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Properties of low binder ultra-high performance cementitious composites: Comparison of nanosilica and microsilica

Mehmet Gesoglu *, Erhan Güneyisi, Diler Sabah Asaad, Guler Fakhraddin Muhyaddin

Department of Civil Engineering, Gaziantep University, Gaziantep, Turkey

HIGHLIGHTS

- Ultrahigh strength concrete with low powder was produced.
- Effects of nanosilica and microsilica were investigated.
- Effect of 1% of nanosilica equals to almost that of 10% microsilica.
- The highest strength properties were achieved at 2% nanosilica.
- Combined use of nanosilica and microsilica had better performance.

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ABSTRACT

This paper presents the effect of using binary and ternary blends of nanosilica (NS) and microsilica on the mechanical properties of low binder ultra-high performance cementitious composites (UHPCs). For this, two concrete groups were designed with and without silica fume by weight of cement with a constant water/binder ratio and total binder content. Commercially available NS was used in partial substitution of cement at 0%, 0.5%, 1%, 2% and 3% by weight. The results show that among different NS contents, UHPC containing 2% NS exhibited the best results of compressive strength, splitting tensile strength, modulus of elasticity, flexural strengths, load–displacement behavior and fracture energy at 90 days. The samples of UHPC containing binary cementitious materials (NS and SF) gave better results than concretes containing only NS. Additionally, the effect of 1% NS is almost equal to that 10% of SF.

1. Introduction

During the last 20 years, ultra-high performance concrete or cementitious composites (UHPCs) have become an introduction of the most favorable ingenious high technology types of concrete [1–3]. UHPC has been applied to many huge strategic and sensitive projects like, coupling beams in high-rise buildings, precast members, infrastructure rehabilitations, blast resistant structures, and special facilities like nuclear waste storage containers [4]. The main composition of UHPC involves a large content of cement and silica fume as binder, fine sand of 150–600 μm sizes, and crushed quartz of about 10 μm sizes. Very low water-to-binder ratio is also typically used in UHPC mixes resulting in reduced workability that may be managed by adding an effective superplasticizer (SP) [5,6]. In order to obtain the desired mechanical properties of UHPC, enhancing the stiffness and strength of the interfacial transition zone (ITZ) to a level comparable to that of bulk paste aggregate is vital. This might be achieved by using silica materials such as silica fume and (or) nanosilica, regardless of its forms that can be an amorphous state [7].

In cementitious systems, silica fume (SF) is the most commonly used amorphous silica which possesses an average particle size of about 10 times smaller than cement. It has been used in the ranges of 10–25% by weight of cement since the 1950s, thus its pozzolanic and filling effects on the concrete properties have been widely known [8]. Pozzolanic reaction of silica with calcium hydroxide forms more C–S–H gel at final stages (chemical effect) while filling the remaining voids in the fresh and partially hydrated cement paste (physical effect) increased the density of concrete [9]. Moreover, some researchers like Dunster [10] agreed that contribution of SF with concrete constituents would save the cement that accounts for sustainability of economic and environmental development.

Nano technology has attracted considerable interest due to the new potential uses of particles in nanometer scale associated with high specific surface area, high purities, and small primary particles [11]. Nano-scale SiO_2 seems to be the most popular nano-

* Corresponding author.
E-mail address: mgesoglu@gantep.edu.tr (M. Gesoglu).

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particle in the researches because of its great benefits in the concrete. Nano-SiO_2 cannot only fill the voids between cement and silica fume particles; its high specific surface area to the volume ratio yields a high rate of pozzolanic reaction that leads to the potential for tremendous chemical activity. Recent studies have revealed that addition of nano-silica provided many significant improvement in mechanical [12], durability [13], physical [14] and micro structure of concretes [15].

Researchers have proven that the finer the silica particles the higher strength of UHPC. Nevertheless, there are divergent opinion and poor vision about the optimum percentage of the nano-sized particles when replaced with cement to produce concrete. In the case of conventional concretes, Sobolev et al. [16] reported that addition of 0.25% of SiO_2 nanoparticles increased the 28-day compressive and flexural strengths by as much as 10% and 25%, respectively. Zaki and Ragab [17] studied the effect of NS on the strength of self-compacting concretes with 0.35 and 0.39 water/binder (*w*/*b*) ratios. They used NS at 0.5%, 0.7%, and 1% replacement levels by weight of cementitious materials. The measured compressive strengths at the ages of 7, 28, 90, and 365 days showed that NS used at 0.5% replacement level gave the highest results, irrespective of the testing ages. Safan et al. [18] utilized Cu–Zn nano-ferrite in producing Portland cement pastes and mortars at *w*/*c* ratios of 0.25 and 0.40, respectively. The optimum dose of nano materials was found to be 1% of cement by weight that enhanced the compressive strength of the cement paste and mortar by as high as 45%. In the study of Du and Pang [19], however, increase in the compressive strength of the mortar with 0.3 *w*/*c* ratio continued up to 1.5% of colloidal NS, thereafter the tendency seemed to be constant up to 2.0%. Nazari and Riahi [20] reported that 4% of nano-silica by weight of cement gave the best improvement in mechanical properties of self-compacting concretes at 0.4 *w*/*b* ratio.

In spite of the beneficial effects of nano-materials mentioned above, there are some researches in which the use nano-materials was found to be insignificant on the mechanical properties of conventional concretes. According to Senff et al. [21], using nano-SiO_2 and nano-TiO_2 in making cement pastes and mortars did not lead to any significant enhancement on the compressive strength. Even in the study of Ltifi et al. [22], a lower compressive strength was monitored for the mortars with 3% nano-silica compared to the plain specimens. Furthermore, Hosseini et al. [23] and Abbas [24] observed the negative effects of high dosages of NS on workability which was attributed to dispersion problems and conglomeration of particles. Indeed, each kilogram of NS added required 0.4 kg of water to maintain the same workability.

Comparing to the other types of concrete, there is little studies on properties of ultra-high performance concrete (UHPC) containing nano materials in which the effect of such material is varying and contradictory. Rong et al. [25] stated that incorporating 3% of nano-SiO_2 led to the maximum compressive and flexural strengths by as high as 100% compared to the reference concretes. According to Yu et al. [26], however, the effect of nano-silica was rather little such that the mixes with 4% of nanosilica by weight of 875 kg of total binder had only 3.6 MPa higher compressive and 2.7 MPa higher flexural strengths than those of reference UHPCs. Compressive strength of UHPCs decreased from 200 to 150 MPa when Wille and Naaman [27] only substituted the Portland cement by 1% of NS in the mixtures.

