P)

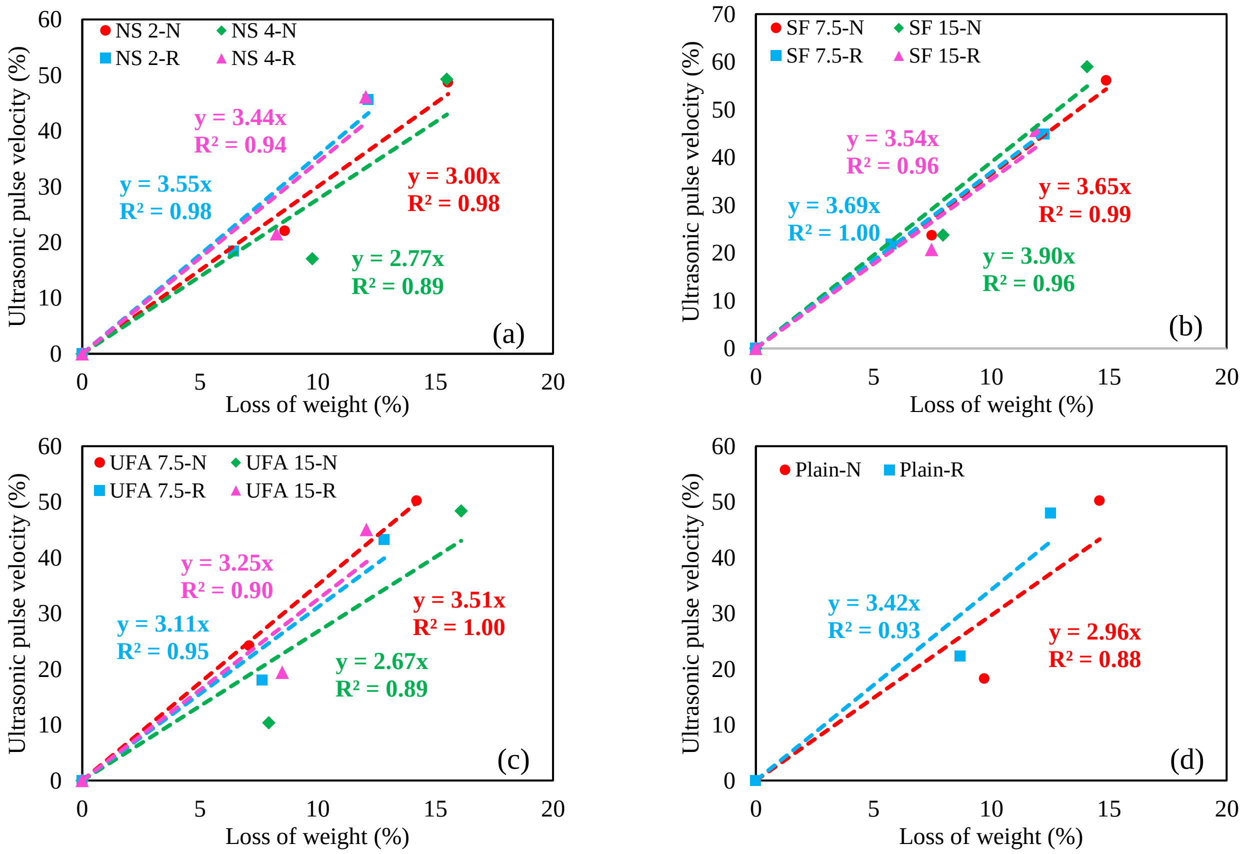

Fig. 11 Relationship between weight loss and ultrasonic pulse velocity loss of different mixes; (a) nanosilica, (b) silica fume, (c) ultrafine fly ash, and (d) plain

