Research Article

Flexural Behavior Performance of Reinforced Concrete Slabs Mixed with Nano- and Microsilica

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Present technology has been evaluated greatly over the past decades, where new particles are being designed and fabricated to fulfill specific needs. The field of nano- and micromaterials has prospered in many disciplines. It has been recently used in reinforced concrete in the production of high-strength, high-performance concrete. Microsilica (MS) and nanosilica (NS) particles have proven to be highly profitable to the concrete mix. Concrete has become denser with considerable improvement in their mechanical characteristics, particularly compressive strength. This proposed method includes a comparative study of the flexural bending behavior of conventional reinforced concrete (without MS or NS) slabs with other slabs. Each has various mixes of MS and NS particles incorporated into the concrete mix. The material content utilized in the slabs is kept constant by replacing a portion of the cement with an equivalent amount of either NS or MS particles or both. MS particles are altered from 0, 5, and 10% while NS particles are altered from 0, 0.5, and 1.0%. It cracks the widths and has higher final load-bearing capacity.

1. Introduction

Present-day modern concrete mixes now not satisfy the growing desires for advanced strengths and outstanding durability. Constructions have invaded severe exposure conditions such as those in arid, coastal, and marine environments, where sizable deterioration of systems has been recorded. The need for highly priced restoration and rehabilitation measures has boomed to hold structures to function successfully, at some stages inside the live carrier lives. An evolving need for denser and higher electricity concrete is to be fulfilled nicely by using new contemporary materials that are probably designed and fabricated on a micro- and nanoscale. Material advances have superior micro- and nanosilica that have been efficiently followed to reap immoderate and extremely high-energy concrete that displays exceptional sturdiness characteristics. Cement is the most used advent commodity in some unspecified time in the future of the world. Still, its production consequences in excessive gasoline consumption levels and sizable tiers of surroundings' pollutants are alarming that many European countries have banned its manufacturing [1].

In addition, when emitted into the environment, microsilica (a by-product of industry) leads to high levels of air pollution. The essential strategy is to rid the environment of microsilica emission and reduce cement consumption, hence obtaining superior concrete mixes that are more durable and denser and provide much higher mechanical

TABLE 1: Chemical analysis of used OPC.

Oxides	Al_2O_3	SiO_2	Fe_2O_3	CaO	MgO	SO_3	L.O.I	Insoluble residue
%	4.78	20.38	3.93	62.85	1.95	2.18	2.68	0.69
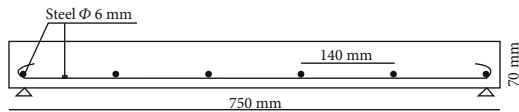
FIGURE 1: Slab mold and reinforcement details.

TABLE 2: Physical properties of microsilica and nanosilica.

Property	Microsilica	Nanosilica
Surface area (cm^2/gm)	170000	240000
Particle size	$1.0\,\mu m$ (1×10^{-6} m)	5 to 20 nm (5 to 20×10^{-9} m)
Specific gravity	2.20	2.40
Unit weight (kg/m^3)	345	505
Colour	Grey	White

strength [2]. Silica fume is collected, refined, and used in concrete mixes in the form of microsilica or nanosilica as a partial substitute for cement, effective on both levels, reducing cement consumption and reducing environmental pollution [3]. Silica fume either nano- or microparticles is pozzolanic in nature. Microsilica (MS) is a polymorph (amorphous) silicon dioxide, but nanosilica (NS) is made up of an amorphous silica (SiO_2) core with a hydroxyl surface [4].

The amorphous structure of nanomaterials such as nanosilica physically affects the hydrate products. Still, the pozzolan material reacts with the carbon hydroxide (CH) generated from the reaction of water with both dicalcium silicate (2CaO). SiO_2 and tricalcium silicate (3CaO·SiO_2). In this process, nanosilica (NS) with particle sizes ranging from 1 to 500 nm is amorphous silicon dioxide, which can accelerate the wetting rate of bonding materials due to their high surface area and amorphous nature [5]. In addition, NS has a relatively high pozzolanic activity, which aids in additional CSH gel formation, as working NS is intended to be a site for CSH gel growth and speeds up the hydration of fly ash and cement [6]. Also, NS particles are smaller than cement and fly ash particles, improving particle packing and purification of porous structures [7–9]. Ultrahigh strength concrete is achieved with minimal pores as the hydrates work to harden between the cement paste and the aggregate particles [10]. It is worth noting that incorporating the methods of nanosilica (NS) in the mix, either by addition or replacement, and the method of its mixing in its either wet or dry condition, both have considerable influence on the mechanical properties of concrete [11]. Effective dispersion of nanosilica particles in concrete mixtures leads to better mechanical and durable properties, resulting in high-strength concrete [12, 13]. Much recent research has

been done on the use of nanomaterials in concrete. Still, only a few studies have examined the use of a mixture of nanosilica and microsilica in concrete [14].