2. Experimental study

2.1. Materials and mixture proportioning

The cementitious materials used in concrete production were ordinary Portland cement (CEM I 42.5 R) conforming to the TS EN 197 [28] (mainly based on the European EN 197-1), Silica fume (SF), and nanosilica (NS). Chemical composition, physical and mechanical properties of them are given in Table 1. Quartz aggregate with a specific gravity of 2.65 was utilized in three fractions, namely 0–0.4, 0.6–1.2, and 1.2–2.5 mm. A new-generation superplasticizer (SP) of polycarboxilate type was used to fulfill the workability specifications in ASTM C 494 [29].

The mixture proportioning studied in the experimental program is shown in Table 2. Group 1 and 2 in the mix design codes show 0% and 10% SF respectively with a mutual NS content of 0%, 0.5%, 1%, 2% and 3%. Superplasticizer was used in varying amounts to adjust the workability enough for the mixtures. The mixtures in Table 2 were designated according to NS and SF replacement level. For example, SF0NS1 indicates the mixture containing 0% of silica fume and 1% of nanosilica.

2.2. Concrete mixture proportioning, casting, and sample preparation

The mixtures were prepared by means of a special designed, vertical axis, high speed mixer which has mixing speed of as high as 470 rpm. Dry powders and aggregates were mixed with the speed of 100 rpm for about 3 min. After a half of water addition, mixture was remixed for about 5 min with the speed of 100 rpm. Finally, SP and remaining water were added to premixed material and mixing was resumed at 470 rpm for about 5 min. Fresh concretes were then poured into the molds and compacted by using a vibrating table. The specimens were then covered with polyethylene sheets and kept in the molds for 16 h at room temperature of 22 ± 2 °C. Thereafter, they were cured in standard conditions of water curing until the testing age. A typical mixture consists of three 50-mm cubes, three 100-mm cubes, and three 150-mm cubes to determine compressive strength, splitting tensile strength, and modulus of elasticity, respectively. Moreover, flexural strength and fracture energy were measured on three prisms of 70 × 70 × 280 mm dimensions.

2.3. Testing methods

Compression test was conducted on 50 mm cubes at 1, 3, 7, 14, 28, 56, and 90 days with respect to ASTM C39 [30]. Splitting test was performed on 100 m cubes at 28, 56, and 90 days as ASTM C496 [31]. Static modulus of elasticity was determined on 150 cubes at 90 days in accordance with ASTM C469 [32]. For this, the cube specimens were loaded and unloaded three times up to 40% of the ultimate load determined from the compression test. The first set of readings from each cube was discarded, and the

Table 1
Properties of Portland cement, silica fume and nanosilica.

Constituent (%)	Cement	Silica fume	Nanosilica
CaO	62.12	0.45	–
SiO_2	19.69	90.36	99.8
Al_2O_3	5.16	0.71	–
Fe_2O_3	2.88	1.31	–
MgO	1.17	–	–
SO_3	2.63	0.41	–
K_2O	0.88	1.52	–
Na_2O	0.17	0.45	–
Cl	0.0093	–	–
Loss on ignition	2.99	3.11	–
Insoluble residue	0.16	–	–
Free CaO	1.91	–	–
Specific surface (m^2/kg)	394[a]	21,080[b]	150,000[b]
Specific gravity	3.15	2.2	2.2

[a] Blaine specific surface area.
[b] BET specific surface area.

Table 2
Mixture proportions of UHPC containing NS and SF (Part 1 and 2).

Group	Mix designation	Cement (kg/m^3)	Silica fume (kg/m^3)	Nanosilica (kg/m^3)	Water (kg/m^3)	Superplasticizer (kg/m^3)	Quartz aggregate (kg/m^3)
1	SF0NS0	800	0	0	160	21.6	1471.3
	SF0NS0.5	796	0	4	160	25.2	1461.1
	SF0NS1	792	0	8	160	28.8	1450.8
	SF0NS2	784	0	16	160	36.0	1430.2
	SF0NS3	776	0	24	160	43.2	1409.7
2	SF10NS0	720	80	0	160	29.6	1422.9
	SF10NS0.5	716	80	4	160	33.6	1411.6
	SF10NS1	712	80	8	160	37.6	1400.3
	SF10NS2	704	80	16	160	44.8	1379.8
	SF10NS3	696	80	24	160	52.0	1359.2

elastic modulus was reported as the average of the other two sets of readings.

Fracture energy, termed as a work of fracture, is an indirect surface energy measure of cementitious materials [33]. The test for determining the fracture energy was performed in accordance with the recommendation of RILEM 50-FMC/198 Technical Committee [34]. The displacement was measured simultaneously by using a linear variable displacement transducer (LVDT) at mid-span. As shown in Fig. 1a, Instron 5500R closed-loop testing machine with a maximum capacity of 250 kN were used to applied load. Fig. 1b shows the prepared beam for the fracture energy tests. The opening notch was achieved through reducing the effective cross section to 42 × 70 mm via a diamond saw to accommodate large aggregates in more abundance. Thus, the notch to depth ratios (a/W) of specimens was 0.4. According to RILEM [34], the fracture energy, G_F, of a single edge notched beam can be calculated under three point bending as:

$$G_F = \frac{W_0 + mg\delta_s \frac{S}{U}}{B(W-a)} \tag{1}$$

where W_0 is the area under the load–deflection curve; m is the mass of the beam; g is the acceleration due to gravity; δ_s is the specified deflection of the beam, while S, U, B, W, and a are span, length, width, depth, and notch depth of the beam, respectively. For each mixture, at least five specimens were tested at the age of 90 days. All the beams were loaded at a constant rate of 0.02 mm/min. In accordance with literature, the net flexural strength, f_{flex}, was calculated Eq. (2) (P_{max} is the ultimate load) by assuming no notch sensitivity [35,36]. Moreover, characteristic length (l_{ch}) as a measure of ductility was computed using Eq. (3) as a function of modulus of elasticity (E), fracture energy (G_F), and splitting tensile strength (f_{st}) [37].