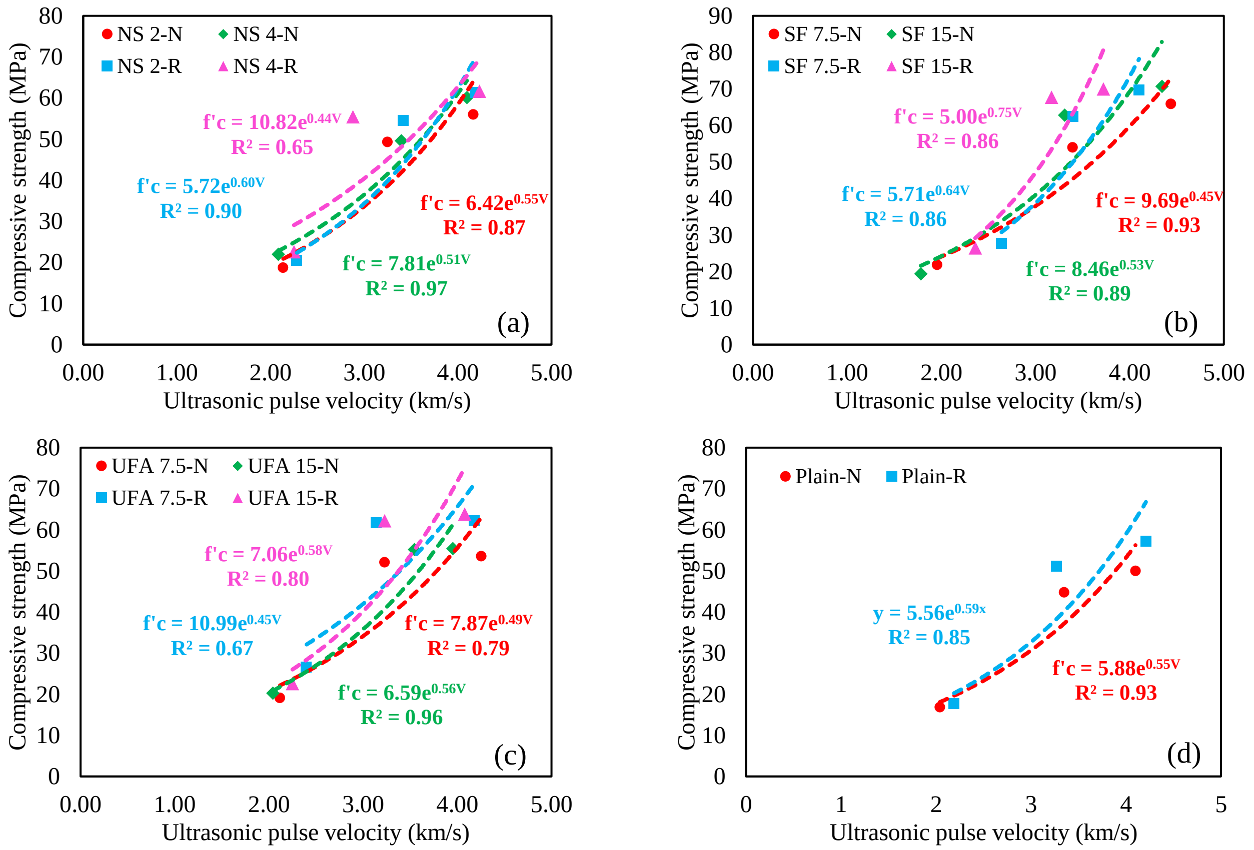

Fig. 12 Empirical relationships between compressive strength and UPV for different mixes; (a) nanosilica, (b) silica fume, (c) ultrafine fly ash, and (d) plain

aggregate compared with natural fine aggregate. To compare the performances of the two fine aggregates, the UPV range can be considered; hence, based on Table 5, UPV variation at ambient temperature for the specimens containing natural fine aggregate is in the 3.95-4.44 km/s range and for the specimens containing RRB fine aggregate in the 4.19-4.39 km/s range. Regarding the table, mean UPV values for the mixes containing natural fine aggregate (7 mixes) and the mixes containing RRB fine aggregate (7 mixes) were 4.19 and 4.28 km/s, respectively, with the best mixing quality for the SF 7.5-N mix with a UPV of 4.44 km/s. Altogether, using RRB fine aggregate increased the mean UPV value in most mixes (except for the mixes containing SF).