The disadvantages of using micro- and nanoparticles in concrete include the high specific surface area of the binding material. The specific surface area for microsilica is $17\,m^2$/g (70 times greater than OPC), while that for nanosilica is $25\,m^2$/g (100 times greater than OPC). The introduction of nanosilica particles (finer than microsilica) increases the surface area of the mixture's reactive powders, which causes a further decrease in the consistency and operability of the mixture [15]. Consequently, using an effective high-range water reducer is inevitable to maintain consistency and workability of the mix and elevate strength to ultrahigh levels [16, 17]. On the mortar level, micro- and nanosilica cement mortars are highly superior to traditional cement mortars when mixed and cured under high temperatures [18, 19]. Ultrasonic technology under high temperatures is a very effective dispersion technique used in mixing nanosilica particles. Mortar analysis indicates better homogeneity of the mix and superior mechanical strength and superb durability resulting in ultra-high-strength and ultra-high-performance concrete [20–22]. Also, previous researchers mentioned a decrease in porosity and permeability of the slurry as nanomaterials [23] replaced the cement. The study focused on the partial replacement of cement by NS, MS, and a combination of both and their effect on the flexural behaviour of supported one-panel slabs subjected to uniformly distributed loads.

2. Experimental Program

Detailed descriptions of materials used by this investigation, particularly cement, aggregates, steel bar, microsilica, nanosilica, water, and chemical admixtures, are given in this section.

2.1. Material Properties

2.1.1. Cement. Ordinary Portland Cement (OPC) (CEM I 52.5 N) was produced by Beni Suef Cement Factory. The chemical analysis of the used cement supplied by the
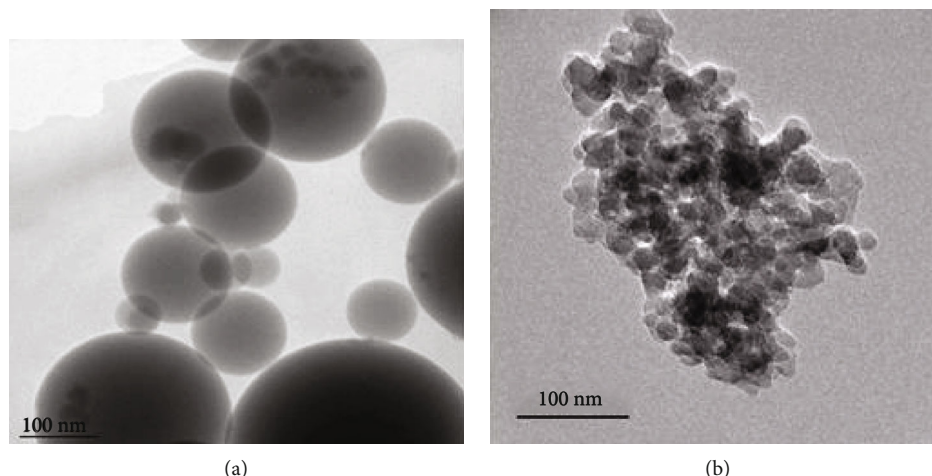
(a)

(b)

Figure 2: Transmission electron microscope (TEM) images of micro- and nanosilica.

Table 3: Chemical analysis of microsilica and nanosilica.

Oxides	Microsilica Result (%)	Nanosilica Result (%)
Al_2O_3	1.10	7.39
SiO_2	96%	92.5
Fe_2O_3	1.45	0.08
CaO	1.2	0.06
MgO	0.18	0.21
SO_3	0.25	0.20
Na_2O	0.45	0.02
K_2O	1.20	0.04
L.O.I	—	0.15
H_2O	0.85	—

manufacturer and the limits according to the Egyptian Standard Specification (ESS) (4756-1/2009) are presented in Table 1.

2.1.2. Aggregates. The coarse aggregate used is crushed dolomite with a specific gravity of 2.6 and a water absorption of 0.95% with a maximum nominal size 10 mm. The fine aggregate is siliceous sand with a specific gravity of 2.57, a fineness modulus of 3.11, and a dry unit weight of 1.78 t/m³ according to the Egyptian Standard Specification—ESS 1109(2002). All aggregates used in this research are locally available from quarries in Andhra Pradesh, India.

2.1.3. Reinforcement Bars. Reinforcement steel rods were used with a nominal diameter of 6 mm and having a yield stress of 269 MPa and ultimate tensile strength of 386 MPa (Figure 1).

2.2. Mineral Admixtures (Pozzolans)

2.2.1. Microsilica. The microsilica used in this research as a mineral admixture is imported from Sisco Research Laboratories (SRL)—Chennai. The manufacture data sheet contains the physical composition, properties, and shape (Table 2 and

Figure 2(a)). The chemical composition of microsilica depends strongly on raw materials and the production process parameters. According to the international standard ASTM 1240-01, pr EN 13263-1 is shown in Table 3).