$$f_{flex} = \frac{3P_{max}S}{2B(W-a)^2} \tag{2}$$

$$l_{ch} = \frac{EG_F}{f_{st}^2} \tag{3}$$

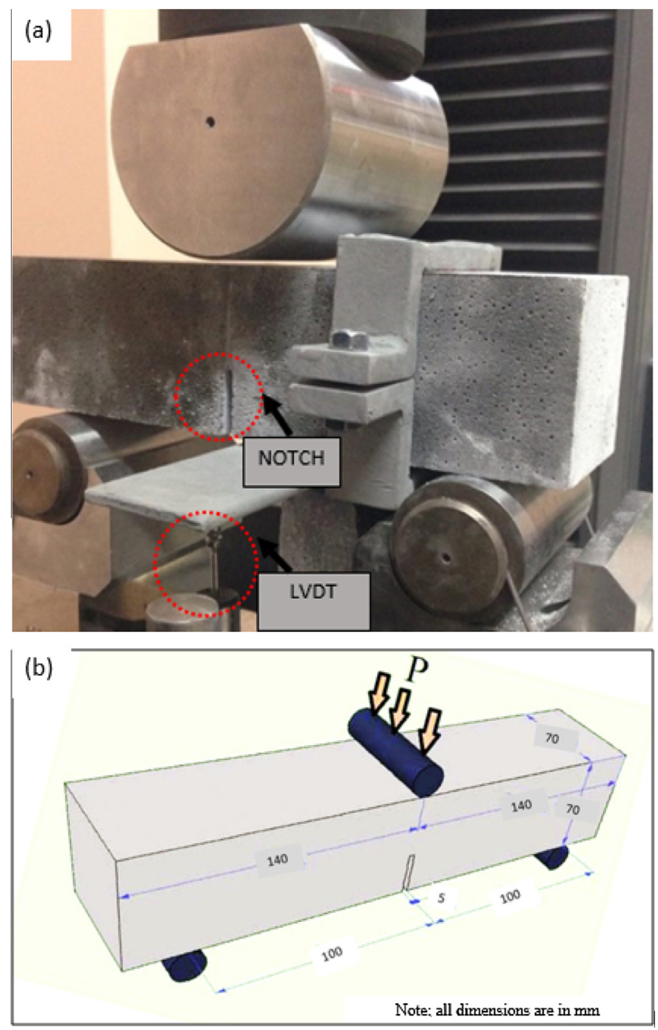

Fig. 1. (a) Photographic view of notched beam specimen, and (b) dimensions of the notched beam specimen.

3. Test results and discussions

3.1. Compressive strength

Effects of using nanosilica (NS) on the compressive strength development of the UHPC with and without silica fume (SF) are shown in Fig. 2a, b, respectively. Interestingly three distinct scenarios are observed: Firstly, compressive strength of the concretes continuously increased up to 2% NS content beyond which strength began to decrease, irrespective of SF content. Secondly, the silica fume concretes had lower compressive strength up to 7 days after that its beneficial effect appeared, irrespective of NS content. Indeed, among the different NS contents studied, UHPCs with 2% NS had the highest compressive strength from 7 to 90 days. However, the reduction of the early strength of concrete with NS were observed especially at 1 and 3 ages which could be attributed to the lack of hydration process at the very early ages. Similarly, the positive effect of SF was achieved after 14 days onwards. Finally, the early strength of the nanosilica fume concretes exceeded those of silica fume concretes, especially at 1, 3, and 7 days owing to the fact that the hydration process of cement at early age is significantly increased by nanosilica. However, considering the hydration

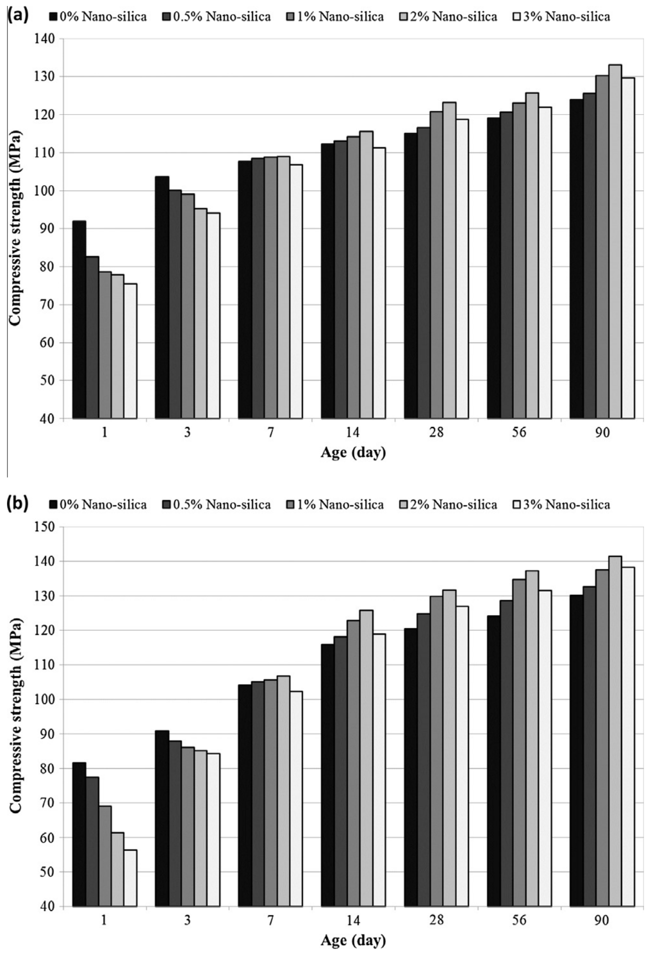

Fig. 2. Compressive strength versus different age water cured in plain UHPC: (a) 0% SF, and (b) 10% SF.

of cement at later age as controlled by the ion diffusion ability through hydrates, a compact gel structure of the pozzolanic hydration products of nanosilica would result in the block of the diffusion and thus decreases the hydration degree of cement and finally the slowdown of the strength gain at later ages [38].

The control UHPCs with and without SF had 90-day compressive strengths of 124 and 130 MPa as seen in Fig. 2a, b, respectively. 2% NS replacement caused 6.8% and 8% higher strengths than the companion reference mixtures, respectively. At 28 days, similarly, the strength enhancement for the concretes with and without SF were almost 6% and 8%, respectively. The results showed that the addition of NS had a modest effect owing to the fact that the most part of the pozzolanic reactivity of NS in the cement paste had been completed at the early ages [39–41]. However, a sharp increase in the strength from 1 to 3 and from 3 to 7 days was observed such that a 45% enhancement of the strength for the SF10NS3 mixture was detected from 1 to 7 days. Moreover, it was observed in Fig. 2a, b that regarding the results gained at 90 days, the compressive strength value of the mixture contained 1% of nanosilica (SF0NS1) was almost equal to that containing 10% of microsilica (SF10NS0). For instance, the concrete with 10% SF had compressive strengths of 116, 121, 125, and 130 MPa at 14, 28, 56, and 90 days, respectively (Fig. 2b). The corresponding strength values for the 1% NS concretes were 114, 121, 122, and 130 MPa, respectively. Depending on the mechanisms of works on concrete, NS was similar to silica fume by an increase in the packing density, particularly providing denser interface between the pastes and aggregate. Moreover, the hydrates of NS is known to be more compact and featureless, while the microstructure of the hydrates of SF is more loose and porous [38].

