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Effect of nanosilica addition on the mechanical properties of cement mortars with basalt fibers with or without silica fume

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ABSTRACT

Fiber reinforced concrete is widely used throughout the world however to reveal its full potential, optimization with different additives should be asserted. In this study, effect of the three different parameters were diagnosed by means of compressive strength, flexural strength and fracture. Ordinary Portland cement mortars were studied with three different basalt fiber contents (0, 0.5, 1%), three different nanosilica addition (0, 1, 2% by wt. of cement) and also silica fume incorporation (0, 5% by wt. of cement). The results showed that adding basalt fiber significantly improved the flexural strength and toughness properties and also with the addition of nanosilica the increase in flexural strength boosted up to 23% level of increase at the presence of silica fume. This synergy effect was found to be significant when incorporating basalt fibers. When nonfibrous specimens were inspected, it is seen that addition of nanosilica was not significantly efficient increasing neither the flexural strength nor fracture properties.

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1. INTRODUCTION

Concrete is the most widely used material construction-al material owing to its remarkable features such as easy molding abilities and ease of supply of the ingredients, high strength and low cost. Nanotechnology is an evolving area of research in material science. Application of ultra-fine additives such as nanosilica is to enhance several properties of the composite. Micro and nano-scaled silica particles exhibit ultra-fine filler effect stimulating the internal cement matrix structure by filling voids with minimal sizes [1].

Nanosilica is the most popular nanomaterial used in the cementitious materials due to its pozzolanic reactivity along with the void-filling abilities. Nanosilica incorporation into concrete results in denser and compact microstructure due to refinement of the pore structure and accordingly permeability is also decreased with the help of nanofilling and pozzolanic characteristics [2, 3]. Nanosilica also serves as a siliceous precursor and acts as a nucleation site to promote further hydration [4]. Another important issue to deal with the proper implementation of nanosilica particles into the cement matrix when mixing since due to its large specific surface area, risk of agglomeration arises [5–7].

Basalt fiber is a new type of inorganic fiber which is being produced from the basalt rock [8]. This type of fibers have several superiorities with respect to others considering

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the environmental issues construction sector has been facing in the last decades. Manufacturing process is although similar to others like glass fibers, production of basalt fibers consume less energy and no additives are needed [9, 10].

Mechanical performance and chemical endurance properties are also more than adequate to facilitate in structural concrete. Besides high tensile strength and good chemical resistance, basalt fibers provide resistance to high temperature, increase in strain capacity, high modulus of elasticity [11]. Production process of basalt fibers is also simple, inexpensive and environmentally friendly creating a perfect sustainable perspective [12].

However, provided that research on these fibers are still limited, in order to increase the use in standard construction facilities, additional studies should be conducted to investigate on the dual or ternary usage of these fibers with different additives. These studies may both optimize the use of basalt fibers and also increase the performance of reinforcing activity by enhancing the cement matrix adhering the fiber structure.

2. MATERIALS AND METHODS

2.1 Materials

CEM I 42.R ordinary portland cement and silica fume were used as binders whereas 0–2 mm river sand was adopted as fine aggregates for mortar specimens. Nanosilica was purchased from Nanografi. Basalt fibers were also used as fiber reinforcements. Properties of materials used are given in Tables 1 and 2.

2.2 Mortar Specimen Preparation

Mortar specimens were prepared conforming to the specifications given in TS EN 196-1 [13]. 18 different mortar specimens were prepared incorporating two different silica fume content (0, 0.5%) and three different nanosilica content (0, 1%, 2%) and three different basalt fiber content (0, 0.5, 1%). For each series, 3 prism specimens for 3, 7 and 28 day flexural and compressive tests were produced whereas 2 more specimens were also produced for 28-day flexural toughness measurements. Mixtures were constructed with constant binder:sand:water ratio as 2:2:1 and mixture proportions were given in Table 1. A total of 187 specimens were cast into 40 x 40 x 160 mm steel molds.