2.2.2. Nanosilica. The used nanosilica consisting of silicon dioxide with a purity of 99.9% is a product of Sisco Research Laboratories (SRL)—Chennai. The physical properties and shape are obtained from the manufacture data sheet (Table 2 and Figure 2(b)). The chemical analysis of NS used supplied by the manufacturing company is shown in Table 3.

2.2.3. Superplasticizer. The high-performance plasticine mixture Sikament NN was used in this work, which is a third-generation upper plasticizer for homogeneous concrete with a density of 1.185 kg/L and pH value of 8. It meets superior requirements of plasticizers according to ASTMC-494 Types A and F and EN934-2:2001. By using this kind of superplasticizer, we can get very high percentage of water reduction resulting in high density and strength. It also improves shrinkage, creep behavior, and water permeability. The dose used of the superstable plasticizer was maintained at 2.5% by weight of cement for all mixtures.

2.2.4. Test Specimens. Several blends were examined in order to achieve target properties. The pilot program included nine mixtures, all of which were engineered based on the absolute volume of the components in a saturated dry surface condition. All slabs are $750 \times 750 \times 70$ mm in dimensions, reinforced with 6 mm diameter steel bars distributed at 140 mm spacing which was maintained (Figure 1). The mixes (M0N0) include a control mix without any mineral admixture additives. Two other mixes (M5N0 and M10N0) consist of cement replaced by 5% and 10% of microsilica, respectively. Another two mixes (M0N0.5 and M0N1.0) consist of cement replaced by 0.5% and 1.0% of nanosilica, respectively. These previous mixes illustrate the effect of replacing cement by either micro- or nanosilica alone without their combined effect. Another four mixes include

TABLE 4: Test program and contents of mixtures.

Slab no.	Cement (kg/m^3)	Coarse aggregates (kg/m^3)	Fine aggregates (kg/m^3)	Microsilica (kg/m^3)	Nanosilica (kg/m^3)	Water (kg/m^3)	Superplasticizer (kg/m^3)	Notes
M0N0	450	1176	588	0	0	180	11.25	Control
M0N0.5	447.75	1176	588	0	2.25	180	11.25	0.5% NS
M0N1.0	445.5	1176	588	0	4.5	180	11.25	1.0% NS
M5N0	427.5	1176	588	22.5	0	180	11.25	5% MS
M5N0.5	425.25	1176	588	22.5	2.25	180	11.25	5%MS + 0.5%NS
M5N1.0	423	1176	588	22.5	4.5	180	11.25	5%MS + 1.0%NS
M10N0	405	1176	588	45	0	180	11.25	10% MS
M10N0.5	402.75	1176	588	45	2.25	180	11.25	10%MS + 0.5%NS
M10N1.0	400.5	1176	588	45	4.5	180	11.25	10%MS + 1.0%NS

FIGURE 3: Slabs before testing.

FIGURE 4: Ultrasonic device for mixing nanoparticles.

different combinations (M5N0.5, M5N1.0, M10N0.5, and M10N1.0). The first consists of 5% microsilica and 0.5% nanosilica, the second consists of 5% microsilica and 1.0% nanosilica, the third consists of 10% microsilica and 0.5% nanosilica, and the fourth consists of 10% microsilica and 1.0% nanosilica. These four mixes illustrate the combined effect of replacing the cement with a combination of both micro- and nanosilica. The cementitious content of all high-strength concrete mixes is kept constant at 450 kg/m^3 (Table 4); then, twelve cubes with dimensions (100 × 100 × 100 mm) are casted and tested throughout this study to reach the target compressive strength. A constant dose of 2.5% high-range water reducer (superplasticizer) by weight of cementitious materials along with a fixed water/cementitious ratio of 0.4 is maintained for all mixes.

2.2.5. Mixing Procedure. All concrete components were mixed using a horizontal mixer. For mixes without nanosilica, coarse and fine aggregates and cementitious materials (cement and microsilica) were added into the mixer in their dry state and mixed for 2 minutes. The mixing water and superplasticizer were added gradually and mixed for another 3 minutes to get uniform and homogeneous mix consistency and texture. The fresh concrete properties were measured immediately after mixing, and the concrete was removed from the mixer and placed in the slab formwork with the rebar rods distributed correctly and with reasonable cover. Concrete slabs and cube samples were kept in molds for

24 h in air and then removed from the formwork and cured daily by wetting with fresh water for 28 days (Figure 3). For mixes with nanosilica, coarse aggregate, fine aggregate, and cement materials (cement and microsilica) were loaded into the mixer and mixed dry for 2 minutes. Three-fourth of the water content is gradually to dry mix and mix it more for another 1 minute. The superplasticizer dose is added to the remaining quarter of the water content; then, the required amount of nanosilica is added to the water and the superplasticizer and mixed well in an ultrasonic device (Figure 4) for a duration of ten minutes at a temperature of 40°C for achieving the best possible dispersion of nanoparticles in solution and preventing the possibility of any agglomeration. Then, it is added to the wet mixture and then mixed for another four minutes until a homogeneous concrete mixture is obtained.

