Innovative Infrastructure Solutions (2023) 8:191
https://doi.org/10.1007/s41062-023-01157-y

TECHNICAL PAPER

Structural performance of polypropylene fibre-reinforced concrete beams incorporating nanosilica and alccofine

M. C. K. Jamenraja[1] · K. Ravichandran[1]

Received: 13 November 2022 / Accepted: 29 May 2023 / Published online: 14 June 2023

Abstract

The paper presents the results of an experimental study conducted to examine the effectiveness of polypropylene fibres on the strength and deformation capacity of concrete beams containing nanosilica and alccofine. Six beams, each 150 mm in diameter and 250 mm in cross section, totalling 3000 mm in length, were cast and tested. Out of six beams, one was the control beam without polypropylene fibres, nanosilica, or alccofine. One beam was made with concrete containing nanosilica (1%) and alccofine (15%). The remaining four beams were prepared with concrete containing alccofine and nanosilica and having polypropylene fibres in four different volume fractions. The volume fraction of polypropylene fibres was taken as the primary variable. All the beam specimens were subjected to a four-point bending test in a loading testing frame. The results showed that the introduction of polypropylene fibres increased the load capacity by 29.35%, reduced the deflection by 35.81%, and enhanced the ductility by 8%.

Keywords Nanosilica · ANSYS · Deformation capacity · Ductility · Polypropylene fibres · Strength

Introduction

The concrete was used around the world as a construction material and as a standard material because of its properties like strength, durability, reflection, and versatility. Due to these features, it is a reliable long-term choice in many local and business contexts. The cement industry uses a tremendous amount of energy and natural resources, which results in the emission of enormous volumes of carbon dioxide. The cement industry is therefore bad for the environment. At the same time, engineers have developed a novel, multipurpose cementitious composite using nanotechnology and fibres that has great mechanical properties, durability, and perhaps many novel properties, such as low electrical resistance, high ductility, self-healing, and cracking self-control. Nanotechnology in cement is a rapidly developing field. Nanomaterials' constituent parts make it easier to develop new cement admixtures, such as novel plasticisers, superplasticisers, nanoparticles, and nanoreinforcing agents. In the past few years, there has been a significant increase in the usage of nanomaterials in RC structures to address the issue of low concrete tensile strength, and fibre-reinforced concrete is also gaining popularity in the building industry around the world. Therefore, utilisation of these micro- and nanomaterials in construction is a matter of great significance, which can save the usage of cement and energy in concrete production. Numerous studies have been conducted to assess the qualities of concrete, including supplementary cementitious elements such as nanosilica and alccofine with microreinforcement.

Many researchers studied the evaluation of utilising micro- and nanocementitious materials and fibres. The properties of concrete can be improved by using randomly oriented discrete fibres that prevent or control crack propagation or coalescence. Conventional concrete, which consists of hardened cement paste and aggregate, has microcracks and porosity, which can be overcome by using fibres [1, 2], such as polypropylene fibres and steel fibres. The fibre reinforcing technique was developed to use the advantages of fibres, such as their inherently remarkable tensile strength, high toughness, and durability, to delay the formation of the initial fracture and limit the propagation of fractures in concrete [3, 4]. Polypropylene fibres improve post-crack