The slightly lower compressive strength of UHPC containing 3% NS may be attributed to improper dispersion of nano particles in the mixture. Nanoparticles have a pronounced tendency towards agglomeration more than the other pozzolans like microsilica because they have high inter-particle van der Waal's forces due to their much smaller sizes [9,42,43]. The disagglomeration of nanoparticles is crucial to achieve the ideal composite materials and the amount of SiO_2 nanoparticles in the mixture can also have been exceeded the quantity for consuming the calcium hydroxide compounds to form C–S–H gel. Therefore, it did not contribute to enhance the strength of UHPC [44]. It is also deduced in the literature that that the C–S–H gel formed in nanosilica modified system has a lower crystallinity. It has been well-documented that the crystallinity of the hydration products has a great influence on the mechanical property of cement-based materials and a suitable ratio of the crystals to the noncrystals is desired to yield a higher mechanical property [45]. Given this, an optimal dosage of nanosilica can achieve a proper crystal-to-noncrystal ratio in nanosilica-added cement so as to acquire a higher compressive strength, and this could be ascribed to the fact that a high dosage of nanosilica is detrimental to the compressive strength gain of cement-based materials [38,45].

Moreover, Table 2 presents the superplasticizer demand of the mixtures to provide the target workability. It was evident that the mixtures with NS required greater amount of superplasticizer, especially at higher replacement levels of NS. Interestingly, the concretes with 1% NS or 10% SF had comparable superplasticizer demand which well agreed the behavior seen in the compressive strengths. The quite limited strength enhancement with the use of NS was also attributed to the increase in the superplasticizer for the sake of constant workability.

3.2. Splitting tensile strength

When an amount of tensile stress is introduced to concrete, first micro-cracks thereafter macro cracks form. The increase in the load encourages critical crack progress at the tip of macro-cracks, which ultimately lead to concrete failure [46]. The easiest way to determine a tensile strength of concrete indirectly is by splitting tensile test. The study of tensile strength is essential to supply information regarding the maximum tensile load that concrete can withstand before cracking. The growth in splitting tensile strength versus NS content is presented in Fig. 3a, b for the UHSCs with and without silica fume, respectively. It was found that the splitting tensile strength increased with curing time and addition of NS up to 2% for the two series of concretes. At the age of 90 days, adding 0.5%, 1%, 2% and 3% of NS cause an improvement of splitting tensile strength by 2%, 9%, 12%, and 8% for the first group and increased to 5%, 14%, 24%, and 13% for the second group, respectively, compared to that with no contain of NS. Thus, the combined use of SF and NS seemed to be more influential on the tensile strength. When compared to the SF concrete the mixture with only 1% of nanosilica gave almost similar splitting tensile strength, irrespective of testing age. Indeed, the concrete with 10% SF had splitting tensile strengths of 7.3, 7.9, and 8.5 MPa at 7, 28, and 90 days, respectively (Fig. 3b). The corresponding strength values for the 1% NS concretes were 7.5, 7.9, and 8.6 MPa, respectively. The enhanced splitting tensile strength of UHPC is attributed to much denser ITZ through contributions of silica nano-particles. Fundamentally the main components of concrete like cement paste and aggregate have a higher tensile strength when tested separately than composite concrete itself. The above phenomenon is due to the negative influence of ITZ, which is known as the weakest part in concrete. Supplying UHPC with NS makes a denser and stronger ITZ by decreasing the voids

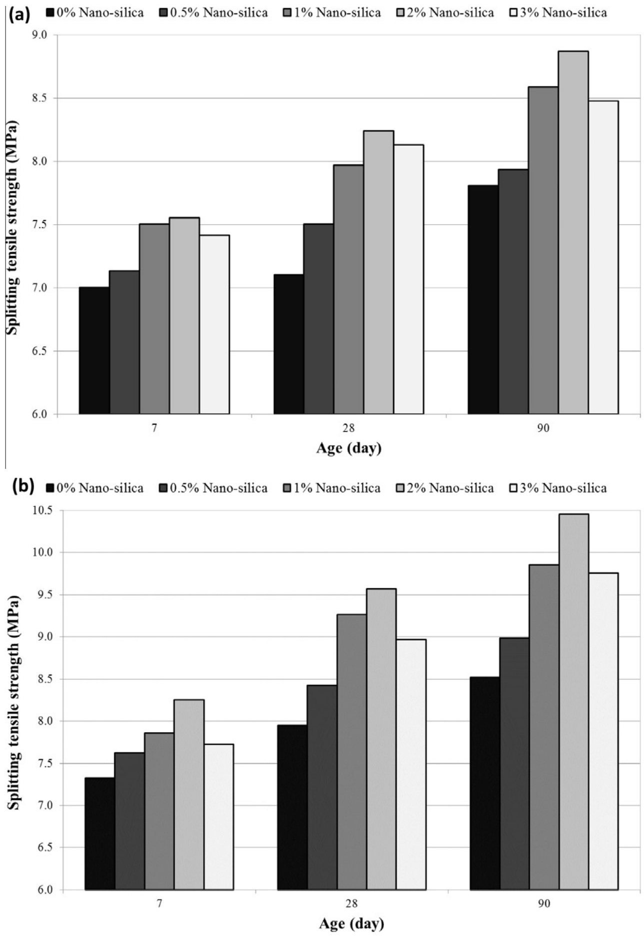

Fig. 3. Splitting tensile strength versus different water cured age: (a) 0% SF, and (b) 10% SF.

existing in ITZ [47]. Subsequently, the ITZ becomes compact and dense due to the filling effects and pozzolanic action of NS so that improvement of tensile strength is observed [11,48].