2.2.6. Setup and Testing. The compressive strength test was conducted on the cured cube specimens (100 × 100 × 100 mm) at ages 28 and 56 days. All cubes exhibited a typical failure mode of a cube (Figure 5) which indicates proper loading of the cube specimens.

The bending test of all panels is performed with a hydraulic jack mounted on the frame of the testing machine. A load cell is placed beneath the jack drum which is connected to a data logger that records readings of simultaneous load and deflection measured with variable linear differential

Figure 5: Hydraulic machine used in a compressive test and mode of a crushed cube.
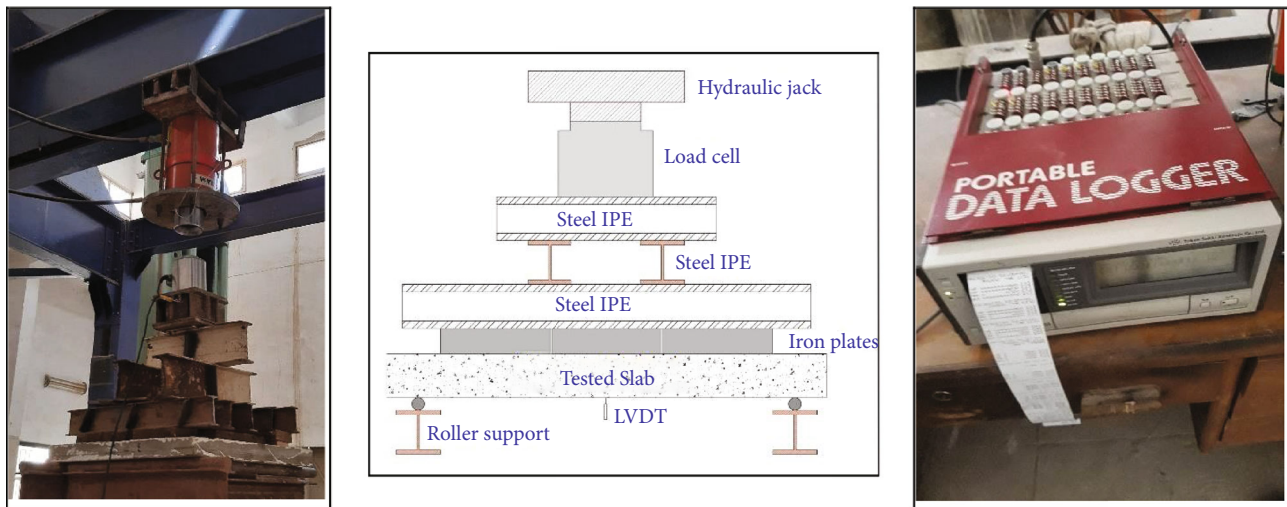

Figure 6: Test preparation and instrumentation.

transformers (VLDTs) located at the center of the slab. A series of I-shaped beams and slabs are stacked in a pyramid shape to transfer the concentrated drum load to a uniformly distributed load on the upper face of the slab (Figure 6).

3. Experimental Results and Discussion

3.1. Compressive Strength. The compression test was conducted on all ratios, the comparison was made between the lowest value of compressive strength M0N0 (control specimen) and the highest value of compressive strength that has the high proportions of the replacement ratio M10N1.0 (10%MS + 1.0%NS) at ages 7 and 28 days. Values of compressive strength are recorded, and the average of three specimens is calculated and values are 27.5 MPa and 30.6 MPa for M0N0 and M10N1.0 at 7 days and 36.6 MPa and 40.7 MPa at 28 days, respectively. Early strength improvement effect of nanosilica-modified concrete is more obvious, which was due to the higher pozzolan activity of nanosilica particles [24, 25].

3.2. Flexural Strength. Samples M0N0, M0N0.5, and M0N1.0 all contain 0% microsilica, with a binder content of 450 kg/m³, a water-cement ratio of 0.4, and a superplasticizer dose of 2.5% cement weight, with 0, 0.5, and 1.0% nano-

silica, respectively. The bending strength at the load causing the initial cracking increased significantly from M0N0 by 7.8% and 15.7% for nanosilica 0.5% and 1.0%, respectively, indicating some resistance to initial cracking of the concrete (Figure 7(a)), whereas the final failure strength has slight increment from M0N0 by 0.42% and 1.26% for 0.5% and 1.0% nanosilica, respectively. This slight improvement in early bending resistance results from simple replacement of cement with nanosilica (Figure 7(b)).