Fig. 10 shows the effect of the pozzolan type used in the concrete mixes on UPV. Based on the results, at ambient temperature, using NS with a replacement level of 4% in the mix containing natural fine aggregate led to a 1.65% reduction in UPV relative to a replacement level of 2%, while the higher content of this pozzolan in the mixes containing RRB fine aggregate increased UPV values by 1.92% relative to its lower content, which indicates an improvement in concrete quality and uniformity.

Furthermore, using SF in the mixes containing natural fine aggregate had an effect similar to that of using NS, and the higher pozzolan content reduced UPV by 2.18%, while in the case of the mixes containing RRB fine aggregate, as the replacement level of SF increased, a 1.29% reduction was seen in the mean UPV value relative to the lower pozzolan content. Similar to the SF case, as the replacement level of UFA in the mixes containing RRB fine aggregate increased, the mean UPV values saw a reduction, with a 2.45% reduction for the higher UFA content relative to the lower content; however, as the level of this pozzolan in the mixes containing natural fine aggregate increased, UPV saw a reduction of more than 7%.

As temperature increased to reach 400°C, UPV values showed a reduction in all the concrete mixes, indicating a higher porosity and a lower density of concrete after exposure to 400°C. At this temperature, using 100% RRB fine aggregate in the plain concrete led to a 2.39% reduction of the mean UPV value, and also, compared with the results at ambient temperature, reduction of UPV values for the plain specimens containing RRB and natural fine aggregates was 22.33 and 18.29 %, respectively. This suggests that as temperature increased up to 400°C, the concrete mix without pozzolan and containing RRB fine aggregate had a porosity increase greater than that of the mix containing natural fine aggregate. As a comparison between the effects of using the two fine aggregate types, the UPV variation at this temperature for the specimens containing natural fine aggregate was in the 3.23-3.54 km/s range, while that for the specimens containing RRB fine aggregate was in the 3.27-3.54 km/s range. With respect to Table 5, it is seen that mean UPV values for the mix group containing natural fine aggregate (7 mixes) and the mix group containing RRB fine aggregate (7 mixes) are 3.35 and 3.41 km/s, respectively, and also, the best mixing quality belongs to the UFA 15-N and UFA 7.5-R mixes with a UPV of 3.54 km/s. The effect of using RRB fine aggregate at this temperature in terms of UPV was not consistent, in that in some mixes it increased the mean UPV while in others it decreased the mean UPV.

Furthermore, Fig. 10 demonstrates that at 400°C, the usage of NS with a replacement level of 4% increases UPV by 4.57% in the mixes with natural fine aggregate, while it decreases UPV by 2.08% in the mixes with RRB fine aggregate relative to a replacement level of 2%. In addition, using SF in the mixes containing natural fine aggregate led to a performance similar to that at ambient temperature, and the higher content of the pozzolan reduced UPV by 2.33% relative to the lower content; however, in the mixes containing RRB fine aggregate, as the replacement level of SF increased, the mean UPV values increased by 0.43% (almost the same values).

The higher UFA content in the mixes containing RRB fine aggregate, contrary to the case for SF, led to a mean UPV value smaller than that for the lower UFA content, with the reduction being 4.12%, while the higher UFA content in the mixes containing natural fine aggregate increased the mean UPV value by 9.73% relative to the lower UFA content.

As temperature further increased up to 800°C, UPV values in all the concrete mixes continued their decreasing trend, and contrary to the case at the other temperatures, at this temperature being the maximum temperature limit under study, UPV values for all the RRB fine aggregate-containing mixes were obtained greater than the corresponding values for the natural fine aggregate-containing mixes. The UPV values at this temperature for the specimens with natural fine aggregate and RRB fine aggregate varied in the 1.78-2.14 and 2.19-2.45 km/s ranges, respectively. Based on Table 5, the mean UPV value for the natural fine aggregate group (7 mixes) and the RRB fine aggregate group (7 mixes) is 2.02 and 2.33 km/s, respectively, and also, the best mixing quality pertains to the UFA 7.5-R mix with the UPV of 2.45 km/s. Note that the mean loss of UPV (for 7 mixes) at 800°C relative to ambient temperature for the specimens containing natural and RRB fine aggregates was 51.77 and 45.45%, respectively; hence, it can generally be said that the application of RRB fine aggregate instead of natural fine aggregate led to a concrete with a better UPV value and higher quality especially at 800°C, with a lower loss for UPV values.