✉ M. C. K. Jamenraja
mckjamen93@gmail.com

K. Ravichandran
krcrithiesh@gmail.com

1 Department of Civil and Structural Engineering, Annamalai University, Chidambaram, India

resistance, ductility, toughness, fatigue strength, and impact strength in concrete [5–7]. Alccofine is a ground-granulated base slag ultrafine product with a lot of glass and pozzolanic reactivity. Concrete's compressive strength, as well as its fluidity and workability, is improved when alccofine additives are used [8, 9]. Fibre-reinforced concrete with alccofine demonstrated superior durability and strength properties than control concrete. [10–13] Because of its capacity to react with free lime during the cement hydration process, nanosilica has a stronger pozzolanic nature than other nanofiller materials [14], forming more C–S–H gel, which improves the strength and durability of concrete [4]. The nanosilica pozzolanic reaction would occur first, resulting in a relatively high 7-day strength [15, 16], followed by the microsilica pozzolanic reaction, resulting in a relatively high 28-day strength [17, 18]. The combination of 2% nanosilica, 1% nanoalumina, and 0.5% polypropylene fibre had the lowest sorptivity. In addition, the microstructure analysis indicated that the nanomaterials significantly improved the matrix and that the porosity of the matrix was considerably reduced [19]. This research work has been taken up to examine the effect of introducing polypropylene fibres into the concrete containing nanosilica and alccofine. Alccofine 1203 is a slag-based product that has undergone considerable processing to improve its reactivity and glass content. Alccofine was studied by researchers [20, 21] and shown to be an effective pozzolanic substance. Alccofine is produced by the granulation process and results in a controlled distribution of particle size. Jelodar et al. [22] studied an experimental investigation on the mechanical characteristics of cement-based mortar containing nanosilica, microsilica, and PVA fibre. The authors considered 28 mix designs with various percentages of particles and fibres, and 112 different specimens were prepared to conduct the experimental research. The authors concluded that a mix containing 8% silica fume was the optimal mix design in binary mode, whereas 8% silica fume and 2% nanosilica were the optimal mix design in the ternary mode condition. The authors reported a flexural strength improvement of 24% and a compressive strength increase of 49% under the binary mode condition, whereas a flexural strength enhancement of 3.5% and a compressive strength of 4.6% were obtained. Shameer et al. [23] conducted an experimental study on the properties of ternary blended steel fibre-reinforced concrete; the authors were replacing cement with GGBS (35%), and nanosilica (1%), which was found to be the optimum combination. Hooked-end steel fibres were used in volume fractions of 0.5%, 1%, 2%, and 2.5%. The authors carried out compressive strength, flexural strength, and modulus of elasticity tests. The authors concluded that the incorporation of 2% steel fibres resulted in a 70% improvement in flexural strength and a 24.65% increase in modulus of elasticity when compared to the control beam. Murthi et al. [24] investigated enhancing the strength properties of high-performance concrete using ternary blended cement. The authors considered fine aggregate to be composed of 60% river sand and 40% recycled aggregate; crushed rock was used as coarse aggregate. The authors replaced cement with bagasse ash and nanosilica. The authors observed that with the addition of nanosilica up to 1.5%, the initial and final setting times decreased. The authors reported that adding 0.5% and 1% nanosilica increased compressive strength by 38.3% and 80.07%, respectively. Swetha et al. [25] investigated strength and durability studies on steel–fibre-reinforced ternary blended concrete containing nanosilica and zeolite. The authors replaced cement with zeolite and nanosilica. Dramix steel fibres were used in volume fractions of 0.5%, 1%, and 1.5%. Six beam specimens were cast and tested under static loading conditions. The authors found that adding 1% nanosilica, 10% zeolite, and 1.5% fibres resulted in a 40% increase in strength, a 86.83% and 41.66% reduction in deflection and crack width, and a maximum increase of 35.32% in energy ductility and 34.37% in deflection ductility when compared to the reference beam. Tuqa Waleed Ahmed et al. [26] reviewed the properties and performance of polypropylene fibre-reinforced concrete; the authors replaced cement with silica fume. Polypropylene fibres were used in volume percentages of 0%, 0.15%, 0.3%, 0.45%, 0.6%, 0.75%, and 0.9%. The authors reported that 0.6% fibres increased the 24.8% compressive strength, and the increase may be due to high fineness and length variation in the staple, which create a bridge action for preventing the creation of more microcracks. The authors also observed that mechanical properties decreased by more than 0.6% due to fibre inclusion, due to the non-uniform dispersion of fibres leading to a mass collection that created voids. Hemavathi.S. et al., 2019 [27] conducted an experimental investigation on the properties of concrete by using silica fume and glass fibre as admixtures. The authors write that cement has been replaced with 20% silica fume. Natural river sand is replaced with m-sand in three different percentages: 0%, 50%, and 100%. From the experimental results, the optimum percentages were 1% glass fibre, 20% silica fume, and the addition of 30% m-sand to 70% natural sand, achieving maximum compressive strength, flexural strength, and split tensile strength. Sankar et al. [28] studied the experimental and statistical investigation of alccofine-based ternary blended high-performance concrete. The authors reported that higher replacement levels of alccofine (more than 10%) led to a decrease in strength due to the dilution effect. Denser particle packing reduces water absorption in ternary mixes.

The published studies looked at the mechanical properties of concrete using cementitious materials and fibre at the hardening states, as was clear from the previous paragraphs. However, there are not many studies on the effectiveness of reinforced concrete beams when using nanosilica, alccofine,

Table 1 Physical properties of cement

Property	Value
Specific gravity	3.15
Initial setting time	60 min
Final setting time	320 min

Table 2 Physical properties of coarse aggregate

Property	Value
Specific gravity	2.68
Water absorption	0.72
Bulk density	1600 kg/m^3
Shape	Angular

and other kinds of fibres. Therefore, the flexural performance of reinforced concrete beams constructed using nanosilica, alccofine, and polypropylene fibres has been examined and contrasted with a control one in this work.

Research significance

To make concrete more ductile and environmentally friendly, research has been done to change it by adding fibres and partially replacing the cement with micro- and nanofiller. According to the literature reviews, there is minimal data available on ternary blended reinforced concrete beams that are subjected to static loading conditions. An effort has been made to research how alccofine and nanosilica affect the behaviour of polypropylene fibre-reinforced concrete beams. On the basis of the conducted experimental investigation, appropriate conclusions have been obtained.