Specimens M0N0, M5N0, and M10N0 that all possessed 0% nanosilica and water-cement ratio 0.4, and the plasticizer superdose is 2.5% by weight of cement, with 0, 5, and 10% of microsilica, respectively.

According to the literature, the microsilica improves the packing properties of the matrix and thus have a noticeable effect on the bending strength. Flexural strength at the initial cracking load increased significantly by 58.6% and 88.0% for 5% and 10% microsilica, respectively, indicating great resistance to initial cracking of the concrete (Figure 7(c)), whereas the final failure strength has increased marginally by 2.1% for 5% microsilica and 4.2% for 10% microsilica (Figure 7(d)). Other researchers note this apparent improvement in the early bending strength of concrete; at 28 days, the microsilica content increases from 5% to 10% [26]. The addition of mineral admixtures results in an increase in all
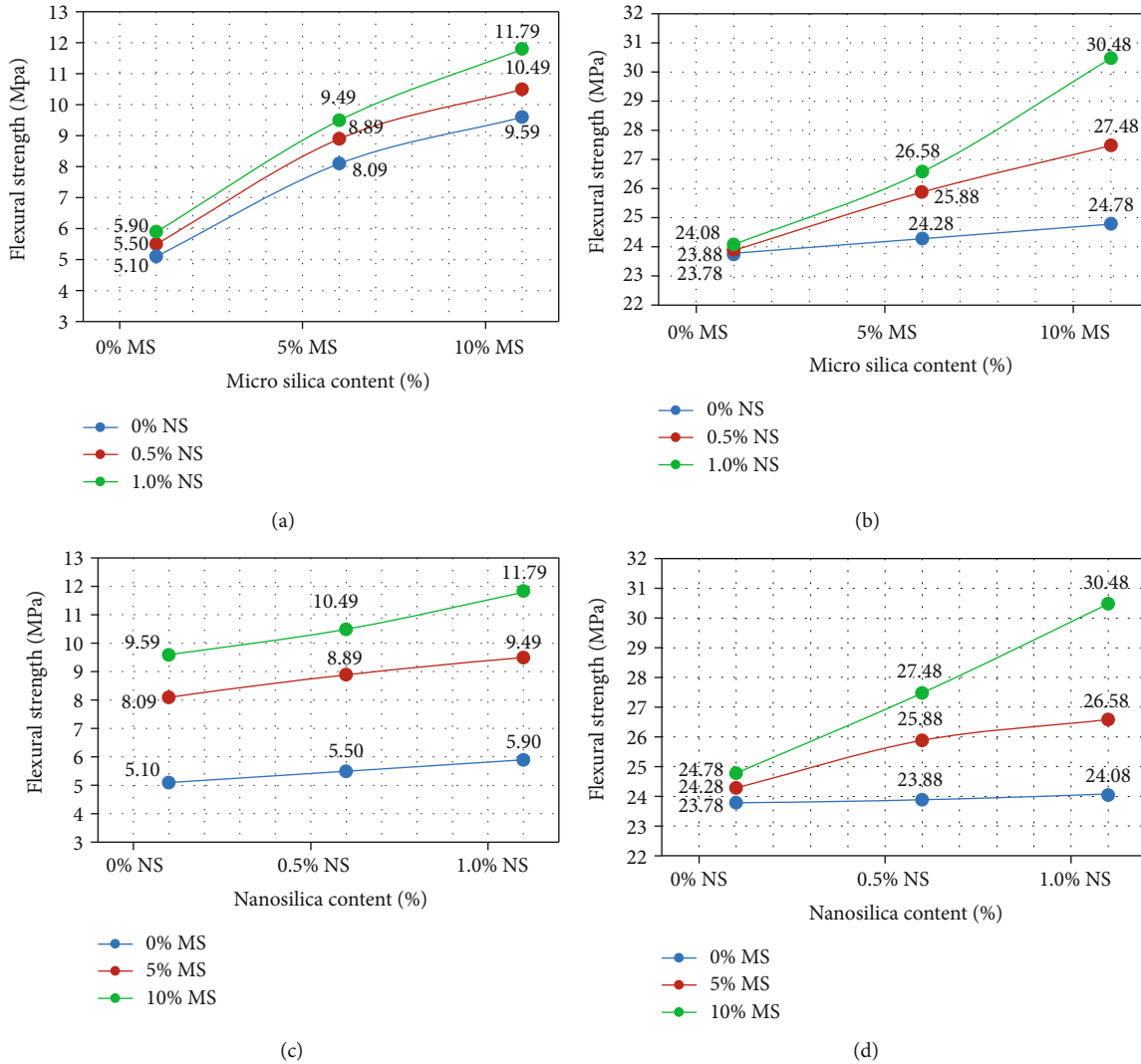
(a)

(b)

(c)

(d)

FIGURE 7: Nano- and microsilica effect on flexural strength of RC slabs.

concrete strengths including compressive, split-tensile, and flexure [27].