In addition, it is seen in Fig. 10 that at 800°C, using the higher contents of the NS, SF, and UFA pozzolans in the mixes containing natural fine aggregate decreases UPV by 2.52, 8.75, and 3.62%, respectively, and using the higher contents of these pozzolans in the mixes containing RRB fine aggregate decreases UPV by 0.8, 2.37, and 5.3%, respectively, relative to using the lower contents of this pozzolans. With respect to Table 5, the COVs of the test specimens for all of the prepared mixes were less than 6% and varied from 0.36 to 5.6% for different temperature groups.

3.5 Relationship between weight loss and ultrasonic pulse velocity

The relationship between the weight loss and UPV loss of the concrete mixes exposed to the elevated temperatures is shown in the graphs presented in Fig. 11, in which it can be seen that a linear relationship exists between the losses of weigh and UPV. By conducting the linear regression analysis on the experimental results of the two parameters, linear equations were obtained for the specimens lacking pozzolan and those having the NS, SF, and UFA pozzolans. A high coefficient of determination was determined for the majority of the mixes. Based on the lines of best fit shown in Fig. 11, the UPV loss of the mixes is 2.67-3.9 times their weight loss. It is found from these results that for the NS pozzolan, a replacement level of 4% by cement weight decreases the slope of the weight loss-UPV loss relationship compared with a replacement level of 2% for both fine aggregate types. Furthermore, based on Fig. 11(b), a different weight loss-UPV loss relationship is observed for each fine aggregate type, in that when using natural fine aggregate, increasing the SF replacement level increases the slope of this relationship, while when using RRB fine aggregate, as the replacement level increases, the slope decreases, suggesting a better performance of RRB fine aggregate in lowering the slope of this relationship. Note that a decrease in the slope of this relationship is regarded as a desirable behavior, indicating a mix with a higher pulse velocity when losing its weight.

The relationship between the losses of weight and UPV for the UFA pozzolan is presented in Fig. 11(c), based on which, using natural fine aggregate leads to a lower weight loss-UPV loss relationship slope for a replacement level of 15% relative to 7.5%, while using RRB fine aggregate leads to a higher relationship slope for a replacement level of 15% relative to 7.5%. In addition, Fig. 11(d) shows that in the pozzolan-lacking specimens, using natural fine aggregate increases the slope of the weight loss-UPV loss relationship, contrary to what previously observed for the weight loss-compressive strength loss relationship.

3.6 Relationship between compressive strength and ultrasonic pulse velocity

There is no specific relationship between the two parameters of UPV and compressive strength so that the former be used for determining and measuring the latter (Nik and Omran 2013). However, since the modulus of elasticity is related to the compressive strength, on one hand, and there is a relationship between UPV and the modulus of elasticity and density of concrete, on the other, there could exist a proper reason to study the concrete compressive strength based on UPV. Many researchers (Gül *et al.* 2006, Nik and Omran 2013) have shown that the relationship between compressive strength and UPV can be represented using the following exponential function (Eq. (2)),