Experimental program

Materials used

The concrete beams were developed using ordinary Portland cement, grade 53, in accordance with IS 12269:2013 [29], as shown in Table 1. According to IS 383:2016 [30], crushed granite with a maximum particle size of 20 mm and 12 mm was utilised as coarse aggregate, as shown in Table 2. As fine aggregate, a mixture of river sand and m-sand was employed, and the physical properties are shown in Table 3. In this study, Astrra Chemicals, Chennai, provided nanosilica as shown in Fig. 1 and alccofine as shown in Fig. 2. Table 4 shows the properties of alccofine and nanosilica. In this study, several volume fractions (0.1 per cent, 0.2 per cent, 0.3 per cent, and 0.4 per cent) of commercially available Recron 3 s polypropylene fibres that comply with ASTM C1116 [31] (Fig. 3) were utilised (Table 5). Conplast SP 430 (Fig. 4), a high-range water-reducing admixture that conformed to ASTM C494 [32] (Table 6), was employed.

Table 3 Physical properties of fine aggregate

Property	River sand (55%) + m-sand (45%)
Specific gravity	2.66
Water absorption	0.43%
Grading zone	II
Fineness modulus	2.58

Fig. 1 Nanosilica

Fig. 2 Alccofine

Table 4 Physical properties of Ns and alccofine

Properties	Nanosilica	Alccofine
Particle size	17 nm	6 microns
Specific gravity	1.6	2.90
Specific surface area	160 (m^2/g)	12,000 (cm^2/g)

**Ns* Nanosilica

Fig. 3 Polypropylene fibre

Table 5 Physical properties of polypropylene fibre

Property	Value
Length	12 mm
Shape	Triangular
Specific gravity	0.91
Elasticity modulus	4000 MPa
Alkaline stability	Very good
Tensile Strength	4 MPa
Elongation	90%
Effective diameter	40 micron

Fig. 4 Super plasticiser

Table 6 Physical properties of super plasticiser

Property	Value
Appearance	Liquid
Specific gravity	1.18
Colour	Brown
Chloride content	Nil

High yield strength ribbed reinforcement bars of Fe 500D were used for the main reinforcement.

Control specimens

All the tests were conducted as per code IS516:2004 [33]. The compressive strength, flexural strength, and elasticity modulus of control specimens were measured. Table 7 shows the mix proportions of beam specimens. Table 8 shows the nomenclature of all the test specimens.

Concrete mix design

The mix design was carried out for M25-grade concrete according to IS 10262:2019 [34] for the preparation of control and beam specimens. The mix proportion proposed has a water-to-cement ratio of 0.5. The slump achieved was about 50 mm to 70 mm. The mix proportions used are presented in Table 7.

Details of tested beams

Six reinforced concrete beam specimens with a cross section of 150 mm × 250 mm and a length of 3000 mm were cast and tested. For the beam specimens, the longitudinal steel ratio was 0.603 per cent (2 bars, 12 mm diameter). At 125 mm C/C, 2-legged, 8-mm-diameter shear stirrups were installed to prevent early shear failure and ensure flexural action of beams until collapse. Table 8 lists the specifics of the tested beams. Figure 5 represents the reinforcement details of the beams.

Test set-up

A total of six beams were tested under flexure using a four-point bending test pattern in a standard loading frame of 500 kN capacity. A beam was made to rest on simple support over a span of 2.8 m. Deflections were measured at mid-span and at load points using mechanical dial gauges with an accuracy of 0.01 mm. The crack width was measured using a crack detection microscope with a precision of 0.02 mm. Crack development has been monitored throughout the loading history. Figure 6 shows the loading set-up and equipment used in the test. Table 9 shows the results of the tests of control specimen.

Test results and discussion

Load–deflection relationship

The load–central defection responses of the tested beams are shown in Fig. 7. The force–displacement responses in all beam specimens were found to be linear up to the first

Table 7 Mix proportions of beam specimen

Mix. no	Specimen	*W*/*c* ratio	Water content (kg)	Cement (kg)	NS (kg)	Alccofine (kg)	Coarse aggregate (kg)	River sand (kg)	M-sand (kg)	Fibre volume (%)
1	CBS	0.50	168	350	0	0	1257	380.6	311.4	0
2	NAS0	0.50	168	294	3.5	52.5	1257	380.6	311.4	0
3	NAS1	0.50	168	294	3.5	52.5	1257	380.6	311.4	0.1
4	NAS2	0.50	168	294	3.5	52.5	1257	380.6	311.4	0.2
5	NAS3	0.50	168	294	3.5	52.5	1257	380.6	311.4	0.3
6	NAS4	0.50	168	294	3.5	52.5	1257	380.6	311.4	0.4

Table 8 Nomenclature of test specimens

Description
CBS: Control
Ns: Nanosilica
NAS0: Specimen with 15% alccofine and 1% NS (replacement of cement)
NAS1: Specimen with 15% alccofine and 1% NS (replacement of cement) and 0.1% polypropylene fibre (added by volume of concrete)
NAS2: Specimen with 15% alccofine and 1% NS (replacement of cement) and 0.2% polypropylene fibre (added by volume of concrete)
NAS3: Specimen with 15% alccofine and 1% NS (replacement of cement), and 0.3% polypropylene fibre (added by volume of concrete)
NAS4: Specimen with 15% alccofine and 1% NS (replacement of cement), and 0.4% polypropylene fibre (added by volume of concrete)

