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Using Nano-SiO_2 to improve the Mechanical and abrasion Properties of High-Volume Fly Ash Concrete Subjected to Elevated Temperatures

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ABSTRACT

Fly ash (FA) disposal resultant from coal-fired electrical power-stations combustion is one of the main-environmental challenges. The disposal of FA is accompanying with leaching of heavy metal and immense threat of pollution. To eliminate these problems, FA with high-volume (HVFA) can be incorporated into concrete as a part of cementitious material. In this work, cement was partially replaced with FA at ratio of 60%, by weight, to obtain HVFA-concrete (F60). Because the early strength of HVFA concrete is low, F60 was improved by incorporation of 2% (F60n2) and 5% (F60n5) nano-SiO_2 (NS) as a partially replacement of FA, by weight. Mechanical strength and modulus of elasticity were measured. The compressive strength and abrasion resistance before and after subjected to 200-800 ^{o}C for 2 h were investigated. The results showed an improvement in the HVFA concrete properties with the inclusion of NS particles. HVFA concrete showed better performance than the control at elevated temperatures. This better performance increased with the incorporation of NS particles.

Keywords: High-volume fly ash, recycling, mechanical properties, Abrasion resistance, Nano silica, high temperature.

I. Introduction

Concrete is a major material used in construction field because concrete is a cheap material which has an acceptable durability. But cement production has a negative effect on the environmental. So, many countries trend to limit cement industry. This negative effect led to searching about using cementitious materials (SCMs) as a partially replacement of cement especially in a large amount. Fly ash is one of the chosen materials used as a partially replacement of cement in the concrete by a typical ratios of approximately 20–25%. Currant researches incorporated HVFA in concrete aiming to get rid of FA and limiting pollution occurs by cement industry. Generally, if 50% or more of PC is replaced by FA, the concrete is termed as HVFA concrete [1]. Because the early strength of HVFA concrete is low, using mineral additives like Nano silica, silica fume, rice husk ash to improve the mechanical properties of HFVA concrete are recommended [2,3].

Many researchers studied the effect of HVFA on the mechanical properties of concrete compared with those of normal concrete. Rashad [4] presented an overview of the previous studies carried out on the use of high-volume Class F FA as a partially replacement of cement. They found that the reduction in the compressive strength of concrete at age of 28 days was between 38-43%, when cement was partially replaced by 50% FA [1,5,6]. While, the reduction in compressive strength was between 26-41% when 60% of FA was incorporated [7-9]. Also it was observed that using 70% fly ash deceased the compressive strength by around 49-67% [10-12]. The main conclusion obtained from the previous studies that the reduction in the compressive strength increased with increasing in FA content. In the same manner, a lot of studies reported a reduction in the flexural strength, splitting tensile strength, and modulus of elasticity for concrete at age of 28 days with the inclusion of HVFA as cement replacement. This reduction increased with increasing FA content [13-17].

A lot of approaches have been conducted to enhance the strength at early ages of HVFA matrices. These approaches include adding other cementitious materials such as silica fume (SF) and MK, including ultra-fine FA, adding nano particles, including fibers and including chemical activators. Special curing conditions such as steam curing and high temperature curing also can be used [4]. In this regards, Musa et al. [18], studied the mechanical properties and the performance of HVFA concrete containing NS (53.78 % FA + 1.22% NS) as a cement replacement. The main conclusion found by this study is that the addition of NS increased the compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, and abrasion resistance of HVFA rolled-compacted concrete (RCC) pavement. Also Min Liu, et, al. [19] studied the effect of adding 1-4% NS on the early strength of mortar containing 50% FA as replacement of cement under the effect of steam curing. It was found that NS largely and steam curing increased the 9 h strength of HVFA mortar. The more NS added the higher strength increase rate was obtained. Shikh, et al., [20] studied the effects of incorporated 2 % NS 10% micro silica (MS) and their combined on the bond behavior of steel and polypropylene (PP) fibers in HVFA mortar containing 40, 50 and 60% FA as a cement replacement, by weight. The main conclusions from the results indicated that maximum pull-out force of both steel and PP fibers decreased with increasing FA content at both 7 and 28 days. The addition of 2% NS and 10% MS showed almost similar improvement in the maximum pull-out force of steel and PP fibers at both ages. Rashad, prepared HVFA concrete by partially replacing cement with 70% FA. Then FA was partially replaced with 10% and 20% SF, by weight, [21], 10% and 20% slag, by weight, [22] or SF coupled with slag [23]. The specimens were exposed to elevated temperatures in the range of 400-1000 ^{o}C for 2 h. The results indicated a higher relative strength of all HVFA concrete types. The incorporation of slag showed a negative effect on HVFA concrete before and after different heating. The incorporation of SF exhibited a good fire performance up to 600 °C. The incorporation of 10% SF + 10% slag exhibited a good fire performance followed by the 5% SF + 5% slag up to 600°C. For all mixes, severe degradation in residual strength was observed at 800 and 1,000°C. Rahel Kh. et al, [24], investigated the fire resistance of HVFA mortars with NS addition, in this study, cement was partially replaced by HVFA combined with colloidal NS to produce high strength mortars with high residual strength after exposure to high temperatures of 400 °C and 700 °C. The results indicated that, high strength mortars that have equivalent residual strength after exposure to 700 ^{o}C in comparison with that of the control cement mortar specimens before exposure to high temperature can be produced by replacing cement with HVFA and using colloidal NS