$$f_c' = Ae^{(BV)} \tag{2}$$

where f_c' is the concrete compressive strength, V is the

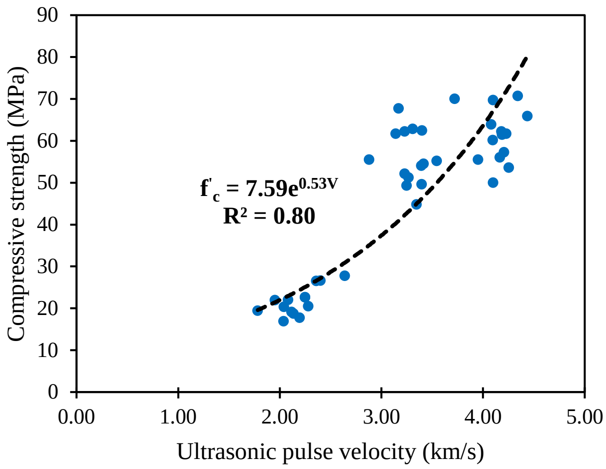

Fig. 13 General empirical relationship between compressive strength and UPV

ultrasonic pulse velocity, and *A* and *B* are empirical constants. In the current work, applying the nonlinear regression analysis, proper exponential functions for determining the compressive strength-UPV relationship of concretes containing the pozzolans of NS, SF, and UFA were determined, as shown in Fig. 13. Considering the high coefficients of determinations (R2) (except for NS 4-R and UFA 7.5-R), it is safe to say that there is a good agreement between the experimental data and the regression curves. Fig. 12 plots the relationships between the compressive strength and UPV of the concrete mixes containing the pozzolans of NS, SF, and UFA, in comparison with the experimental results.

Here, based on the nonlinear regression analysis of all the experimental results covering all the test temperatures, a general equation (Eq. (3)) governing the UPV-compressive strength relationship was determined as follows, presenting a good coefficient of determination. In Fig. 13, this equation is plotted.

$$f_c' = 7.59e^{0.53V} \qquad R^2 = 0.8 \tag{3}$$

Eq. (3) shows that at all temperatures, given just the UPV values, the corresponding values of compressive strength can be predicted appropriately, without knowing the type of fine aggregate as well as the type and replacement level of pozzolan.

4. Conclusions

This paper presented an experimental program aimed at reusing refractory brick fine aggregate as a natural fine aggregate replacement together with employing the pozzolans of nanosilica (NS), silica fume (SF), and ultrafine fly ash (UFA) in concrete. A total of 14 concrete mixes were prepared during this program, where the loss of the compressive strength, weight, and ultrasonic pulse velocity (UPV) parameters in the specimens after their exposure to temperatures of 400 and 800°C was investigated. The main results obtained in this study are as follows.

• Using 100% RRB fine aggregate increased the compressive strength of the concrete specimens in all the mixes and all the temperatures, except for the SF 15 mix at ambient temperature, for which the compressive strength of the specimen containing RRB fine aggregate saw a reduction of about 1% relative to the one containing natural fine aggregate. In addition, in the plain (pozzolan-lacking) concrete mixes, using RRB fine aggregate instead of natural fine aggregate improved the compressive strength at 23, 400, and 800°C by 14.4, 14.3, and 4.7%, respectively.

• At 400°C, the mixes containing UFA had the lowest mean compressive strength loss of 1.7%, while the mixes containing SF showed highest mean compressive strength values. With an increase in temperature from 400 to 800°C, the mean strength loss values of the mixes having pozzolans became so close to each other that they could not be differentiated. However, considering the mean values of the residual compressive strength, the usage of SF especially in combination with RRB fine aggregate was more appropriate, and it can be said that SF demonstrated the best performance.

• The equation proposed by EN 1994-1-2 provides a good estimation for the experimental results of the normalized compressive strength in the mixes containing natural fine aggregate at temperatures up to around 250°C (up to 400°C for ACI 216), above which (above 400°C for ACI 216), the prediction curves proposed by EN 1994-1-2 underestimate the experimental results for all the mixes. For the mixes containing RRB fine aggregate, the predictions of the two codes were close to the experimental results below 200°C and smaller than the experimental results above 200°C.

• As temperature increased, the weight loss of all the concrete specimens also increased. The results show that at all the temperatures, using 100% RRB fine aggregate reduced the weight loss of the concrete specimens in all the mixes and affected the concrete integrity positively. The higher replacement levels of the SF and UFA pozzolans in the mixes containing RRB fine aggregate led to an increased rate of weight loss while the higher replacement level of NS led to a decreased rate of weight loss.

• As temperature further increased to reach 800°C, the UPV values for all the concrete mixes continued to decrease, and contrary to the other temperatures, at this temperature being the maximum temperature limit tested, the UPV values of all the mixes containing RRB fine aggregate were obtained greater than those of the mixes containing natural fine aggregate.