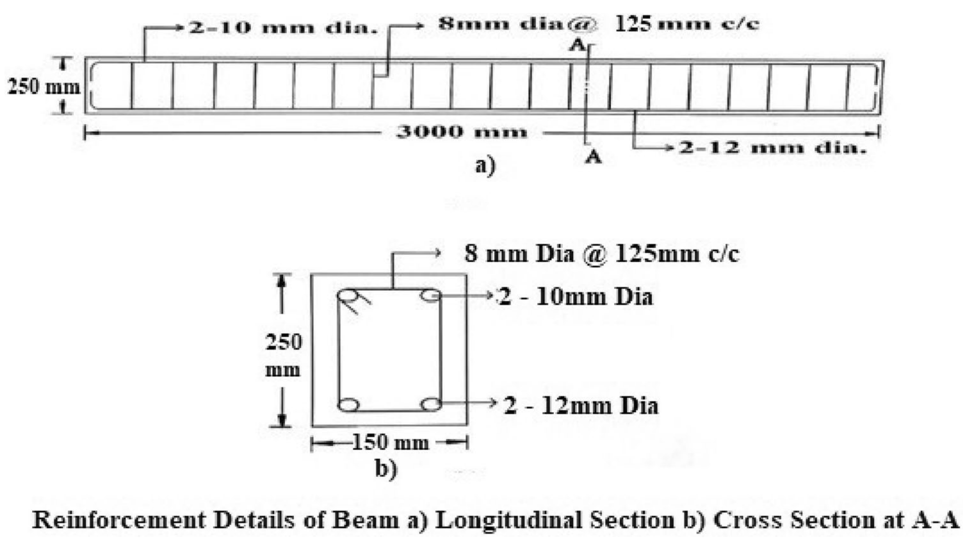


Fig. 5 Reinforcement details of beam

crack stage. After the commencement of the first crack stage, the gradient of the response curves rapidly dropped, with a higher number of cracks emerging as the longitudinal rebars began to yield. After the yield stage, the gradient of the response curves dropped considerably, indicating that deflection had increased. This was the case until the maximum load was achieved. The test observations are presented in Table 10. Figure 8 shows the cracking history of beam specimens.

Influence of polypropylene fibre with NS and alccofine on strength

The load at the first crack stage (through visual examination) for a polypropylene fibre-reinforced concrete beam with NS and alccofine is presented in Table 11. The effect of the polypropylene fibre-reinforced concrete beam with NS and alccofine on the first crack load was calculated as

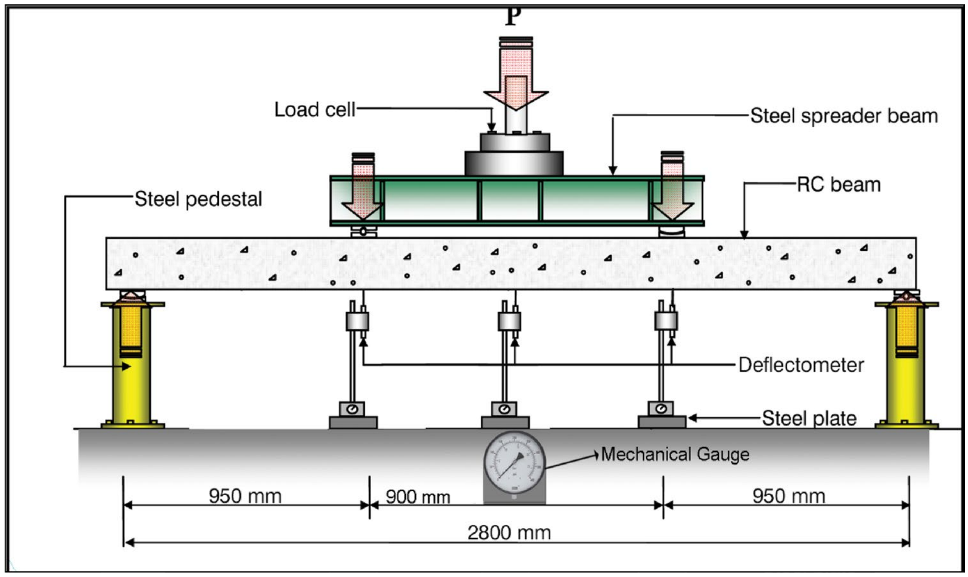


Fig. 6 Loading arrangement and instrumentation

Table 9 Results of the tests

S. No	Designation	Alccofine %	PPF %	Ns %	Avg. compressive strength of 28 days (N/mm^2)	Avg. flexural strength of 28 days (N/mm^2)	Avg. values of modulus of elasticity [*E* (Gpa)]
1	CC	0	0	0	33.02	6.5	26.03
2	NA0	15	0	1	35.19	6.9	26.28
3	NA1	15	0.1	1	36.59	7.1	27.02
4	NA2	15	0.2	1	38.95	7.8	27.47
5	NA3	15	0.3	1	41.26	8.2	28.25
6	NA4	15	0.4	1	37.35	8.5	29.22