A comparison was made between the flexural strength for mixes M5N0, M5N0.5, and M5N1.0 at cracking and failure states, respectively. The cement content in mixes was 450 kg/m³, the silica fume content was 5%, and the content of nanosilica was 0, 0.5, and 1.0%, respectively. The data in figures clearly show a remarkable increase in flexural strength at both cracking and failure states due to a marginal implementation of nanosilica [28]. The flexural strength at cracking increased by 9.9 and17.3% for nanosilica contents 0.5 and 1.0%, respectively (Figure 7(a)), while the flexural strength at failure increased by 6.6 and 9.5% for nanosilica contents 0.5 and 1.0%, respectively (Figure 7(b)). Similar results are recorded for the specimens M10N0, M10N0.5, and M10N1.0 which have the same aggregate, w/c ratio, silica fume content, and curing conditions [29]. The data in figures clearly show an improvement in bending strength as a result of adding nanosilica by 0.5 and 1.0%, where the strength at cracking was increased by about 9.4 and 22.9% (Figure 7(a)), while the strength at failure was increased by

about 10.9 and 23.0% for M10N0.5 and M10N1.0, respectively (Figure 7(b)).

Apparently, the results of implementing nanosilica in the combination or presence of microsilica indicate extra improvement and much higher flexural strengths as compared to nanosilica specimens with no microsilica added [30]. In this study, specimen with 10% microsilica and 1.0% of nanosilica replacement of cement show a superior performance, where the flexural strength of the slab increased by about 131.2% at the cracking state and 28.2% at the failure state as compared to that of the control slab [31].

3.3. Load Deflection Behavior. Incorporation of microsilica alone showed a better pattern of load deflection (Figure 8(a)), compared to incorporating nanosilica alone (Figure 8(b)). As higher loads are achieved with lower deflection values, this may be attributed to the fact that the microparticles together with the cement particles result in better packing characteristics than the nanoparticles with the cement particle [32]. This conclusion is better reinforced
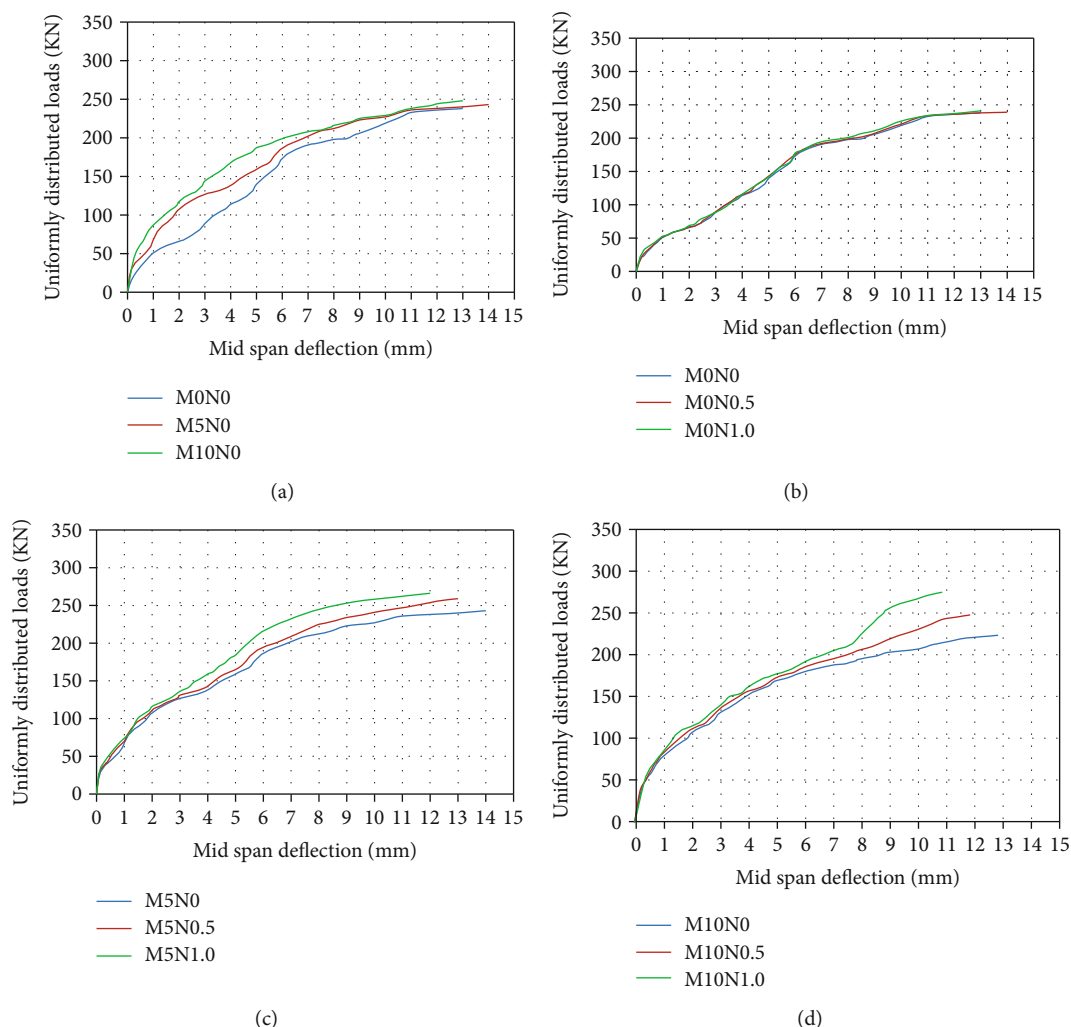
Figure 8: Effect of nanosilica and microsilica on the values of deflection.

