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 constructional 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...
the environmental issues construction sector has been fac-
ing 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 prop-
erties are also more than adequate to facilitate in structural
concrete. Besides high tensile strength and good chemical
resistance, basalt fibers provide resistance to high tempera-
ture, increase in strain capacity, high modulus of elasticity
[11]. Production process of basalt fibers is also simple, in-
expensive 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 construc-
tion 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 rein-
forcing activity by enhancing the cement matrix adhering
the fiber structure.

2. MATERIALS AND METHODS

2.1 Materials

CEM I 42.5 R ordinary portland cement and silica fume
were used as binders whereas 0–2 mm river sand was ad-
opted 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 mor-
tar 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 where-
as 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 pro-
portions 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 wa-
ter 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 mix-
ture for 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).

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 deter-
mine 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 ca-
pacity. 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 spec-
imen 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:

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

where $\sigma$ 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 af-
fter the three-point bending test.

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

| Composition (%) | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | CaO | MgO | SO$_3$ | Na$_2$O | K$_2$O | 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             |
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 up to the peak load. After the peak load, deflection softening stage occurs with the decreasing amount of loading.

### 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               |
| SF0NS1BF0.5 | 990        | 0               | 1000     | 500       | 10             | 12.5            |
| SF0NS2      | 980        | 0               | 1000     | 500       | 20             | 0               |
| SF0NS2BF0.5 | 980        | 0               | 1000     | 500       | 20             | 12.5            |
| SF0NS2BF1   | 980        | 0               | 1000     | 500       | 20             | 25              |
| SF3         | 950        | 50              | 1000     | 500       | 0              | 0               |
| SF3NS0BF0.5 | 950        | 50              | 1000     | 500       | 0              | 12.5            |
| SF3NS0BF1   | 950        | 50              | 1000     | 500       | 0              | 25              |
| SF3NS1      | 940        | 50              | 1000     | 500       | 10             | 0               |
| SF3NS1BF0.5 | 940        | 50              | 1000     | 500       | 10             | 12.5            |
| SF3NS1BF1   | 940        | 50              | 1000     | 500       | 10             | 25              |
| SF3NS2      | 930        | 50              | 1000     | 500       | 20             | 0               |
| SF3NS2BF0.5 | 930        | 50              | 1000     | 500       | 20             | 12.5            |
| SF3NS2BF1   | 930        | 50              | 1000     | 500       | 20             | 25              |
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-
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 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].
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 fibers 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 efficiency 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.

### Table 4. Results for the flexural toughness

| Specimens       | $P_y$ (N) | $\delta_p$ (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               |
| SF0NS1BF0.5     | 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              | 435               |
| 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               |
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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 declare that they have no financial support.

PEER-REVIEW

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REFERENCES

[1] Singh, L. P., Karade, S. R., Bhattacharyya, S. K., Yousuf, M. M., Ahalawat, S. (2013). Beneficial role of nanosilica in cement based materials – A review. Construction and Building Materials, 47, 1069–1077. [CrossRef]

[2] Rong, Z., Sun, W., Xiao, H., & Jiang, G. (2015). Effects of nano-SiO₂ particles on the mechanical and microstructural properties of ultra-high-performance cementitious composites. Cement and Concrete Composites, 56, 25–31. [CrossRef]

[3] Liu, X., Feng, P., Shu, X., & Ran, Q. (2020). Effects of highly dispersed nano-SiO₂ on the microstructure development of cement pastes. Materials and Structures/Materiaux et Constructions, 53(1), 4. [CrossRef]

[4] Wang, J., Du, P., Zhou, Z., Xu, D., Xie, N., & Cheng, X. (2019). Effect of nano-silica on hydration, microstructure of alkali-activated slag. Construction and Building Materials, 220, 110–118. [CrossRef]

[5] Kong, D., Su, Y., Du, X., Yang, Y., Wei, S., & Shah, S. P. (2013). Influence of nano-silica agglomeration on fresh properties of cement pastes. Construction and Building Materials, 43, 557–562. [CrossRef]

[6] Kong, D., Corr, D. J., Hou, P., Yang, Y., & Shah, S. P. (2015). Influence of colloidal silica sol on fresh properties of cement paste as compared to nano-silica powder with agglomerates in micron-scale. Cement and Concrete Composites, 63, 30–41. [CrossRef]

[7] Kong, D., Pan, H., Wang, L., Corr, D. J., Yang, Y., Shah, S. P., & Sheng, J. (2019). Effect and mechanism of colloidal silica sol on properties and microstructure of the hardened cement-based materials as compared to nano-silica powder with agglomerates in micron-scale. Cement and Concrete Composites, 98,137–149. [CrossRef]

[8] Militký, J., Kovačič, V., & Rubnerová, J. (2002). Influence of thermal treatment on tensile failure of basalt fibers. Engineering Fracture Mechanics, 69(9), 1025–1033. [CrossRef]

[9] Sim, J., Park, C., & Moon, D. Y. (2005). Characteristics of basalt fiber as a strengthening material for concrete structures. Composites Part B: Engineering, 36(6–7), 504–512. [CrossRef]

[10] Pehlivan, A. O. (2021). Mechanical properties of magnesium phosphate cement incorporating basalt fibers. Cement Wapno Beton, 26(3), 233–241.

[11] Fiore, V., Scalici, T., Di Bella, G., & Valenza, A. (2015). A review on basalt fibre and its composites. Composites Part B: Engineering, 74, 74–94. [CrossRef]

[12] Zhang, X., Zhou, X., Xie, Y., Rong, X., Liu, Z., Xiao, X., Liang, Z., Jiang, S., Wei, J., & Wu, Z. (2019). A sustainable bio-carrier medium for wastewater treatment: Modified basalt fiber. Journal of Cleaner Production, 225, 472–480. [CrossRef]

[13] TSI. 2016. TS EN 196-1 - Methods of Testing cement – Part 1: Determination of Strength. Ankara, Turkey.

[14] ASTM international. 2015. C1437 - Standard test method for flow of hydraulic cement mortar. In ASTM International

[15] ASTM international. 2019. ASTM C1609 / C1609M-19a Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading). Conshohocken, PA.

[16] Dias, D. P., & Thaumaturgo, C. (2005). Fracture toughness of geopolymeric concretes reinforced with basalt fibers. Cement and Concrete Composites, 27(1), 49–54. [CrossRef]

[17] Liu, X., Feng, P., Shu, X., & Ran, Q. (2020). Effects of highly dispersed nano-SiO₂ on the microstructure development of cement pastes. Materials and Structures/Materiaux et Constructions, 53(1), 4. [CrossRef]

[18] Brescia-Norambuena, L., González, M., Avudaippan, S., Saavedra Flores, E. I., & Grasley, Z. (2021). Improving concrete underground mining pavements performance through the synergic effect of silica fume, nanosilica, and polypropylene fibers. Construction and Building Materials, 285, 122895. [CrossRef]

[19] Zhao, Z., Kwon, S. H., & Shah S. P. (2008). Effect of specimen size on fracture energy and softening curve of concrete: Part I. Experiments and fracture energy. Cement and Concrete Research, 38, 1049–1060. [CrossRef]

[20] Jiang, C., Fan, K., Wu, F., & Chen, D. (2014). Experimental study on the mechanical properties and microstructure of chopped basalt fibre reinforced concrete. Materials and Design, 58, 187–193. [CrossRef]