**PPF* Polypropylene fibre, *Ns* nanosilica

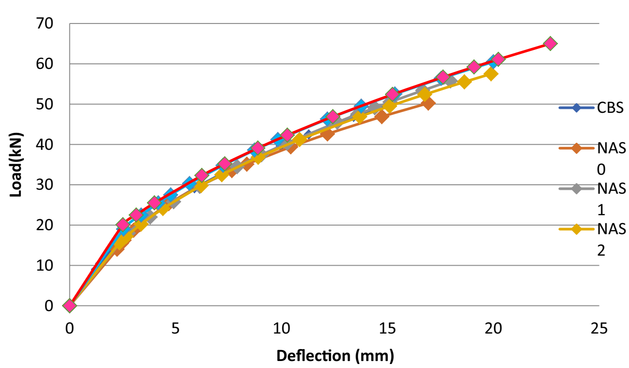


Fig. 7 Load—central defection responses of the tested beams

the percentage increase in strength with respect to the virgin specimen. The specimens NAS1, NAS2, NAS3, and NAS4 exhibit an increase of 10.76%, 24.70%, 38.46%, and 53.84%, respectively, with respect to the NAS0 beam. The NAS0 beam exhibits an increase of 12.06% with respect to the CBS (control beam) and polypropylene fibres have a beneficial effect even at the first cracking stage. The results presented in Table 11 and Fig. 9 show that polypropylene fibres have an appreciable effect on the first crack loads. The load at yield stage (load beyond which force displacement response becomes nonlinear) for a polypropylene fibre-reinforced concrete beam with NS and alccofine is presented in Table 11. The experimental load at the yield stage was obtained (by visual inspection) and corresponded to the stage of loading beyond which the force–displacement response was not linear. The specimens NAS1, NAS2, NAS3, and NAS4 exhibit an increase of 4.62%, 14.9%, 19.1%, and 21.7%, respectively, with respect to the NAS0 beam.

The specimens at NAS0 showed an increase of 3.81% with respect to the control beam. The results presented in Table 11 and Fig. 10 show that polypropylene fibre-reinforced concrete beams with NS and alccofine have a noticeable influence on the yield loads of test beams. The load at ultimate stage (load beyond which the beam would not sustain additional displacement at the same load level) for a polypropylene fibre-reinforced concrete beam with NS and alccofine is presented in Table 11. The specimens NAS1,

Table 10 Test results of the beams

S. No	Beam	First crack load (kN)	First crack def (mm)	Yield load (kN)	Yield deflection (mm)	Ultimate load (kN)	Ultimate def (mm)
1	CBS	14.50	2.11	31.02	7.32	50.00	15.22
2	NAS0	16.25	2.56	32.25	7.62	52.25	16.84
3	NAS1	18.00	2.77	33.74	8.1	55.75	17.95
4	NAS2	20.25	3.00	37.08	8.55	57.50	18.77
5	NAS3	22.50	3.38	38.42	8.92	60.50	20.65
6	NAS4	25.00	3.88	32.95	9.7	65.00	22.87

Table 11 Cracking history and failure mode of tested beams

SI. No	Beam designation	Maximum width of crack (mm)	Maximum no. of cracks	Average spacing of cracks (mm)	Mode of failure
1	CBS	0.48	15	135	Flexure
2	NAS0	0.46	16	120	Flexure
3	NAS1	0.44	18	110	Flexure
4	NAS2	0.38	21	100	Flexure
5	NAS3	0.36	25	82	Flexure
6	NAS4	0.24	37	70	Flexure