Nanoparticles were mixed with a part of mixture water for uniform dispersion. Firstly, binder and sand were blended for 60 seconds in a Hobart mixer and then the aqueous nano-additive suspension was added to the mixture for 60 seconds and basalt fibers were added in a duration of 60 seconds and final mixture was further mixed for 120 seconds more to achieve the proper homogeneity for all mixtures. All specimens were kept in the molds for 24 h in a moist room at a temperature of (23±2) °C and relative humidity of 95%. After demolding specimens were placed in water tanks at 20 ˚C until the age of testing (Table 3).

Table 1. Properties of basalt fibers

Diameter (μm)	Length (mm)	Tensile strength (MPa)	Elasticity (GPa)	Density (kg/m^3)
9–23	12	4840	89	2700

2.3 Flowability of Mortar Specimens

Flowability of fresh mortars were conducted according to ASTM C1437-15 [14]. Flow mold with a 50 mm height was placed on the jumping table and filled as two layers of mortar by tamping 20 times for each layer before lifting the mold. After lifting the mold, 25 strokes were applied to the fresh mortar in 15 seconds using the jumping table. Average diameter of the spread mortar mixture was measured in two perpendicular directions of the spread mix to determine the flowability of the mortar mixtures.

2.4 Mechanical Testing of Specimens

The flexural and compressive strengths were measured at the ages of 3, 7 and 28 days according to TS EN 196-1 [13]. Mortar specimens were loaded until crushing under three-point flexural loading with a displacement rate of 0.5 mm/min by a servo-hydraulic closed loop-controlled flexural loading machine with 100 kN maximum force capacity. The span length for flexural loading was used as 120 mm. The load-displacement curves were obtained by the 2 LVDTs that were attached to two sides of the prism specimen and the vertical deflection was taken as the average of these 2 recordings. Three-point loading test results were used to assess the flexural stress values by Equation 1:

$$\sigma = \frac{3PL}{2bd^2} \tag{1}$$

where σ is the flexural stress; P is the maximum load; d, b and L are the depth, width and span length, respectively. The compressive strength tests were carried out at a loading rate of 0.5 MPa/sec on the half prisms that were formed after the three-point bending test.

Fracture toughness is a significant parameter to monitior the toughness capacity of cementitious materials. Toughness of the mortar matrix was examined by applying the specifications given in ASTM C1609 [15]. Tough-

Table 2. Properties and compositions of cement and silica fume

Composition (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI	Density (kg/m^3)
Cement	19.81	5.58	3.42	63.70	1.22	3.34	0.24	0.66	1.85	3110
Silica fume	96.31	0.91	0.42	0.78	0.43	–	–	–	1.20	2350

Table 3. Mix proportions of cement mortar specimens

Mixture	Cement (g)	Silica fume (g)	Sand (g)	Water (g)	Nanosilica(g)	Basalt fiber (g)
Control	1000	0	1000	500	0	0
SF0NS0BF0.5	1000	0	1000	500	0	12.5
SF0NS0BF1	1000	0	1000	500	0	25
SF0NS1	990	0	1000	500	10	0
SF0NS1BF0.50	990	0	1000	500	10	12.5
SF0NS1BF1	990	0	1000	500	10	25
SF0NS2	980	0	1000	500	20	0
SF0NS2BF0.5	980	0	1000	500	20	12.5
SF0NS2BF1	980	0	1000	500	20	25
SF5	950	50	1000	500	0	0
SF5NS0BF0.5	950	50	1000	500	0	12.5
SF5NS0BF1	950	50	1000	500	0	25
SF5NS1	940	50	1000	500	10	0
SF5NS1BF0.5	940	50	1000	500	10	12.5
SF5NS1BF1	940	50	1000	500	10	25
SF5NS2	930	50	1000	500	20	0
SF5NS2BF0.5	930	50	1000	500	20	12.5
SF5NS2BF1	930	50	1000	500	20	25