One the other hand, the enhanced extents of splitting tensile strength were immediately limited after adding 2% of NS by weight of cementitious materials. This may be because of the amount of NS particles which is greater than the amount necessary to combine with the other cementitious material particles during the process of hydration. For instance, depending on the specific surface area (given in Table 1), the 2% of nanosilica of the mixture SF10NS3 covered nearly an area of 4.5 km^2, which is greater than totally covered area of 2.1 and 0.4 km^2 by each of SF and Portland cement, respectively. Thus, excess silica will leach out and cause dispersion of nanoparticles and weak zones formed within the system as a consequence lack in the strength [49]. As in the case of compressive strength, a high dosage of nanosilica has negative effect on the strength gain due to lower crystallinity of the hydration products which has a great influence on the mechanical property of cement-based materials, thus ratio of the crystals to the noncrystals calls for a suitable ratio to yield a higher mechanical property [38,45].

3.3. Modulus of elasticity and modulus of rupture

Inasmuch it provides useful information about the capability of concrete to deform elastically, modulus of elasticity is one of the most important material properties utilized in the concrete design structures. Researchers investigated that a limited amount of silica nanoparticles giving a steeper slope in the stress–strain relationship curve by redistribution stress and reduced the localized strain [50]. It means that concrete with an optimized content of nanoparticles had better stiffness because the compactness of the paste bond with aggregates being better [51]. Fig. 4 demonstrated the 90-day static modulus of elasticity of the UHPC for different NS content. The behavior herein was much similar to that seen the compressive strength. It was observed in Fig. 4 that the effect of using NS was to increase the static elastic moduli of the concretes with and without SF. The increasing tendency continued up to 2% NS content after which a reduction began. When a 2% NS was utilized, the concretes had higher elastic moduli by 5.5% and 7.3% for the first and second group mixes, respectively. Moreover, test results suggested that the effect of 1% NS (SF0NS1) on the modulus of elasticity was almost equal to that of 10% SF (SF10NS0). As seen also from the second group mixes, the effect of combined use of nano and microsilica was more pronounced with nano-individual replacement. This may be attributed to the better enhancement of binary effect on potential for the stress transfer during the initial elastic stage loading.

Fig. 5 illustrates the variation in modulus of rupture with respect to the different percentage of NS. Flexural strength increased with increasing the NS content, irrespective of the concrete groups. Flexural strength of control UHPCs with and without

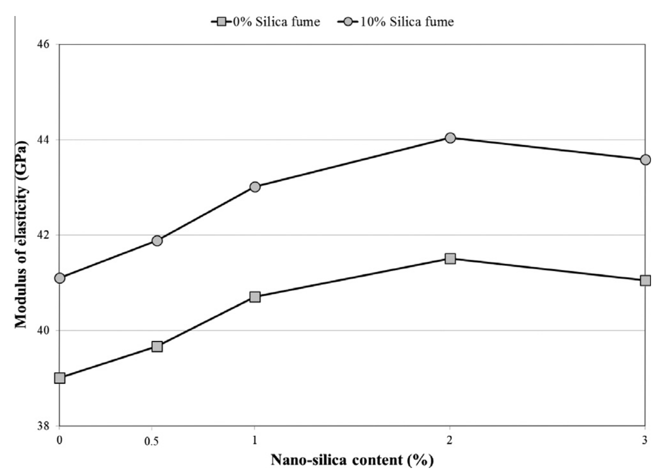

Fig. 4. Elastic moduli versus different NS content of plain UHPC at 90 days.

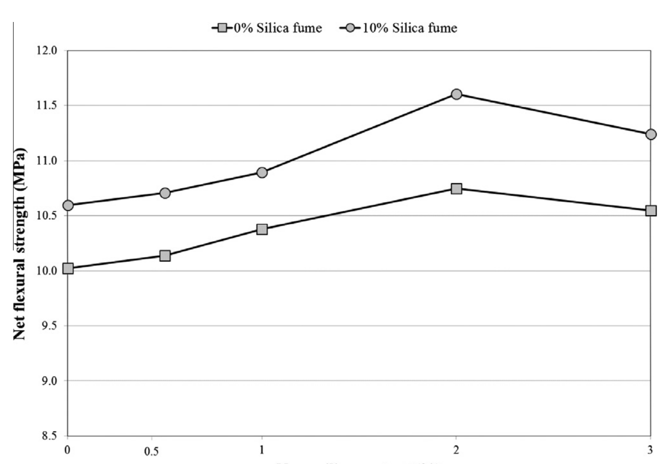

Fig. 5. Flexural strength versus different NS content of UHPCs at 90 days.

SF enhanced from 10 to 10.7 MPa and from 10.6 to 11.6 MPa, respectively for a given 2% NS content. Thereafter, the concrete was adversely affected by NS at 3% replacement level. Furthermore, In spite of decreasing the flexural value with more addition of NS than 2%, the results were still higher than their control mixtures by 5% and 6% for the first and second groups respectively. Same results were recently reported by the other researchers [52,53]. Improving in the modulus of rupture may be due to the quick consumption of calcium hydroxide associated with the nucleation of NS which helps in improving the bond between aggregate and cement mortar [47]. Then, more energy is needed to break UHPC leading to superior energy absorption capacity under bending.

3.4. Load–displacement curves and fracture energy

The load–displacement curves for notched beams of UHPCs are schemed in Fig. 6a, b. It can be seen that the peak load which represents the maximum load of the load-displacement curve, noticeably depends on NS replaced. Besides, it is obvious that the slope of the prepeak region and early postpeak of the curve, to some extent, related to nanosilica content. The load–displacement curves for the beam incorporating NS exhibited a steady drop in load carrying capacity after the peak load compared to steeper drop in the mixes with no silica. This is because of increased energy required for debonding constituents of concretes containing NS. Moreover, the pre- as well as the early postpeak regions in load–displacement curve mainly depends on the microcracks and their expansion, but the declining slope at the end of the softening branch is highly related to mechanisms resulting from the aggregate interlock and other frictional effects [54], where NS content has a remarkable role.

3.5. Fracture energy

Fracture energy (GF), which is known as total energy or specific energy, is actually the energy required to create a crack with unit surface area. In computing total energy, the area underneath the load versus displacement curve as well as the weight of the prism were employed as the energy provided by the own weight of the beam. The displacement up to the final failure reached was used for the calculation of energy supplied by the own weight of the beam [55]. In the present study, as shown in Fig. 7, the total fracture energy of UHPC was dependent on the amount of NS available in concrete mixes. It was expected like the other previous mechanical property tests that the UHPC with 2% nanosilica gave the highest value of the fracture energy regardless of the concrete groups. The fracture energy increased by 1%, 5%, 10% and 6% as well as 1%, 4%, 14% and 8% for the first and second group respectively, compared to the reference mixtures at 90 days, when 0.5%, 1%, 2% and 3% of NS were incorporated. The main reason behind this increase may be the fact that porosity in the cement paste and the ITZ zone being reduced due to filling properties of NS. As a result, the cement paste and ITZ zone would have a significant strength and subsequently, cracks were more likely to pass across the aggregates than cement paste and ITZ zone.