This study focuses on the effect of using Nano silica to improve the mechanical properties of HVFA concrete exposed to elevated temperatures. To produce HVFA concrete, cement was partially replaced with 60% Class F FA. Because the early strength of HVFA concrete is low, FA was partially replaced with 2% and 5% NS. Flexural strength, tensile splitting strength and modulus of elasticity. In addition, compressive strength and abrasion resistance before and after exposure to 400, 600 and 800 ^{o}C for 2 h were investigated. This study could add violable data for HVFA concrete system.

II. Excremental details

2.1 Materials

The cement used in this investigation was CEM I 42.5 N complies with Egyptian Standard specifications E.S.S No. 4756-1. Its specific gravity and Blaine surface area was 3.15 and 300 m^2/kg, respectively. The properties of used coarse aggregate (crushed stone – with nominal maximum size of 10 mm) and fine aggregate (silica sand) in this experimental work comply with E.S.S No. 1109. Potable water was used for all mixes. The FA was obtained from disposal waste resulting from the combustion of pulverized coal in the coal-fired furnaces. It complies with the requirements of BS3892: Part and classified as a low calcium Class F FA in ASTM-C618. Its specific gravity and Blaine surface area FA was 2.4 and 400 m^2/kg. The NS is a synthetic product with spherical particles (size 8-18 nm). Its average Blaine surface area was 240000 m2/kg. These particles were supplied from Sigma-Aldrich (Germany). Fig. 1 shows TEM morphology of NS. Figs. 2, and 3 shows XRD pattern of NS, FA respectively. Strong broad peak of NS was centered on around 22◦ 2θ, which indicates the amorphous characteristic of SiO2. The chemical composition of cement, FA and NS was determined by X-ray fluorescence (XRF) spectrometry analysis and listed in Table 1. High-range water reducer (HRWR) has a sulphonated naphthalene base was used with a fixed dosage of 2.0% from the total cementitious materials weight to accomplish high followability.

Table 1 Chemical composition of PC, FA and NS

Oxide (%)	PC	FA	NS
CaO	63.47	2.35	0.01
SiO_2	20.18	59.05	98.6
Al_2O_3	4.83	23.3	0.01
MgO	2.47	1.85	-
Fe_2O_3	3.16	4.84	0.01
SO_3	3.26	0.65	0.46
K_2O	0.52	1.82	0.045
Na_2O	0.16	0.91	0.21
TiO_2	0.3	1.03	-
MnO	0.22	0	-
P_2O_5	0.09	0.73	-
L.O.I.	1.34	3.47	0.65