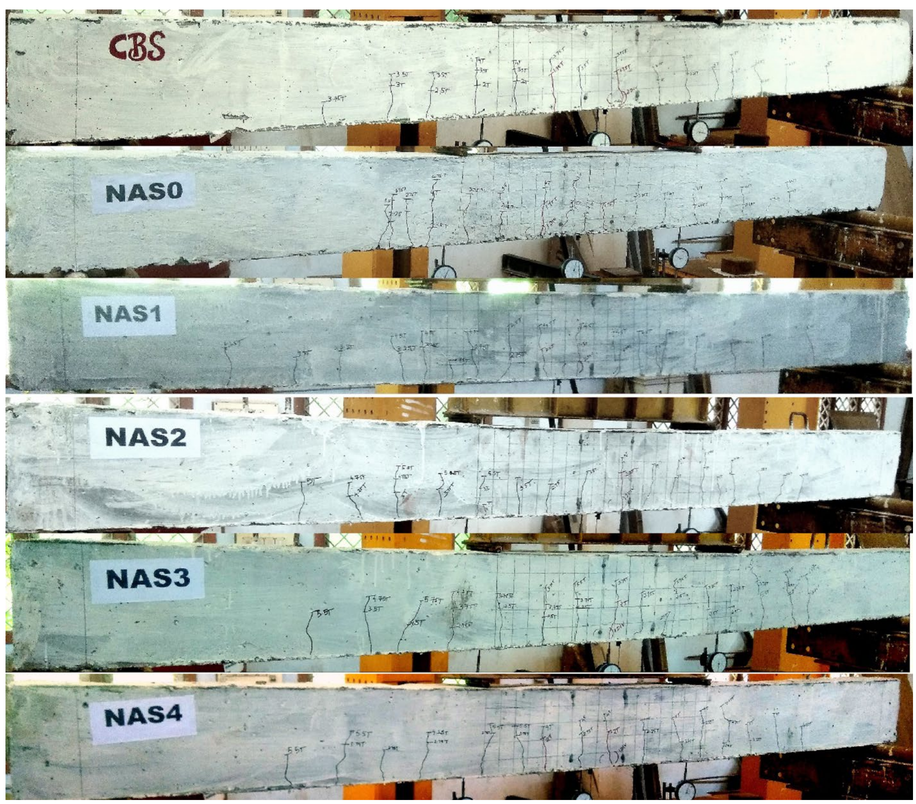


Fig. 8 Cracking history of specimens

NAS2, NAS3, and NAS4 exhibit an increase of 10.95%, 14.42%, 20.39%, and 29.35%, respectively, with respect to the NAS0 beam. The specimens NAS0 showed an increase of up to 0.49% with respect to the control beam. The results presented in Table 11 and Fig. 11 show that polypropylene fibre-reinforced concrete beams with NS and alccofine have a noticeable influence on the ultimate loads of the test beams. The following factors may have contributed to the rise in strength: The incorporation of polypropylene fibre with NS and alccofine increased the fibre–matrix interfacial

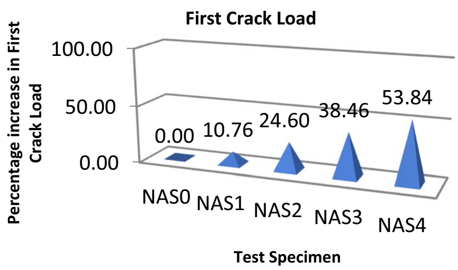


Fig. 9 Effect of fibres on first crack load

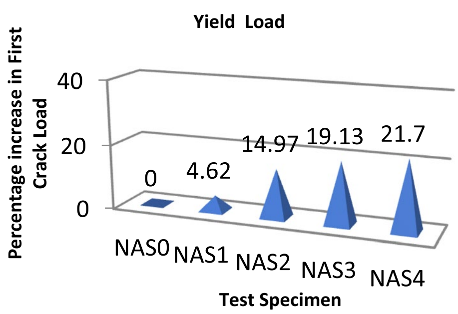


Fig. 10 Effect of fibres on yield load

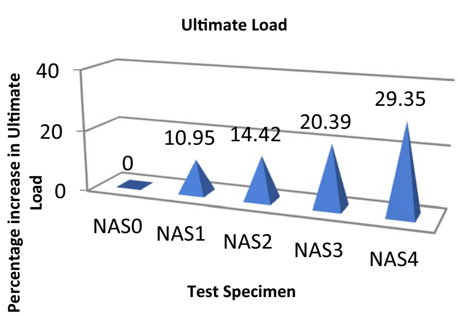


Fig. 11 Effect of fibres on ultimate load

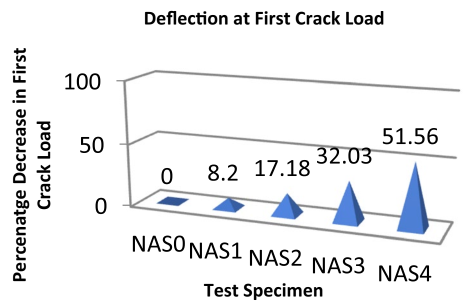


Fig. 12 Effect of fibres on deflection at first crack load

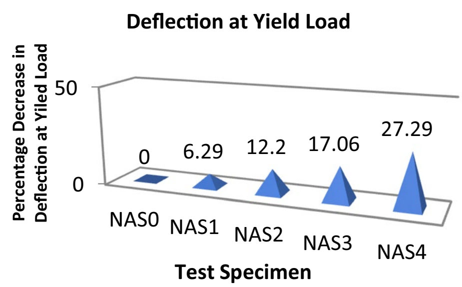


Fig. 13 Deflection at yield load

connection significantly. Polypropylene fibre's tying effect prevents concrete microcracking, resulting in increased flexural stiffness. Furthermore, the addition of polypropylene fibre to concrete resulted in favourable synergetic effects.