3.6. Characteristic length

Characteristic length, l_{ch}, is an appropriate parameter to assess the concrete brittleness so that the smaller the l_{ch}, the more brittleness the material. Fracture energy, modulus of elasticity, and tensile strength influence the characteristic length of concrete, the two former being directly proportional while the latter being inversely diversely effective on the value as seen in Eq. (3). The variation in the characteristic length of the UHPCs with and without SF is shown in Fig. 8 with respect to the different replacement levels of NS. The effects of both SF and NS seemed to be insignificant on the brittleness of such concretes as the characteristic length was almost constant ranging between about 42 and 46 mm, irrespective of the NS content. This behavior was attributed to the combined effect of the high cementitious materials content associated with the very low water to binder ratio as well as lack of coarse aggregate, thus leading to intrinsically rather brittle

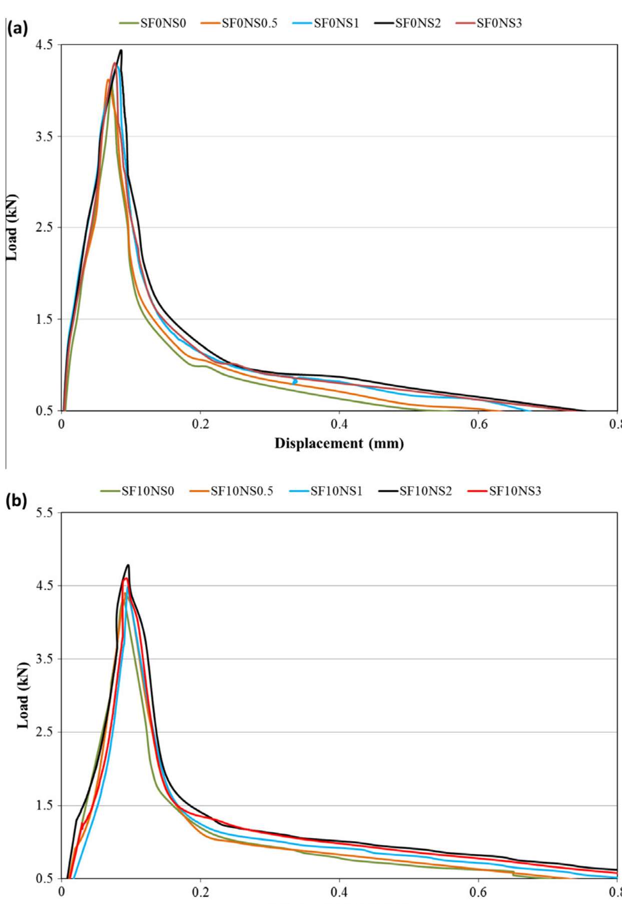

Fig. 6. Load versus displacement curves of UHPC with respect to NS content: (a) 0% SF, and (b) 10% SF.

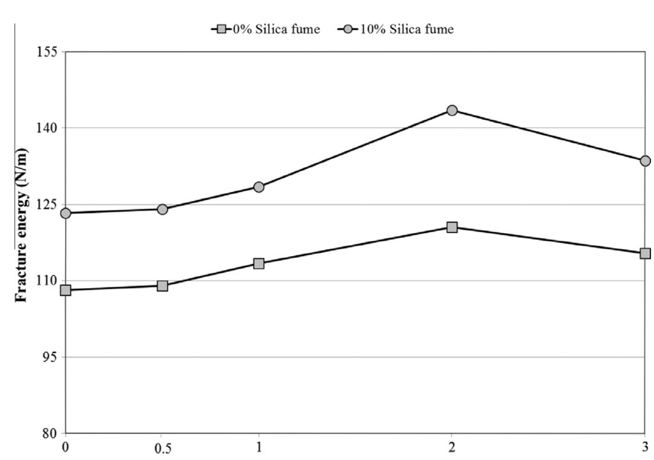

Fig. 7. Fracture energy versus different NS content of plain UHPC at 90 days.

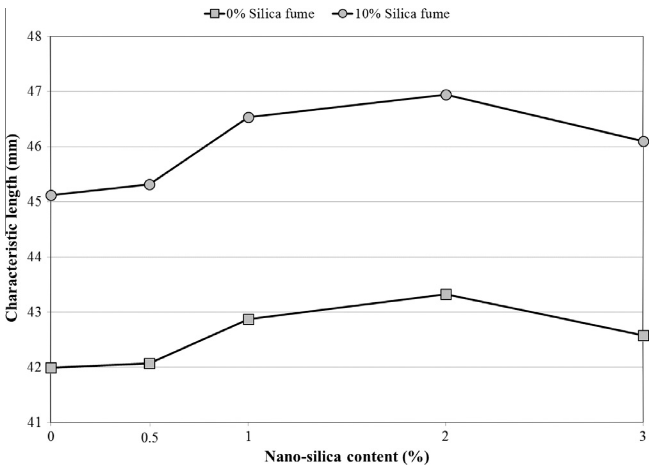

Fig. 8. Characteristic length versus different NS content of plain UHPC at 90 days.

material. There is a lack of study on the characteristic length of UHPC while many reports have been provided on normal concretes. When compared to the 42 mm characteristic length of UHSC, Petersson [56] recorded it between 200 and 500 mm and Zhang et al. [57] measured it between 412 and 235 mm for compressive strength range of 40–80 MPa. Furthermore, Eskandari et al. [58] revealed that it ranged from 266 to 446 mm for self-compacting high strength concretes.