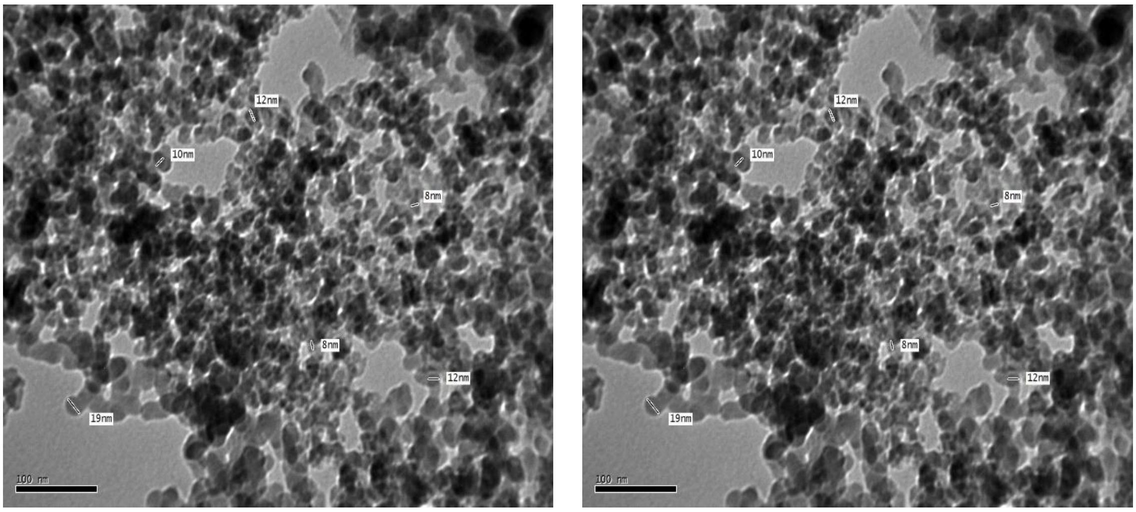

Fig. 1: TEM Micrograph of NS

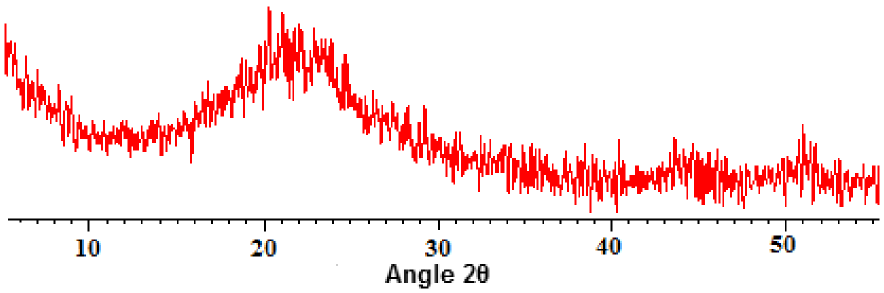

Fig. 2: XRD Pattern of NS

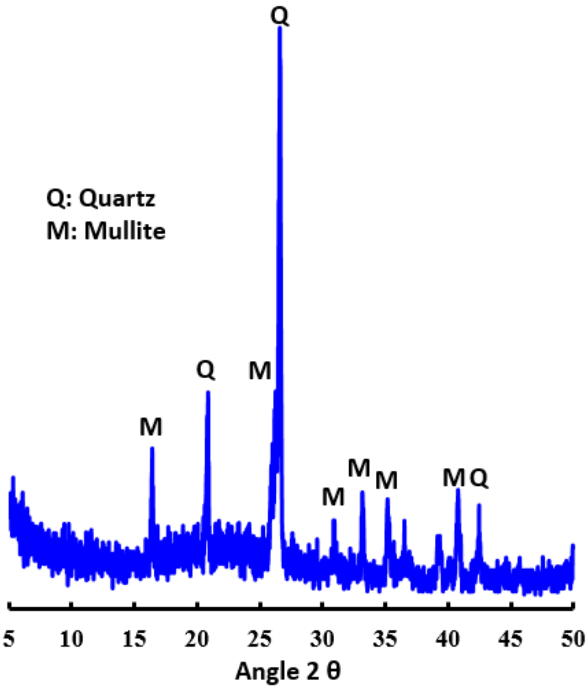

Fig. 3: XRD Pattern of FA

2.2 Mixture proportions

Four concrete mixtures were cast. All concrete mixtures were proportioned for constant effective w/b ratio of 0.4 and total cementitious content of 400 kg/m^3. The first mixture was made of only PC as the main binder material. This mixture was designated as (F0) and used as a control. In the second mixture, PC was partially replaced with FA at level of 60%, by weight. This mixture was designated as (F60). In the third and fourth mixtures, FA was partially replaced with NS at levels of 2% and 5%, by weight. These mixtures were designated as F60n2 and F60n5, respectively. The mixture proportions are summarized in Table 2.

Table 2 Concrete mixture proportions

Mixture	Ingredient /m^3					
Designation	PC (kg)	FA (kg)	NS (kg)	CA/Sand[1]	W/b	HRWR (liter)
F0	400	0	0	1.8	0.4	8
F60	160	240	0	1.8	0.4	8
F60n2	160	235.2	4.8	1.8	0.4	8
F60n5	160	228	12	1.8	0.4	8

[1] Coarse aggregate to fine aggregate ratio by weight

2.3 Methods

The mixing process was kept constant to supply the same homogeneity and uniformity for all mixtures. It started by mixing all of powders/aggregates for 3 min using pan mixer. NS (if any), mixing water and HRWR were mixed together with helping of ultrasonic mixer for a period of 5 min. The sonicated mixture was added to the powders/aggregates and mixed for 6 min. until the mixture became homogenous. The fresh concretes were cast into cubes of 100 mm side long moulds comply with BS 1881 (for compressive strength tests), cylinders of 150 × 300 mm comply with ASTM C469-02 (for modulus of elasticity tests), cylinders of 150 × 300 mm comply with ASTM C496/C496M-17 (for splitting tensile strength tests), prisms of 100 × 100 × 500 mm comply with ASTM C78 (for flexural strength tests) and samples with dimensions of 71 × 71 × 30 mm comply with ES: 269-2/2003 (for abrasion resistance tests). After casting, the moulds were vibrated for 1 min to remove air bubbles. The specimens were demolded after 24 h form casting and cured in water till the age of testing.

After curing, four specimens were tested in splitting tensile strength, flexural strength, modulus of elasticity and abrasion resistance at age of 28 days and the average was determined. For compressive strength tests, the similar number of specimens were tested at ages of 7, 28, 90 and 180 days. At age of 28 days, some compressive strength and abrasion resistance specimens were dried at 100 ± 2 ^{o}C for 24 h, then transferred to a symmetrical electrical furnace to be exposed to 400, 600 and 800 ^{o}C at a rate of 6.67 ^{o}C/min and held at each peak temperature for 2 h. After finishing, the specimens were then left to cool inside the furnace so as to avoid temperature shock. The specimens were then brought out from the furnace and weighed then tested in compression and abrasion to determine the residual compressive strength and abrasion resistance.