when a blend of both nano- and microsilica is used with the cement particle where a better grading of the binding materials is available; hence, a more improved packing result is achieved (Figures 7(d) and 8(c)). Results of the specimen that incorporates 10% microsilica in addition to 1.0% of nanosilica show a superior load deflection curve where higher loads are achieved at lower deflections [33].

This indicates the improved strength of the concrete matrix which is able to resist more compression above the neutral axis of the slab hence considerably affecting its flexural capacity. This improvement can be attributed to the effect of nanosilica and microsilica fillings that have a large surface area which improves chemical reaction because of pozzolanic activity. Hence, additional C-S-H gel was formed for generating more force resulting in less deflection [34].

3.4. Crack Patterns. The reference slab specimen M0N0 exhibited initial cracking at much lower loads, with wider intervals and small width (Figure 9(a)). These cracks extended in length due to the load propagation till the slab failed in flexure at a lower failure load due to the compression failure of the concrete in the top fibers of the slab [35–38]. In addition to silica cement replacing mineral

admixtures either nano- or microparticles, it is realized that the initial cracks occur much later at much higher loads indicating better concrete resistance to cracking (Figures 9(b)–9(i)). These cracks are few in number and wider, which is noticeable when the plate fails, which occurs at a much higher load due to the better performance of the concrete compression area [39–41]. Accordingly, the bending ability of the slab is greatly improved. Similar results have been reported [42] whereas the presence of nanocrystal line silica greatly changes the hardness.

Properties of C-S-H calcium silicate hydrate of the concrete matrix thus improve the bending ability of the reinforced slabs. All previous research has indicated that nanoparticles can improve fresh and hardened-state properties [43].