4. Conclusions

The following conclusions can be drawn from this study:

1. NS is similar to silica fume by increasing the packing density, particularly interface between the pastes and aggregate. The effect of the 1% of nanosilica is almost equal or near to that of 10% of microsilica at 90 days. On the other hand, with the more addition of NS than 2%, e.g., 3%, the results were still higher than those of the control concrete (0% NS).
2. It was observed that the binary use of nano and microsilica had better performance on the characteristics of UHPCs compared to the individual incorporation.
3. The addition of 2% NS caused compressive strength and modulus of elasticity by about 8% and 7%, respectively, at 90 days.
4. It was found that the splitting tensile strength of UHPC developed with curing time and using NS up to 2%. Adding 0.5%, 1%, 2% and 3% NS improved the splitting tensile strength by 2%, 9%, 12% and 8% for the first group and 5%, 14%, 18% and 13% for the second group respectively, compared to their control concretes.
5. The load–displacement curves for beam incorporating NS exhibited a constancy drop in load carrying capacity after the peak load compared to steeper drop in the mixes with no silica. This is because of increased energy required for de-bonding constituents of concretes containing NS.
6. The generated plain UHPC with 2% nanosilica gave the highest value of the fracture energy. In the case of 0.5%, 1%, 2% and 3% of NS replacement levels, the fracture energy increased by 1%, 5%, 10% and 6% as well as 1%, 4%, 14% and 8% for the first and second group concretes, respectively compared to their reference mixtures at 90 days.
7. Both SF and NS on the brittleness of such concretes seemed to be insignificant owing to the combined effect of the high cementitious materials content associated with the very low water to binder ratio as well as lack of coarse aggregate.

References

[1] P. Acker, M. Behloul, DUCTAL_technology: a large spectrum of properties, a wide range of applications, in: First International Symposium on Ultra High Performance Concrete, Kasesel, Germany, 2004
[2] M. Rebentrost, G.W. Experience and applications of Ultra-high performance concrete in Asia, in: Second International Symposium on Ultra High Performance Concrete, Kassel, Germany, 2008.
[3] M.S. Fehling, S. Stürwald (Eds.), The Third International Symposium on Ultra High Performance Concrete and Nanotechnology for High Performance Construction Materials, Kassel University Press, Kassel, Germany, 2012.
[4] S. Zhao, W. Sun, Nano-mechanical behavior of a green ultra-high performance concrete, Constr. Build. Mater. 63 (2014) 150–160.
[5] B.A. Graybeal, Characterization of the behavior of ultra-high performance concrete (Ph.D. thesis), University of Maryland, USA, 2005.
[6] N. Tue, M. Orgass, J. Ma, Influence of addition method of superplasticizer on the properties of fresh UHPC, in: Proceedings of the 2nd international symposium on ultra high performance concrete, Kassel (Germany), 2008, pp. 93–100.
[7] J. Smith, G. Cusatis, D. Pelessone, E. Landis, J. O'Daniel, J. Baylot, Discrete modeling of ultra-high-performance concrete with application to projectile penetration, Int. J. Impact Eng. 65 (2014) 13–32.
[8] Ch. Schröfl, M. Gruber, J. Plank, Preferential adsorption of polycarboxylate superplasticizers on cement and silica fume in ultra-high performance concrete (UHPC), Cem. Concr. Res. 42 (2012) 1401–1408.
[9] G. Quercia, G. Hüsken, H.J.H. Brouwers, Water demand of amorphous nano silica and its impact on the workability of cement paste, Cem. Concr. Res. 42 (2012) 344–357.
[10] A. Dunster, Silica Fume in Concrete, Information Paper N° IP 5/09, IHS BRE Press, Garston, UK, 2009. pp. 1–12.
[11] F. Sanchez, K. Sobolev, Nanotechnology in concrete – a review, Constr. Build. Mater. 24 (11) (2010) 2060–2071.
[12] F. Taheri-Behrooz, B. Memar Maher, M.M. Shokrieh, Mechanical properties modification of a thin film phenolic resin filled with nano silica particles, Comput. Mater. Sci. 96 (2015) 411–415.
[13] H. Du, S. Du, X. Liu, Durability performances of concrete with nano-silica, Constr. Build. Mater. 73 (2014) 705–712.
[14] M. Aly, M.S.J. Hashmi, A.G. Olabi, M. Messeiry, E.F. Abadir, A.I. Hussain, Effect of colloidal nano-silica on the mechanical and physical behaviour of waste-glass cement mortar, Mater. Des. 33 (2012) 127–135.
[15] M. Oltulu, R. Sahin, Pore structure analysis of hardened cement mortars containing silica fume and different nano-powders, Constr. Build. Mater. 53 (2014) 658–664.
[16] K. Sobolev, I. Flores, L.M. Torres-Martinez, P.L. Valdez, E. Zarazua, E.L. Cuellar, Engineering of SiO_2 nanoparticles for optimal performance in nano cement based materials, in: Nanotechnology in Construction: Proceedings of the NICOM3 (3rd International Symposium on Nanotechnology in Construction). Prague, Czech Republic, 2009, pp. 139–148.
[17] S.I. Zaki, S. Ragab Khaled, How nanotechnology can change concrete industry, in: 1st International Conference on Sustainable Built Environment Infrastructures in Developing Countries, ISSN 2170–0095, Oran, Algeria, 12–14 October, 2009, vol. 1, pp. 407–414.
[18] M.A. Safan et al., Compressive strength of Portland cement pastes and mortars containing Cu–Zn nano-ferrite, Int. J. Nano Dimension 3 (2) (2012) 91–100.
[19] H. Du, S.D. Pang, Effect of colloidal nano-silica on the mechanical and durability performances of mortar, Key Eng. Mater. 629 (2014) 443–448.
[20] A. Nazari, S. Riahi, The effects of SiO_2 nanoparticles on physical and mechanical properties of high strength compacting concrete, Compos. Eng. 42 (3) (2011) 570–578.
[21] L. Senff, D. Hotza, S. Lucas, V.M. Ferreira, J.A. Labrincha, Effect of nano-SiO_2 and nano-TiO_2 addition on the rheological behavior and the hardened properties of cement mortars, Mater. Sci. Eng., A 532 (2012) 354–361.
[22] M. Ltifi, A. Guefrech, P. Mounanga, A. Khelidj, Experimental study of the effect of addition of nano-silica on the behaviour of cement mortars, Procedia Eng 10 (2011) 900–905.
[23] P. Hosseini, A. Booshehrian, A. Madari, Developing concrete recycling strategies by utilization of nano-SiO_2 particles, Waste Biomass Valor 2 (3) (2011) 347–355.
[24] R. Abbas, Influence of nano-silica addition on properties of conventional and ultra-high performance concretes, HBRC J 5 (1) (2009) 18–30.
[25] Zh. Rong, W. Sun, H. Xiao, G. Jiang, Effects of nano-SiO_2 particles on the mechanical and microstructural properties of ultra-high performance cementitious composites, Cem. Concr. Compos. 56 (2015) 25–31.
[26] R. Yu, P. Spiesz, H.J.H. Brouwers, Effect of nano-silica on the hydration and microstructure development of Ultra-High Performance Concrete (UHPC) with a low binder amount, Constr. Build. Mater. 65 (2014) 140–150.
[27] K. Wille, A.E. Naaman, Effect of Ultra-high-performance concrete on pullout behavior of high-strength brass-coated straight steel fibers, ACI Mater. J. 110 (4) (2013).
[28] TS EN 197-1, Cement- Part 1: Composition, specifications and conformity criteria for common cements, Turkish Standards, 2002.
[29] ASTM C494/C494M-13, Standard Specification for Chemical Admixtures for Concrete, ASTM International, West Conshohocken, PA, 2013. <www.astm.org>.
[30] ASTM C39, Standard test method for compressive strength of cylindrical concrete specimens, in: Annual Book of ASTM Standard, 2012.