• It is worth noting that the mean loss of UPV (for 7 mixes) at 800°C relative to that at ambient temperature for the mixes containing natural and RRB fine aggregates was 51.77 and 45.45%, respectively. Therefore, it can be concluded that the usage of RRB fine aggregate instead of natural fine aggregate results in a concrete with a better quality and a higher UPV value particularly at 800°C, with lower loss values for the UPV.

• With respect to the results obtained at 800°C, using the higher content of the NS, SF, and UFA pozzolans in the mixes containing RRB fine aggregate reduced the UPV values relative to the lower content of these pozzolans by

0.8, 2.37, and 5.3%, respectively, while in the mixes containing natural fine aggregate, the higher content of the three pozzolans also decreased the UPV values relative to the lower contents by 2.52, 8.75, and 3.62%, respectively.

References

ACI 228.2R-98 (2004), Nondestructive test methods for evaluation of concrete in structures. American Concrete Institute; Farmington Hills, MI. USA.

ACI Committee 216 (1989), Guide for determining the fire endurance of concrete elements (ACI 216R-89), American Concrete Institute; Farmington Hills, MI. USA.

Albano, C., Camacho, N., Hernandez, M., Matheus, A. and Gutierrez, A. (2009), "Influence of content and particle size of waste pet bottles on concrete behavior at different w/c ratios", *Waste Management*, **29**(10), 2707-2716. https://doi.org/10.1016/j.wasman.2009.05.007.

Arioz, O. (2007), "Effects of elevated temperatures on properties of concrete", *Fire Safety J.*, **42**(8), 516-522. https://doi.org/10.1016/j.firesaf.2007.01.003.

ASTM C192/C192M (2002), Standard practice for making and curing concrete test specimens in the laboratory, American Society for Testing and Materials; Philadelphia, PA, USA.

ASTM C33 (2003), Standard specification for concrete aggregates, American Society for Testing and Materials; Philadelphia, PA, USA.

ASTM C494 (2016), Standard specification for chemical admixtures for concrete, American Society for Testing and Materials; Philadelphia, PA, USA.

ASTM C597 (2016), Standard test method for pulse velocity through concrete, American Society for Testing and Materials; Philadelphia, PA, USA.

Bakharev, T. (2006), "Thermal behaviour of geopolymers prepared using class F fly ash and elevated temperature curing", *Cement Concrete Res.*, **36**(6), 1134-1147. https://doi.org/10.1016/j.cemconres.2006.03.022.

Baradaran-Nasiri, A. and Nematzadeh, M. (2017), "The effect of elevated temperatures on the mechanical properties of concrete with fine recycled refractory brick aggregate and aluminate cement", *Construct. Build. Mater.*, **147**, 865-875. https://doi.org/10.1016/j.conbuildmat.2017.04.138.

Bastami, M., Baghbadrani, M. and Aslani, F. (2014). "Performance of nano-Silica modified high strength concrete at elevated temperatures", *Construct. Build. Mater.*, **68**, 402-408. https://doi.org/10.1016/j.conbuildmat.2014.06.026.

BS 1881-116 (1983), Testing concretes. Method for determination of compressive strength of concrete cubes, British Standards Institution; London, UK.

Cheng, F.P., Kodur, V.K.R. and Wang, T.C. (2004), "Stress-strain curves for high strength concrete at elevated temperatures", *J. Mater. Civil Eng.*, **16**(1), 84-90. https://doi.org/10.1061/(ASCE)0899-1561(2004)16:1(84).

Chindaprasirt, P., Chareerat, T., Hatanaka, S. and Cao, T. (2010), "High-strength geopolymer using fine high-calcium fly ash", *J. Mater. Civil Eng.*, **23**(3), 264-270. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000161.

Cree, D., Green, M. and Noumowé, A. (2013), "Residual strength of concrete containing recycled materials after exposure to fire: A review", *Construct. Build. Mater.*, **45**, 208-223. https://doi.org/10.1016/j.conbuildmat.2013.04.005.