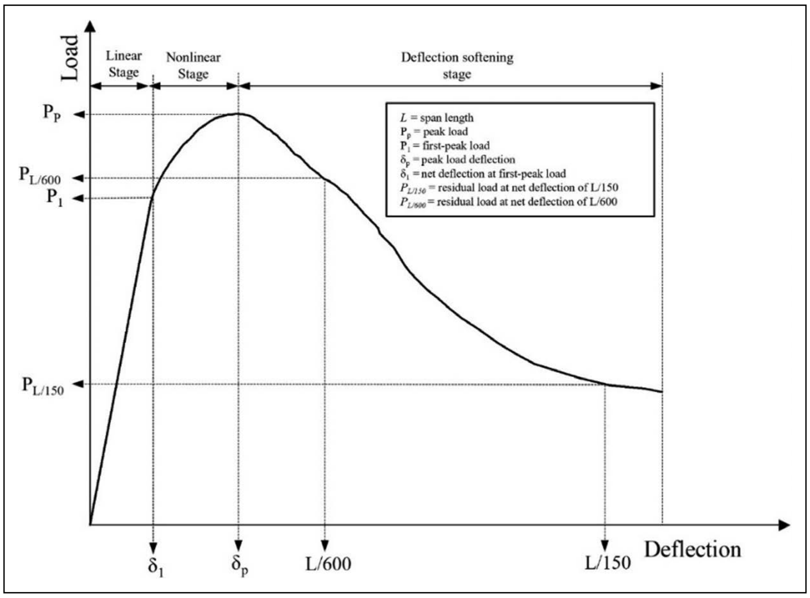

Figure 1. The load-deflection response curve.

ness values were calculated as the net area under load-displacement curves between the zero deflection and net deflection points. Net deflection points were selected as L/150 and L/600 according to ASTM C1609. Load ($P_{L/600}$ and $P_{L/150}$) and energy absorption ($T_{L/600}$ and $T_{L/150}$) values were also obtained.

Toughness results were obtained by the load-deflection curves as given in Figure 1. As depicted in Figure 1, flexural behaviour is inspected in 3 different stages. First stage is the linear elastic region also known as pre-crack stage, second stage is the non-linear stage whereas the third stage is the deflection softening stage also called post crack stage. In the first stage, flexural capacity of the cement matrix is of importance and when the loading exceeds the first crack load, cement matrix in the tensile zone is cracked thus triggering the nonlinear propagation upto the peak load. After the peak load, deflection softening stage occurs with the decreasing amount of loading.

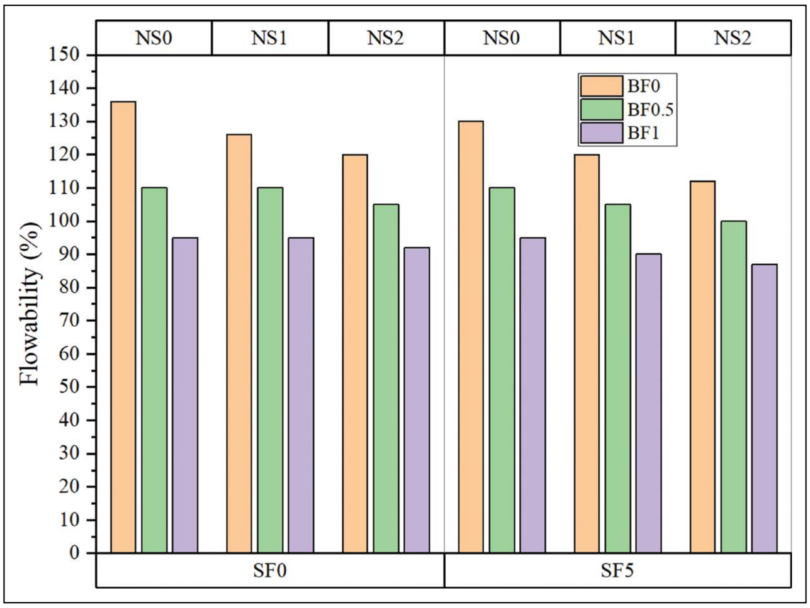

Figure 2. Flowability test results of mixtures.