[31] ASTM C496, Standard test method for splitting tensile strength of cylindrical concrete specimens, in: Annual Book of ASTM Standard, 2011.
[32] ASTM C469, Standard test method for static modulus of elasticity and Poisson's ratio of concrete in compression, in: Annual Book of ASTM Standard, 2010.
[33] A. Hillerborg, Concrete fracture energy tests performed by 9 different laboratories according to a draft RILEM recommendation. Lund Sweden, Report to RILEM TC50-FMC, Report TVMB-3015, 1983.
[34] RILEM 50-FMC. Committee of fracture mechanics of concrete, Determination of fracture energy of mortar and concrete by means of three-point bend tests on notched beams, Mater. Struct. 18 (106) (1985) 285–290.
[35] K.D. Ravindra, N.A. Henderson, Specialist Techniques and Materials for Concrete Production, Thomas Telford Publishing, Thomas Telford Ltd, 1999.
[36] B. Akcay, A.S. Agar Ozbek, F. Bayramov, H.N. Atahan, C. Sengul, M.A. Tasdemir, Interpretation of aggregate volume fraction effects on fracture behavior of concrete, Constr. Build. Mater. 28 (2012) 437–443.
[37] A. Hillerborg, Theoretical basis of method to determine fracture energy GF of concrete, Mater. Struct. 18 (1985) 291–296.
[38] H. Pengkun, Q. Jueshi, C. Xin, P.S. Surendra, Effects of the pozzolanic reactivity of nanoSiO_2 on cement-based materials, Cem. Concr. Compos. 55 (2015) 250–258.
[39] H. Madani, A. Bagheri, T. Parhizkar, The pozzolanic reactivity of monodispersed nanosilica hydrosols and their influence on the hydration characteristics of Portland cement, Cem. Concr. Res. 42 (2012) 1563–1570.
[40] B. Jo, C.H. Kim, Gh. Tae, J.B. Park, Characteristics of cement mortar with nano-SiO_2 particles, Constr. Build. Mater. 21 (2007) 1351–1355.
[41] A. Pourjavadi, S.M. Fakoorpoor, A. Khaloo, P. Hosseini, Improving the performance of cement-based composites containing superabsorbent polymers by utilization of nano-SiO_2 particles, Mater. Des. 42 (2012) 94–101.
[42] G. Quercia, P. Spiesz, G. Husken, J. Brouwers, Effects of amorphous nano-silica additions on mechanical and durability performance of SCC mixtures, in: Proc. International Congress on Durability of Concrete, 2012.
[43] L. Senff, D. Hotza, W.L. Repette, V.M. Ferreira, J.A. Labrincha, Influence of added nanosilica and/or silica fume on fresh and hardened properties of mortars and cement pastes, Adv. Appl. Ceram. 108 (7) (2009) 418–428.
[44] E. Ghafari, H. Costa, E. Júlio, et al., The effect of nanosilica addition on flowability, strength and transport properties of ultra high performance concrete, Mater. Des. 59 (2014) 1–9.
[45] R.F. Feldman, J.J. Beaudoin, Microstructure and strength of hydrated cement, Cem. Concr. Res. 6 (1976) 389–400.
[46] N. Banthia, Fiber Reinforced Concrete, ACI SP-142ACI, Detroit, MI, 1994. pp. 91–119.
[47] P.F. Torgal, S. Miraldo, Y. Ding, J.A. Labrincha, Targeting HPC with the help of nanoparticles: an overview, Constr. Build. Mater. 38 (2013) 365–370.
[48] A.M. Said, M.S. Zeidan, M.T. Bassuoni, Y. Tian, Properties of concrete incorporating nano-silica, Constr. Build. Mater. 36 (2012) 838–844.
[49] B.B. Mukharjee, S.V. Barai, Influence of nano-silica on the properties of recycled aggregate concrete, Constr. Build. Mater. 55 (2014) 29–37.
[50] O. Gencel, W. Brostow, T. Datashvili, M. Thedford, Workability and mechanical performance of steel fiber-reinforced self-compacting concrete with fly ash, Compos. Interfaces 18 (2) (2011) 169–184.
[51] Saloma et al., Experimental investigation on nanomaterial concrete, Int. J. Civ. Environ. Eng. 13 (03) (2013) 15–20.
[52] M. Amin, K. Abu el-hassan, Effect of using different types of nano materials on mechanical properties of high strength concrete, Constr. Build. Mater. 80 (2015) 116–124.
[53] R. Yu, P. Tang, P. Spiesz, H.J.H. Brouwers, A study of multiple effects of nano-silica and hybrid fibres on the properties of ultra-high performance fibre reinforced concrete (UHPFRC) incorporating waste bottom ash (WBA, Constr. Build. Mater. 60 (2014) 98–110.
[54] M.H.A. Beygi, M.T. Kazemi, I.M. Nikbin, J.V. Amiri, The effect of water to cement ratio on fracture parameters and brittleness of self-compacting concrete, Mater. Des. 50 (2013) 267–276.
[55] E. Guneyisi, M. Gesoglu, T. Ozturan, S. Ipek, Fracture behavior and mechanical properties of concrete with artificial lightweight aggregate and steel fiber, Constr. Build. Mater. 84 (2015) 156–168.
[56] P.E. Petersson, Fracture energy of concrete: practical performance and experimental results, Cem. Concr. Res. 10 (1) (1980) 91–101.
[57] J. Zhang, C.K.Y. Leung, S. Xu, Evaluation of fracture parameters of concrete from bending test using inverse analysis approach, Mater. Struct. 43 (2010) 857–874.
[58] H. Eskandari, S. Muralidhara, B.K.R. Prasad, B. Venkataramareddy, Size effect in self-consolidating concrete beams with and without notches, Sadhana 35 (2010) 303–317.