EN 1994-1-2: Eurocode 4 (2004). Design of composite steel and concrete structures–Part 1-2: General rules for structural fire design, European Committee for Standardization; Brussels, Belgium.

Fernández-Jiménez, A., Palomo, A., Pastor, J.Y. and Martin, A. (2008), "New cementitious materials based on alkali-activated fly ash: performance at high temperatures", *J. American Ceramic Soc.*, **91**(10), 3308-3314. https://doi.org/10.1111/j.1551-2916.2008.02625.x.

Fernández-Jiménez, A., Pastor, J.Y., Martín, A. and Palomo, A. (2010), "High-Temperature Resistance in Alkali-Activated Cement", *J. American Ceramic Soc.*, **93**(10), 3411-3417. https://doi.org/10.1111/j.1551-2916.2010.03887.x.

Gül, R., Demirboğa, R. and Güvercin, T. (2006), "Compressive strength and ultrasound pulse velocity of mineral admixtured mortars", *Indian J. Eng. Mater. Sci.*, **13**(1), 18-24. http://nopr.niscair.res.in/handle/123456789/7210.

Hansen, T. C. (2014), *Recycling of Demolished Concrete and Masonry,* CRC Press, Florida, USA.

Hasan-Nattaj, F. and Nematzadeh, M. (2017), "The effect of forta-ferro and steel fibers on mechanical properties of high-strength concrete with and without silica fume and nano-silica", *Construct. Build. Mater.*, **137**, 557-572. https://doi.org/10.1016/j.conbuildmat.2017.01.078.

IS 13311-1 (1992), Non-destructive testing of concrete – methods of tests, Bureau of Indian Standard; New Delhi, India.

Jalal, M. (2014), "Corrosion resistant self-compacting concrete using micro and nano silica admixtures", *Struct. Eng. Mech.*, **51**(3), 403-412. https://doi.org/10.12989/sem.2014.51.3.403.

Khalaf, F.M. and DeVenny, A.S. (2004), "Recycling of demolished masonry rubble as coarse aggregate in concrete", *J. Mater. Civil Eng.*, **16**(4), 331-340. https://doi.org/10.1061/(ASCE)0899-1561(2004)16:4(331).

Khalaf, F. M. and DeVenny, A. S. (2005), "Properties of new and recycled clay brick aggregates for use in concrete", *J. Mater. Civil Eng.*, **17**(4), 456-464. https://doi.org/10.1061/(ASCE)0899-1561(2005)17:4(456).

Khan, M.S. and Abbas, H. (2015), "Effect of elevated temperature on the behavior of high volume fly ash concrete", *KSCE J. Civil Eng.*, **19**(6), 1825-1831. https://doi.org/10.1007/s12205-014-1092-z.

Kurda, R., de Brito, J. and Silvestre, J.D. (2017), "Combined influence of recycled concrete aggregates and high contents of fly ash on concrete properties", *Construct. Build. Mater.*, **157**, 554-572. https://doi.org/10.1016/j.conbuildmat.2017.09.128.

Li, H., Xiao, H. G., Yuan, J. and Ou, J. (2004), "Microstructure of cement mortar with nano-particles", *Composites Part B Eng.*, **35**(2), 185-189. https://doi.org/10.1016/S1359-8368(03)00052-0.

Liu, Y., Wang, W., Chen, Y.F. and Ji, H. (2016), "Residual stress-strain relationship for thermal insulation concrete with recycled aggregate after high temperature exposure", *Construct. Build. Mater.*, **129**, 37-47. https://doi.org/10.1016/j.conbuildmat.2016.11.006.

Mahdavi, M., Abolmaali, A. and Ghahremannejad, M. (2018), "The effects of pH and temperature on compressive strength of synthetic fiber-reinforced concrete cylinders exposed to sulfuric acid", *Adv. Civil Eng. Mater.*, **7**(1), 403-413. https://doi.org/10.1520/ACEM20180018.