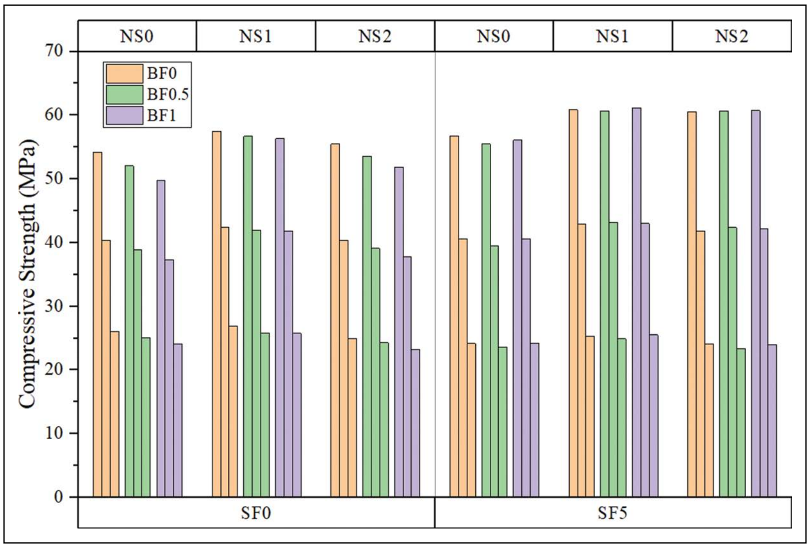

Figure 3. 3, 7 and 28-day compressive strength results.

3. RESULTS AND DISCUSSION

3.1 Workability

Flowability measurements were taken for 18 different mixtures and the results were illustrated in Figure 2. All mixtures were found to be in good workability to produce enough compaction in the steel molds. When all results are compared, it is seen with the increase of all three parameters flowability was influenced adversely. Most significant effect was noticed with the inclusion of the fibers and silica fume addition was the second whereas addition of nanosilica was third. This may be related to the addition of nanoparticles in relatively very small amounts. These results were all found to be relevant since both additions of fibers and addition of micro and nano sized particles affect the workability in earlier studies in literature.

3.2. Compressive and Flexural Strength Results

3, 7 and 28-day average compressive strength results of 6 tests for each mixture type are given in Figure 3.

Compressive strength test results reveal significant findings on the effect of the parameters used in the study. When 28-day results are compared, as anticipated compressive strength of the specimens were found to be increased with the addition of silica fume for all specimen series. Addition of basalt fibers caused a decrease in overall compressive strength values which may also be related to defi-