Influence of polypropylene fibre with NS and alccofine on displacement

Displacement capacity of beams is largely controlled by sectional moments of inertia, elasticity modulus, span, and loading. The addition of polypropylene fibre with NS and alccofine leads to improved stiffness. This augmented stiffness has a significant impact on the displacement response of beams incorporating polypropylene fibre with NS and alccofine at all stages of their response. The specimens NAS1, NAS2, NAS3, and NAS4 showed an increase of 8.2%, 17.18%, 32.03%, and 51.56% in displacement at the first crack stage with respect to the NAS0 beam. The NAS0 specimens showed an increase of up to 17.57% when compared to the reference specimen. The test results presented in Table 11 and Fig. 12 show that NS, alccofine, and polypropylene fibre have an appreciable effect on the deflection under the first crack load. The specimens NAS1, NAS2, NAS3, and NAS4 showed an increase of 6.29%, 12.2%, 17.06%, and 27.29% in displacement at yield stage with respect to the NAS0 beam. The NAS0 specimens showed an increase of up to 3.93% with respect to the reference specimen. The test results presented in Table 11 and Fig. 13 show that polypropylene fibres with NS and alccofine have a noticeable influence on the yield stage deflections of test beams. The specimens NAS1, NAS2, NAS3, and NAS4 showed an increase of 6.59%, 11.46%, 19.06%, and 35.81% in displacement at load at the ultimate stage with respect to the NAS0 beam. The NAS0 specimens showed an increase of up to 5% with respect to the reference specimen. The test results presented in Table 11 and Fig. 14 show that polypropylene fibres with NS and alccofine have a noticeable influence on the ultimate stage deflection of test beams. The improvement in deformation carrying capacity may be due to the following. The bridging action of polypropylene fibre controls the microcracking of concrete, resulting in higher flexural rigidity.

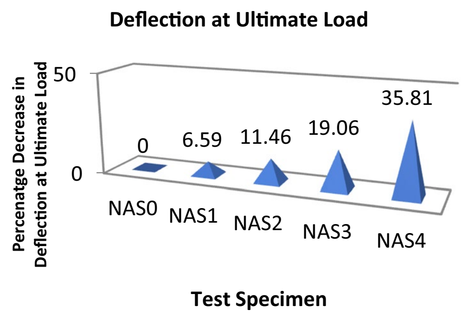


Fig. 14 Deflection at ultimate load

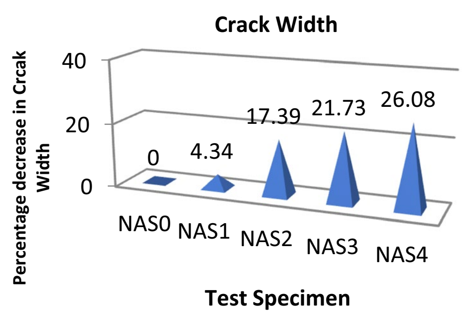


Fig. 15 Impact of polypropylene fibre and NS, alccofine on maximum crack width

Furthermore, the introduction of polypropylene fibre also caused positive synergetic effects with concrete.

Impact of polypropylene fibre with NS and alccofine on failure modes and crack patterns

Figure 8 shows the crack pattern of all tested beams at the ultimate stage. Fine vertical cracks were observed in the moment zone during the early stages of loading. With an increase in applied load, these flexural cracks extended and new flexural cracks were initiated in the moment zone. On further application of load, the flexural cracks formed away from the mid-span and progressed diagonally towards the loading point. The maximum crack width, maximum number of cracks, average spacing of

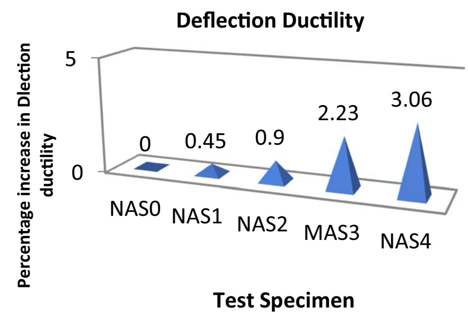


Fig. 16 Impact of polypropylene fibre and NS, alccofine on deflection ductility

cracks, and mode of failure of all specimens are presented in Table 11. The results presented in Table 11 and Fig. 15 show that all the polypropylene fibre R.C. beams with NS and alccofine showed an increase in the number of cracks and a decrease in crack width with respect to the reference beam. Possibly, the higher energy absorption capacity of polypropylene fibre with NS and alccofine would have enabled the tested beams to experience large displacement prior to failure, resulting in wider cracks.

Impact of polypropylene fibre with NS and alccofine on ductility

The deflection ductility index is defined as the ratio of deflection at ultimate load to deflection at yield load. The energy ductility index is defined as the ratio of the area of the load deflection curve up to the ultimate load to the yield load. Table 12 shows the ductility ratio of all tested beams. As a general rule, a structural member's ductility index reflects its capacity to withstand considerable deformation prior to failure and thus offers enough notice of failure. In comparison to the control beam, the ductility of the polypropylene fibre concrete beams treated with NS and alccofine increased by up to 8.78% in energy ductility and 6.25% in deflection ductility. With increasing fibre content, both displacement ductility (Fig. 16) and energy ductility (Fig. 17) increased, and the better energy absorption capacity of NS, alccofine, and polypropylene fibre

Table 12 Ductility Indices of tested beams

SI. No	Beam designation	Deflection ductility	Deflection ductility ratio	Energy ductility	Energy ductility ratio
1	CBS	2.08	1.00	3.53	1.00
2	NAS0	2.21	1.06	3.84	1.02
3	NAS1	2.22	1.067	3.92	1.04
4	NAS2	2.24	1.7	4.07	1.08
5	NAS3	2.29	1.10	4.16	1.12
6	NAS4	2.36	1.13	4.18	1.15