Martin, A., Pastor, J.Y., Palomo, A. and Jiménez, A.F. (2015), "Mechanical behaviour at high temperature of alkali-activated aluminosilicates (geopolymers)", *Construct. Build. Mater.*, **93**, 1188-1196. https://doi.org/10.1016/j.conbuildmat.2015.04.044.

Mousa, M.I. (2017), "Effect of elevated temperature on the properties of silica fume and recycled rubber-filled high strength concretes (RHSC)" *HBRC J.*, **13**(1), 1-7. https://doi.org/10.1016/j.hbrcj.2015.03.002.

Nematzadeh, M. and Baradaran-Nasiri, A. (2017), "Residual properties of concrete containing recycled refractory brick aggregate at elevated temperatures", *J. Mater. Civil Eng.*, **30**(1), https://doi.org/10.1061/(ASCE)MT.1943-5533.0002125.

Nematzadeh, M. and Fallah-Valukolaee, S. (2017), "Effectiveness of fibers and binders in high-strength concrete under chemical corrosion", *Struct. Eng. Mech.*, **64**(2), 243-257.

https://doi.org/10.12989/sem.2017.64.2.243.

Nematzadeh, M. and Mousavimehr, M. (2019), "Residual Compressive Stress–Strain Relationship for Hybrid Recycled PET–Crumb Rubber Aggregate Concrete after Exposure to Elevated Temperatures", *J. Mater. Civil Eng.*, **31**(8). https://doi.org/10.1061/(ASCE)MT.1943-5533.0002749.

Nik, A.S. and Omran, O.L. (2013), "Estimation of compressive strength of self-compacted concrete with fibers consisting nano-SiO2 using ultrasonic pulse velocity", *Construct. Build. Mater.*, **44**, 654-662. https://doi.org/10.1016/j.conbuildmat.2013.03.082.

Peng, G.F., Yang, W.W., Zhao, J., Liu, Y.F., Bian, S.H. and Zhao, L.H. (2006), "Explosive spalling and residual mechanical properties of fiber-toughened high-performance concrete subjected to high temperatures", *Cement Concrete Res.*, **36**(4), 723-727. https://doi.org/10.1016/j.cemconres.2005.12.014.

Rashiddadash, P., Ramezanianpour, A.A. and Mahdikhani, M. (2014), "Experimental investigation on flexural toughness of hybrid fiber reinforced concrete (HFRC) containing metakaolin and pumice", *Construct. Build. Mater.*, **51**, 313-320. https://doi.org/10.1016/j.conbuildmat.2013.10.087.

Saavedra, W.G.V. and de Gutiérrez, R.M. (2017), "Performance of geopolymer concrete composed of fly ash after exposure to elevated temperatures", *Construct. Build. Mater.*, **154**, 229-235. https://doi.org/10.1016/j.conbuildmat.2017.07.208.

Sagoe-Crentsil, K.K., Brown, T. and Taylor, A.H. (2001), "Performance of concrete made with commercially produced coarse recycled concrete aggregate", *Cement Concrete Res.*, 31(5), 707-712. https://doi.org/10.1016/S0008-8846(00)00476-2.

Sarhat, S.R. and Sherwood, E.G. (2012), "Residual mechanical response of recycled aggregate concrete after exposure to elevated temperatures", *J. Mater. Civil Eng.*, **25**(11), 1721-1730. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000719.

Wang, W., Lu, C., Li, Y. and Li, Q. (2017), "An investigation on thermal conductivity of fly ash concrete after elevated temperature exposure", *Construct. Build. Mater.*, **148**, 148-154. https://doi.org/10.1016/j.conbuildmat.2017.05.068.

Xiao, J., Li, J. and Zhang, C. (2005), "Mechanical properties of recycled aggregate concrete under uniaxial loading", *Cement Concrete Res.*, **35**(6), 1187-1194. https://doi.org/10.1016/j.cemconres.2004.09.020.

Zhang, P., Gao, J.X., Dai, X.B., Zhang, T.H. and Wang, J. (2016), "Fracture behavior of fly ash concrete containing silica fume", *Struct. Eng. Mech.*, **59**(2), 261-275. https://doi.org/10.12989/sem.2016.59.2.261.

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