III. Results and discussion

3.1 Initial compressive strength

The compressive strength of the studied concrete mixtures at ages 7, 28, 90, and 180 days are presented in Fig. 4. There were reductions were (73.3, 59.1, 54.3, and 47.9) % for concrete specimens tested at age 7, 28, 90, and180 days respectively. These reductions were obtained which was attributed to the slow pozzolanic reaction of FA (low-calcium) and the dominant dilution effect, especially during the early ages, with only a few parts of the FA participating in the reaction. This effect is reduced with time.

Fig. 4 shows the compressive strength results starting from 7 days up to 180 days for all mixtures. As expected, partially replacing cement with 60% FA significantly reduces the compressive strength. The incorporation of 60% FA reduces the compressive strength by 73.3, 59.1, 54.3, and 47.9% at ages of 7, 28, 90 and 180 days, respectively. The higher reduction in the compressive strength is observed at early age. As the hydration time increases as the compressive strength gap between F0 and F60 decreases. The huge reduction in the early age compressive strength could be relevant to the slow pozzolanic reaction of low-calcium FA, of which a few parts of the FA participating the reaction and the dominant dilution effect [21]. To overcome this problem, FA was partially replaced with 2% and 5% NS. As can be seen from Fig. 4, the incorporation of only 2% NS can effectively enhance the 7, 28, 90 and 180 days compressive strength by 25.8%, 42.6%, 33.2% and 23.8%, respectively. Increasing the dosage of NS to reach 5% leading to more improvement in the compressive strength at all ages, but the highest improvement was noted at early age. The incorporation of 5% NS increases the 7, 28, 90 and 180 day compressive strength by 92.2%, 79.1%, 67.5% and 52.5%, respectively. More than one factor can attribute the improvement of compressive strength of concrete specimens containing NS. The first one is the faster pozzolanic reaction of NS with free lime produced in the hydration reaction of cement. Due to extremely high surface area and small particle size, the NS can react more quickly with free lime in the hydration reaction than FA. It can act as a nucleation site, accelerates the dissolution of C_3S and reacts with CH to form supplementary CSH gel. The second one called seeding effect, of which the ultra-fine particles of NS can act as seeds to hasten the cement hydration. The third one called the packing effect, of which NS can act as a filler which filled the pores among the microstructure of the concrete, due to their nano-size particles, resulting in immobilization of the free water and a more dense system **[**25],[26]**.**

Higher content of NS particles could have no significant effect on the compressive strength due to the agglomeration of the particles in wet mix. Nanoparticles, due to their small size, have high inter-particle van der Waal's forces causing the nanoparticles to agglomerate [3, 27-29]. Hence stored nanoparticles will form agglomerates hundreds of times larger than the primary nanoparticle causing them to lose the desirable surface area to volume ratio. Due to its higher van der Waal's forces, the nanoparticles agglomerate more than other pozzolans e.g. SF, metakaolin, etc.

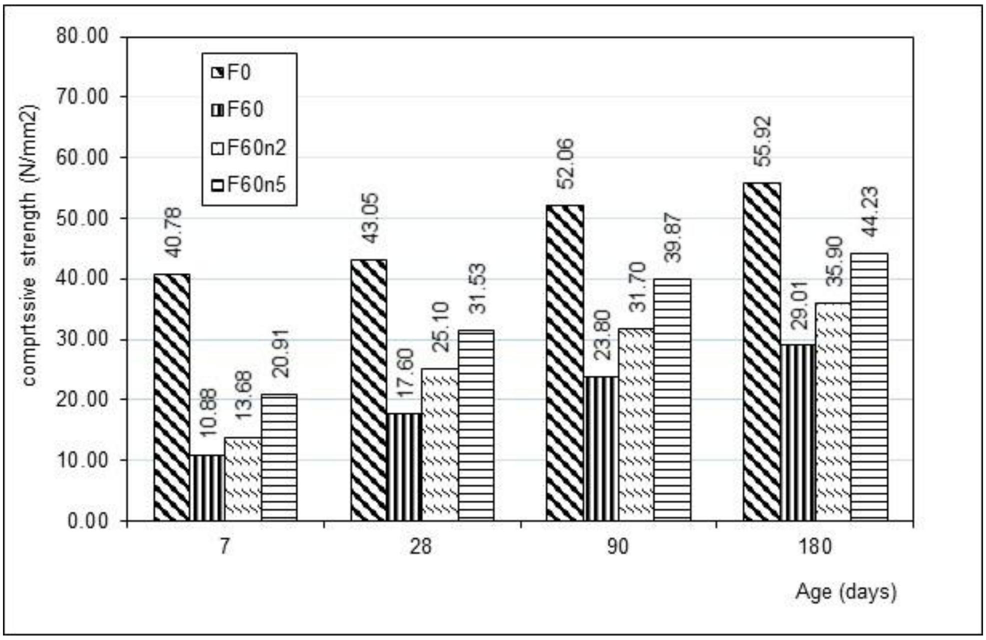

Fig. 4 Compressive strength of different concrete types at different ages

3.2 Flexural strength, splitting tensile strength and modulus of elasticity

Figs. 5-7 shows the flexural strength, splitting tensile strength and modulus of elasticity, respectively, test results for all mixtures at age of 28 days. As can be observed, the incorporation of 60% FA (F60) leads to 37.5% and 41.4% reduction in the flexural strength and splitting tensile strength, respectively. The obtained results are in agreement and follow the same trend of the results of compressive strength. The negative effect of FA is attributed to its lower early strength development resulted in its lower modulus of rupture. Also, because of lower pozzolanic reactivity of FA at early ages, which causes a weak cementitious matrix, thereby reducing the splitting tensile strength. Incorporating 2% NS results in an improvement in both flexural strength and splitting tensile strength by 19.4%, and 14.9% respectively. As the content of NS increased from 2% to 5%, more enhancement was obtained.