4. Conclusions

In this research, the experimental program was implemented for studying the effect of using microsilica as well as nanosilica on properties of reinforced concrete slabs. Based on the results obtained, the following main conclusions can be drawn:
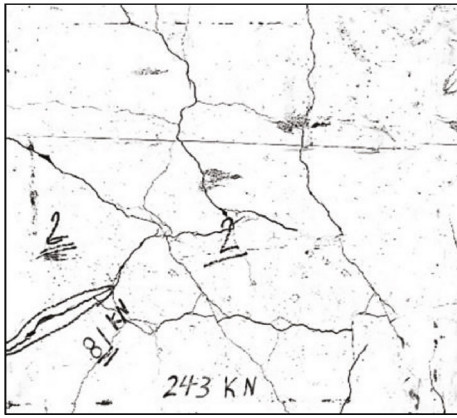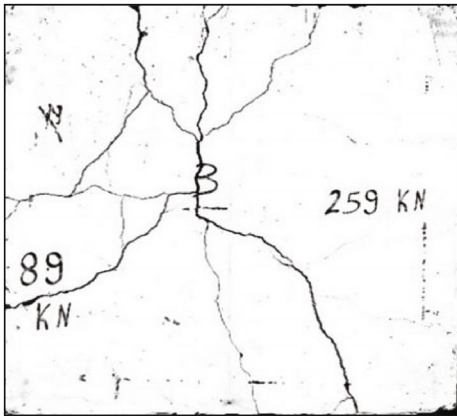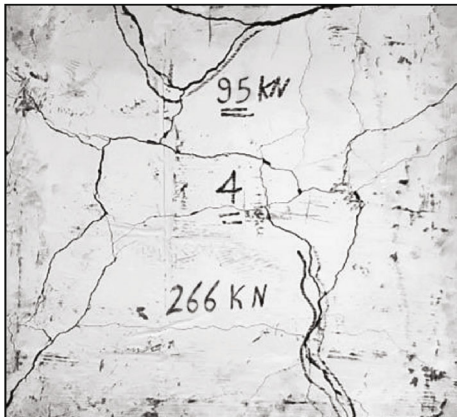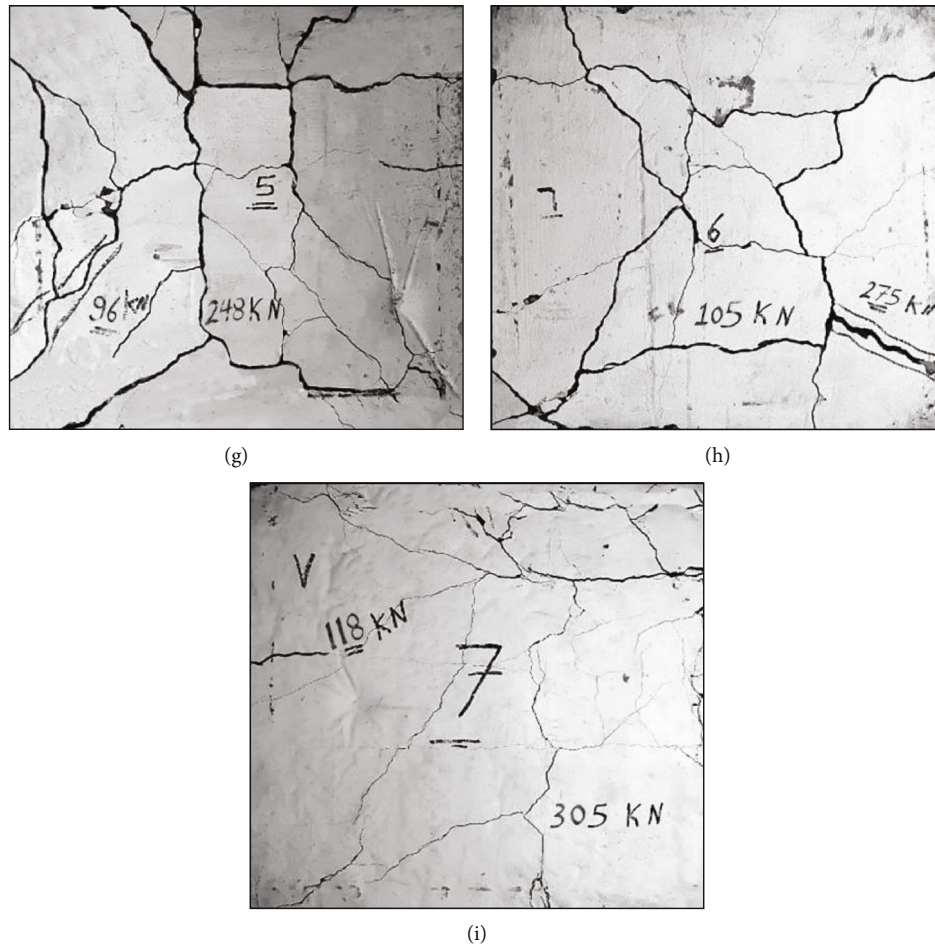
(a)

(b)

(c)

(d)

(e)

(f)

FIGURE 9: Continued.

(g)

(h)

(i)

FIGURE 9: Crack patterns for all test specimens.

(i) Substituting 5% and 10% of cement with microsilica significantly increases bending resistance in both the cracking and failure phases

(ii) Substituting 0.5% and 1.0% cement with nanosilica (in the absence of microsilica) shows good improvement in bending strength of 7.8 and 15.7% in the crushing stage and slight improvement in bending strength of 0.42 and 1.26% in the failure stage, respectively

(iii) Replacing a portion of cement by a combination of nanosilica and 5% microsilica reveals an enhanced improvement in flexural strength of 9.9 and 17.3% at the cracking state and 6.6 and 9.5% at the failure state of 0.5% and 1.0% nanosilica, respectively

(iv) Replacing a portion of cement by a combination of nanosilica and 10% microsilica reveals an enhanced improvement in flexural strength of 9.4 and 22.9% at the cracking state and 10.9 and 23.0% at the failure state of 0.5% and 1.0% nanosilica, respectively

(v) Reinforced slabs with 10% microsilica and 1.0% of nanosilica replacement of cement show a superior performance indicated by the load deflection curve where higher loads are achieved at lower deflections. Hence, the concrete matrix can resist higher compressive strength above the neutral axis by 30.6 MPa and 40.7 MPa at 7 and 28 days, respectively, which considerably affects its flexural capacity, where the flexural strength of the slab increased by 131.2% at the cracking state and 28.2% at the failure state as compared to that of the control slab

(vi) Addition of mineral admixtures of either micro- or nanosilica or a combination of both affects the crack pattern of the slab where cracks are less in number and get wider at failure which occurs at a much higher load due to the better performance of the concrete compression zone

Data Availability

The data used to support the findings of this study are included within the article. Should further data or information be required, these are available from the corresponding author upon request.

Disclosure

It was performed as a part of the employment in Kombolcha Institute of Technology, Wollo University, Kombolcha, Amhara, Ethiopia.

Conflicts of Interest

Acknowledgments

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