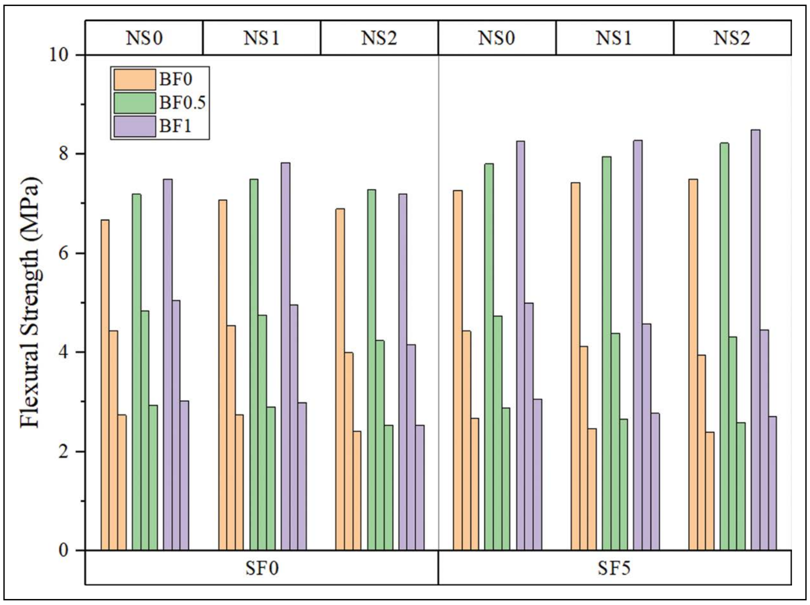

Figure 4. 7 and 28-day flexural strength results of specimens with different additive ratios.

ciencies in the overall matrix integrity due to presence of fibers. With the increase in the fiber content, decrease in the compressive strength was observed to be more critical. Dias and Thaumaturgo reported 3.9% decrease in compressive strength with the fiber content of 0.5% [16]. Nanosilica particles were also found to be efficient enhancing the compressive strength, however with higher amount of nanoparticles were found to be problematic when there is no silica fume in the mixture. Thus, combined effect of these parameters exhibited significant effect on the results. When silica fume is present in the mixture, addition of higher amount of nanosilica was similar to lower amount of nanosilica added specimens. Li et al. [17] investigated the synergy of using nanosilica and silica fume together and reported significant improvement in durability. Brescia-Norambuena et al. [18] also investigated combined use of nanosilica and silica fume and reported important improvements in the mechanical properties.

When 7 day results are examined, similar results were found with respect to 28 day results. However, overall findings were noticed to be closer to each other. Effect of extra nanosilica adversely affected the strength when used without silica fume. When 3 day results are examined, it is seen that mixtures with silica fume were found to have lesser strength which may be explained by the pozzolanic reactions. Also addition of nanosilica was not effective which may also be explained by the puzzolanic activity appearing later.

28-day flexural strength results reveal that inclusion of basalt fibers were significantly effective increasing the ultimate flexural strength (Fig. 4). Control specimens exhibited 7 and 12% increase with the addition of basalt fibers respectively without any other additive. For specimens with

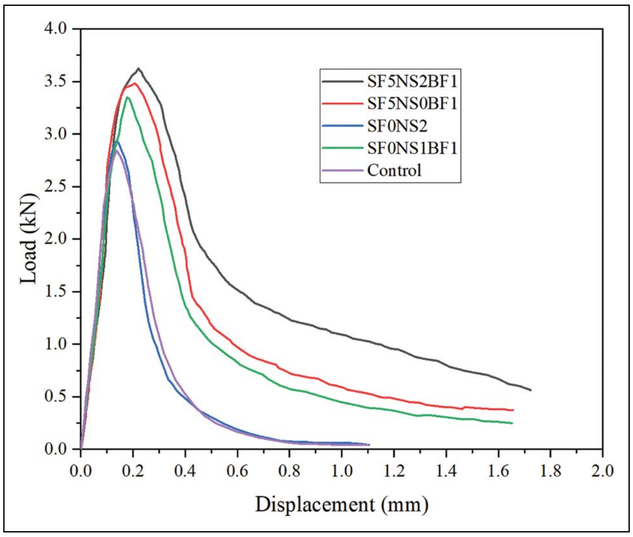

Figure 5. Load-deflection curves.

lower nanosilica addition, basalt fibers were also found to be effective with increases of 12 and 17% although no silica fume was added. However, when there is no silica fume addition, higher NS levels were monitored to have lesser progress. This may be related to possible negative effect of high NS level on the structural integrity of the cement matrix. When specimens with SF are considered, this effect was found to be diminished. Higher NS level was also found to be more effective than all other specimen series. Thus, highest increase in the flexural strength was obtained for SF5NS2BF1 series. It should be clearly said that presence of SF contributes to effectiveness of NS particles in the cement matrix thus promoting their effect on the overall microstructure [18].