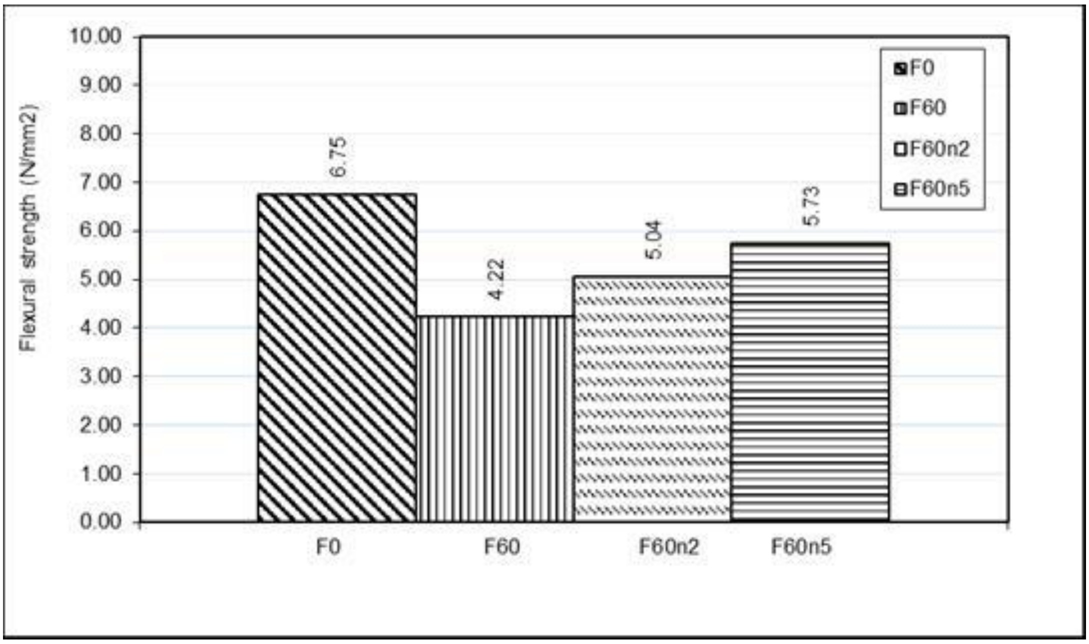

Fig. 5 Flexural strength of different concrete types at age of 28 days

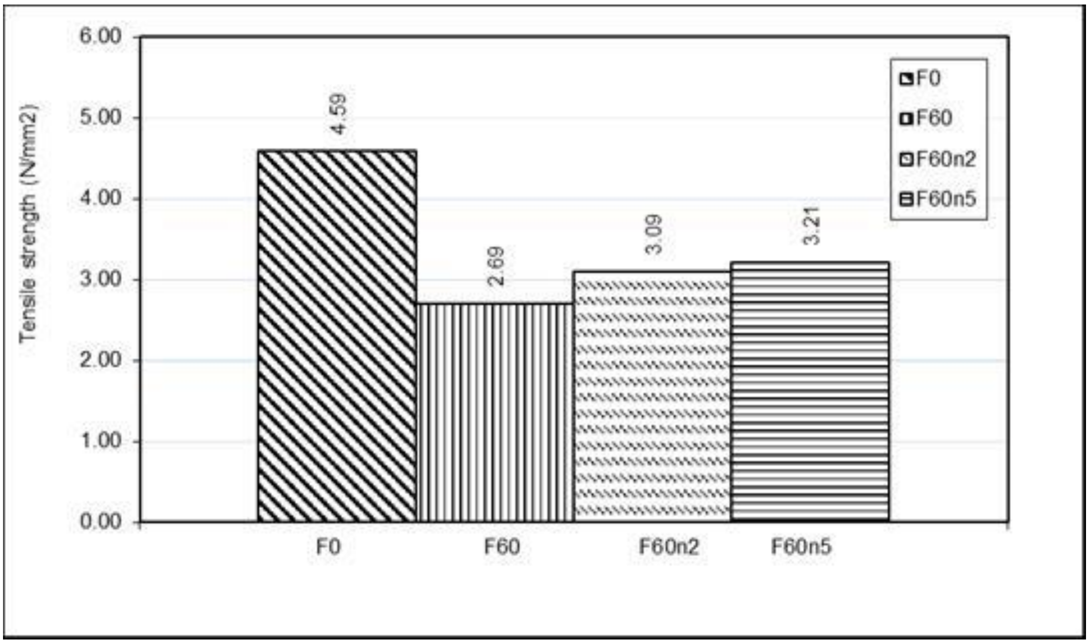

Fig. 6: Splitting tensile strength of different concrete types at age of 28 days

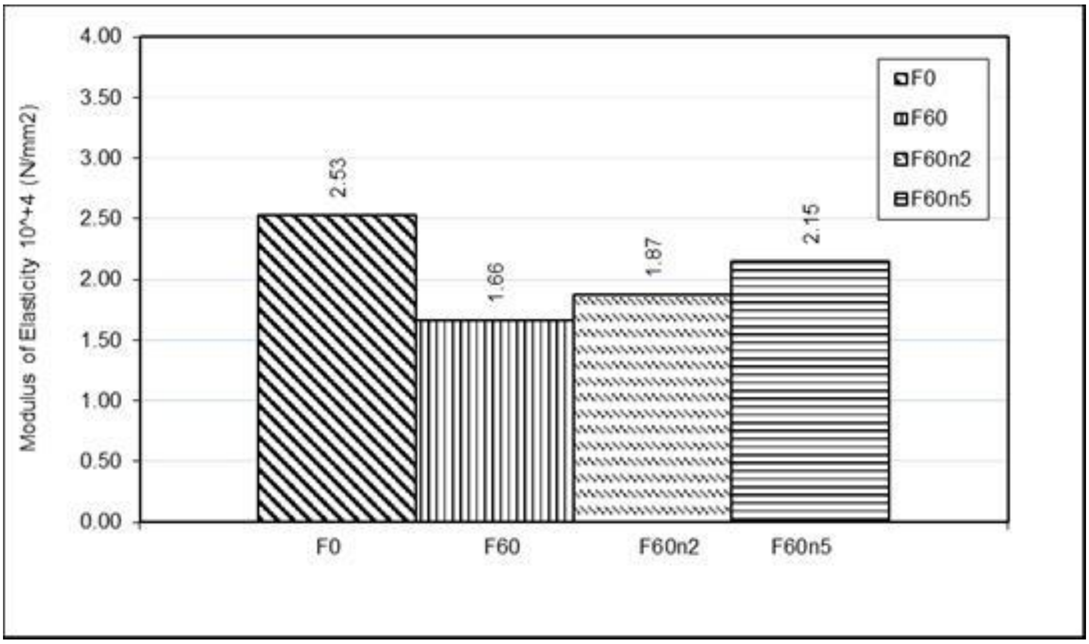

Fig. 7 Modulus of elasticity of different concrete types at age of 28 days

The results of static modulus of elasticity (MOE) at age of 28 days are shown in Fig. 7 which indicates that the MOE of F60 concrete reduces by 34.4% when compared with those of the control (F0). This is due to the same reason mentioned before (i.e slow pozzolanic reactivity of FA). On the other hand, the addition of NS increases the MOE of HVFA concrete. At 28 days, the MOE of F60n2 and F60n5 are greater than that of F60 by 12.65% and 29.52%, respectively. The increase in MOE with the addition of NS to HVFA concrete can be attributed to the pore filling ability as well as the pozzolanic reaction of NS. This increases the compressive strength which subsequently increases the MOE.

3.3 Residual compressive strength after exposure to elevated temperatures

The behavior of concrete mixtures without FA, incorporated HVFA and those incorporated HVFA coupled NS exposed to different high elevated temperatures were investigated by measuring the compressive strength after heating (i.e residual compressive strength). The test results for compressive strength are shown in Fig. 8 which shows the effect of HVFA and using NS on the residual compressive strength The results show that the compressive strength of the PC concrete (F0) approximately did not affected when the specimens exposed to 400 °C, in which the relative compressive strength is 98.49% referred to its control at room temperature. The slight reduction in the compressive strength at 400 °C may be due to the evaporated water and hydrates. On the other hand, all HVFA concrete specimens show a significant increase in the strength after exposed to 400 °C. The compressive strength of F60 concrete at 400 °C increases compared with its reference at room temperature and its relative strength reaches as high as 243.30%. When partially replacing FA with 2% and 5% NS (F60n2, F50n5), an increase in the residual compressive strength was obtained. The residual compressive strength of reaches 50.25 MPa for F60n2 and 60.56 MPa for F60n5. Comparing these compressive strength values with their counterparts, it can be noted that the relative strength reaches 200.2% for F60n2 and 192.1% for F60n5. The main conclusion of this part of the results are that all HVFA concrete types performed better than the PC concrete at 400 °C. They showed rapid gain in their compressive strength. The F60n5 concrete exhibited the highest residual compressive strength followed by F60n2. On the other hand, the F60 concrete exhibited the highest relative strength followed by F60n2 and F60n5. The relative strength of all types of HVFA concretes was higher than that of the PC concrete by about 2.47 to 1.95 times.

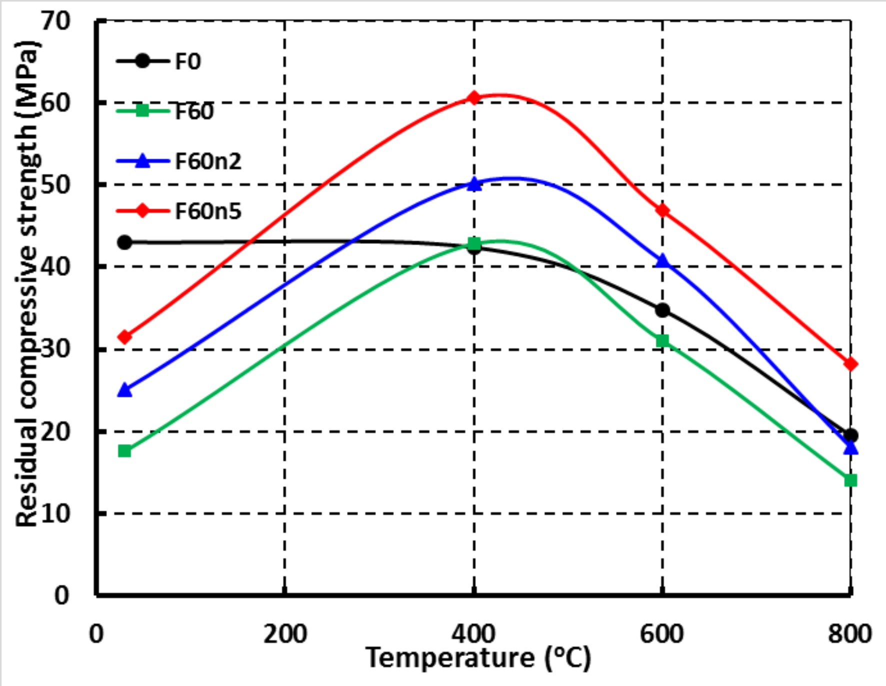

Fig. 8 Effect of elevated temperatures on the compressive strength of different concrete types

With increasing temperature to 600 °C, the compressive strength decreases due to weakling the bond between the aggregate and the cement paste, of which the aggregates expanded, while the paste lost its water. Anyhow, for F0 concrete, the loss of strength becomes more significant at 600 °C compared to that at 400 °C. The retained strength is 80.83% of the 28 days compressive strength. This degradation of strength, also, could be caused by the coarsening of the porestructure of the hardened cement paste [21]. On the other hand, the residual compressive strength values of all HVFA concrete types are still higher than their originals before heating. The residual compressive strength of F60 concrete records 31.05 MPa, which is still higher than its original by about 76.42%. The recorded highest residual compressive strength is 46.86 MPa for F60n5 followed by 40.78 MPa for F60n2. These two values of residual compressive strength are still higher than their originals by 48.6% and 62.7%, respectively. The main features of this part of the results are that even though exposure to 600 °C, the compressive strength of HVFA concrete mixes was still more than their originals. The relative strength of all types of HVFA concretes was higher than that of the PC concrete by about 2.44 to 2.06 times.

Exposure to 800 °C results in a significant decrease in compressive strength for all specimens, which is mainly attributable to the excessive build-up of vapor pressure; this pressure produces large cracks in the specimens. Additionally, the binder products in cement paste dehydrate at this temperature and cause a reduction in strength. However, specimens containing 5% NS shows a higher residual strength. The residual compressive strength for specimens containing 5% NS is comparable to the compressive strength of the unheated specimen, most likely due to the filler effect of the NS and the higher calcium silicate hydrate content of specimens containing both NS and FA,.

3.4 Abrasion resistance after exposure to elevated temperatures

The weight loss, which is inversely proportional to the abrasion resistance, was used to evaluate the abrasion resistance of different types of concrete before and after exposure to elevated temperatures. Therefore, a greater percentage loss implies a lower abrasion resistance, and vice versa. The results of the weight loss tested at room temperature and after exposure to 400, 600 and 800 °C are shown in Fig. 9. The loss increases with incorporation 60% FA as a cement replacement, as can be seen where of which the loss value of F60 is higher than that of F0 by about 157.9%. This could be attributed to the lower pozzolanic reactivity of FA resulted in slower strength development, poor bonding between cement paste and aggregates, and subsequent decreased abrasion resistance. Another contributing factor is a reduction in the compressive strength, of which the abrasion resistance of concrete is directly proportional to its compressive strength. The addition of 2% and 5% NS increases the abrasion resistance of HVFA concrete by decreasing its weight loss by about 24% and 43.9%, respectively. Increasing abrasion resistance with the addition of NS could be attributed to the increased pozzolanic reaction, which led to increased strength, and increased abrasion resistance.

The weight loss of all concrete types after exposure to elevated temperatures is presented in Fig. 9. As can be seen, weight loss of F0 shows marginal change when the specimens exposed to 400 °C, in which the relative weight loss is 103.55% referred to its control at room temperature. This slightly reduction in the weight strength (increase in weight loss) at 400 °C is compatible with deceasing its compressive strength. On the other hand, all HVFA concrete specimens show a significant increase in the strength after exposed to 400 °C. The weight loss for F60 at 400 °C decreases compared with its reference loss at room temperature by about 52.23%. Also, using 2% and 5% NS (F60n2, F50n5) lead to an increase in the abrasion strength by decreasing the weight loss by 48.9% for F60n2 and 54.7% for F60n5 compared with its reference loss at room temperature. The main conclusion of this part of the results are that all HVFA concrete types performed better than the PC concrete at 400 °C. They showed rapid gain in their abrasion strength. The F60n5 concrete exhibited the lowest weight loss followed by F60n2.