Table 4. Results for the flexural toughness

Specimens	P_p (N)	δ_p (mm)	$P_{L/600}$ (N)	$P_{L/150}$ (N)	$T_{L/600}$ (N.mm)	$T_{L/150}$ (N.mm)
Control	2.85	0.137	2.33	0.063	718	411
SF0NS0BF0.5	3.07	0.157	2.57	0.499	1078	424
SF0NS0BF1	3.20	0.177	2.85	0.574	1219	436
SF0NS1	3.02	0.135	2.30	0.065	731	416
SF0NS1BF0.50	3.20	0.155	2.69	0.547	1110	438
SF0NS1BF1	3.34	0.178	3.20	0.569	1265	438
SF0NS2	2.94	0.137	2.24	0.072	692	402
SF0NS2BF0.5	3.11	0.148	2.42	0.626	1010	426
SF0NS2BF1	3.07	0.169	2.80	0.687	1139	418
SF5	3.10	0.147	2.46	0.071	790	445
SF5NS0BF0.5	3.33	0.177	2.97	0.716	1289	436
SF5NS0BF1	3.53	0.206	3.48	0.721	1424	469
SF5NS1	3.17	0.149	2.49	0.067	782	466
SF5NS1BF0.5	3.39	0.189	3.19	0.757	1437	456
SF5NS1BF1	3.53	0.212	3.48	1.188	1785	453
SF5NS2	3.20	0.144	2.40	0.072	799	456
SF5NS2BF0.5	3.51	0.197	3.49	0.785	1476	442
SF5NS2BF1	3.62	0.220	3.56	1.227	1731	454

When 7-day flexural strength values are investigated, similar adverse effect of higher NS level specimens without SF were also noted. Also, it should be clarified that due to pozzolanic activity improvements in the flexural strength were limited with respect to 28-day results. In 3-day results, similar conditions were noticed and especially for this curing period, effect of basalt fibers were also diminished since earlier reactions were limited which affect the interface between the cement matrix and the fibers.

3.3. Fracture Toughness

The load versus deflection graph under flexural loading is given in Figure 5. Each curve resembles the average values of the load-deflection curves for each specimen set which are obtained accurately by using the procedure described in a previous study [19].

Fracture findings exhibited consistent results with the flexural strength results generally (Table 4). Fibrous specimens showed promising results in terms of energy absorption resisting higher loading levels after cracking [20]. Also, peak load values were also higher than specimens without fibers. Contribution of silica fume was also significant for fracture results which may be related to better transition zone between the fibers and the cement matrix. Higher specific surface area of silica fume has acted as microfiller on the bondage of the fibers to the cement matrix increasing the adherence. Also, NS addition was effective especially for mixtures with silica fume, inclusion of NS increased the peak load and also the energy absorption capacity. However, when nonfibrous specimens were compared, similar findings were noted.

4. CONCLUSION

As a result of this study, considerable insight has been gained about the use of basalt fibers in presence of silica fume and nanosilica and the findings on the mechanical properties are summarized as follows:

Addition of basalt fibers adversely affected the compressive strength results between 4%–9%. However, with the presence of silica fume this adverse effect diminished. Flexural strength values were improved with the increasing amount of basalt fibes up to a value of 27%. However, this increase was limited with only 12% without any other addition.

Addition of silica fume into all mixtures were found to be effective for both compressive and flexural strength values. 8% increase was detected for SF addition alone. Also it should be reported that presence of SF increased the effeciency of NS particles increasing the overall contribution by dual usage in cement matrix.

Nanosilica addition was found to be effective for both fibrous and unfibrous specimens and these improvements were found to be the highest when used ternary. Highest increase in compressive strength was noted as 12% for NS2SF5BF1.

Investigating the effect of the synergy of the three important additives into the cement matrix presented promising results that may give contribution to the growing body of literature on the use of micro and nanoscale pozzolanic additives in cementitious composites.

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DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The author declared that this study has received no financial support.

PEER-REVIEW

Externally peer-reviewed.

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