With increasing temperature to 600 °C, the abrasion strength decreases due to weakling the bond between the aggregates and the cement paste, of which the aggregates expanded, while the paste lost its water. Anyhow, for F0 concrete, the weight loss becomes more significant at 600 °C compared to that at 400 °C. The weight loss of F60 concrete is still lower than its original by about 54.33%. F60n5 exhibits the lowest weight loss followed by F60n2. These two values of weight loss are still lower than their originals by 54% and 70.9%, respectively. The main features of this part of the results are that even though exposure to 600 °C, the abrasion strength of HVFA concrete mixes was still higher than their originals. Finally, exposure specimens to 800 °C resulted in a significant decrease in abrasion strength, which is mainly attributable to the excessive build-up of vapor pressure. However, specimens containing 5% NS shows the highest abrasion resistance lowest weight loss). The main contributing factor is a reduction in the compressive strength, as the abrasion resistance of concrete is directly proportional to its compressive strength.

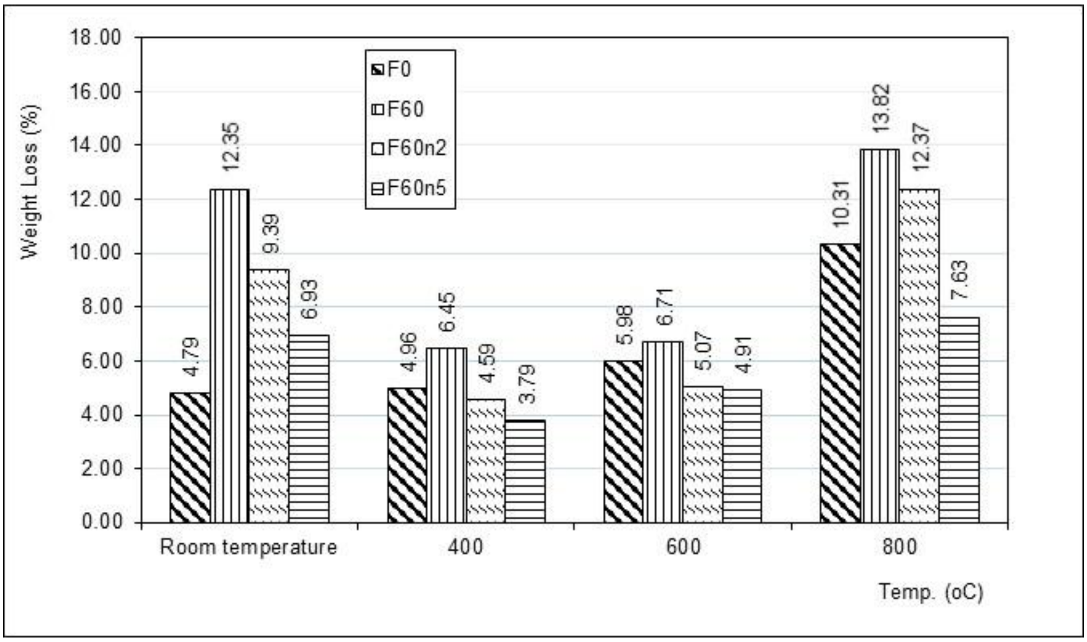

Fig. 9 Effect of elevated temperatures on the weight loss of different concrete types

Conclusions

In this article, the effects of incorporation of HVFA with/without NS on the mechanical strength as well as compressive strength and abrasion resistance before and after exposure to elevated temperatures were studied. The main conclusions of this investigation can be summarized as follows:

1. Using HVFA in the matrix sharply decreased its mechanical strength and abrasion resistance especially at early ages.
2. The addition of 2% NS increased the compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, and abrasion resistance of HVFA concrete, this is due to increasing hydration products.
3. The addition of 5% NS resulted in increasing the compressive strength, splitting tensile strength, flexural strength, and abrasion strength.
4. All HVFA concrete mixes showed a significant increase in the compressive strength, and abrasion resistance after exposure to 400 °C, The incorporation of 2% and 5% NS led to more enhancement of both compressive strength and abrasion resistance at this degree.
5. Even though exposure to 600 °C, the compressive strength of HVFA concrete specimens was still higher than their originals. The relative strength of all types of HVFA concretes was higher than that of the PC concrete by about 2.44 to 2.06 times.
6. With increasing temperature to 600 °C, the abrasion strength decreased due to weakling the bond between the aggregates and the cement paste, of which the aggregates expanded, while the paste lost its water.
7. Exposure specimens to 800 °C resulted in a significant decrease in compressive strength and abrasion resistance for the specimens, which is mainly attributable to the excessive build-up of vapor pressure. However, specimens containing 5% NS showed the highest residual strength. The residual compressive strength for specimens containing 5% NS was comparable to the compressive strength of the unheated control specimen.

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