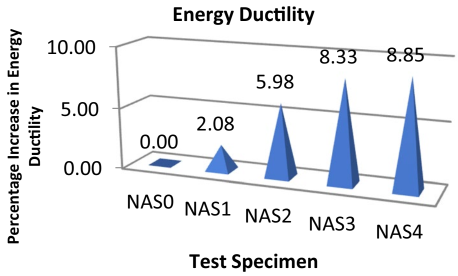


Fig. 17 Effect of fibres on energy ductility

Table 13 Energy capacity for tested beams

S. No	Beam designation	Energy capacity (kN-mm)
1	CBS	488.34
2	NAS0	579.68
3	NAS1	662.06
4	NAS2	796.15
5	NAS3	906.26
6	NAS4	1042.63

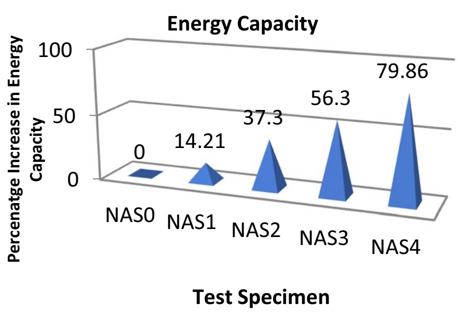


Fig. 18 Effect of fibres on energy capacity

would have allowed the tested beams to display higher ductility. This rise might also be attributed to a stronger fibre–matrix interfacial connection.

Energy capacity

Energy capacity is computed as the area under the load deflection curve up to the ultimate load. Table 13 shows the total energy capacity of all tested beams. Better ductility in a structural part often leads to higher energy capacity. The area under the force–displacement relationship curve was used to calculate the energy capacity. In comparison to the control beam, the fibre-reinforced concrete beams with NS and alccofine demonstrated a maximum increase in energy capacity of roughly 79.86%. The energy capacity (Fig. 18) rises when fibre content, NS, and alccofine quantum increase. The increased energy absorption capacity of polypropylene fibre with NS and alccofine would have allowed the tested beams to have more ductility, which would have resulted in a larger energy capacity.

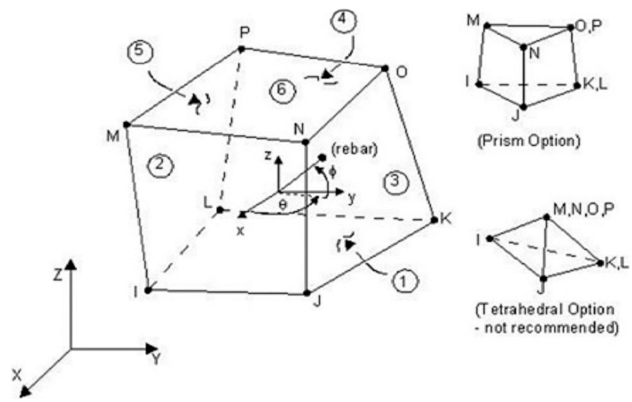


Fig. 19 Solid 65 element (concrete)

Finite element analysis

To validate the experimental results with finite element analysis, a static structural analysis is executed using ANSYS Workbench R19.2 to simulate the performance of fibre-reinforced concrete beams. The models are simulated to fail under the incremental two-point load at the mid-span of the beam, where large deflections occur. The response of the models is validated against the load deflection curves from the experimental results.

Engineering data

A collection of material statistics is available in the engineering statistics modules. The data within the library cannot be modified because it is part of the software set-up, but engineering records for new materials can be entered or changed. For the model, the concrete density, Young's modulus, and Poisson's ratio are provided as inputs and assigned. Figures 19, 20 shows the concrete and Reber element.

Geometry

A design simulation model is a geometrical feature-based, completely stable modeller designed to be derived from any other CAD programme or produced with it, allowing for the creation of 2D sketches and 3D component models. The modelling of concrete and steel and the 3D modelling of concrete are shown in Figs. 21, 22, and 23. Using the Solid 65 element, concrete was modelled. This element has eight nodes, each of which has three degrees of freedom.

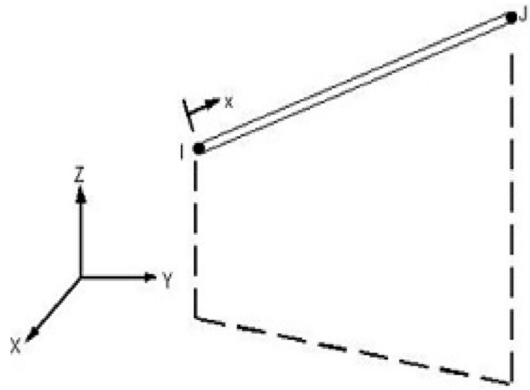


Fig. 20 Link 180 element (rebar)

The element is capable of crushing, three orthogonal cracks, and plastic deformation.

Meshing

In Ansys Version R19.2, adaptive convergence was adopted for the meshing of elements. By default, the mesh is recreated with a denser distribution of elements, and the model is re-analysed until the results converge satisfactorily. Rectangular mesh is preferred for solid 65 element for improved convergence. As a result, the mesh was set up to produce square or rectangular elements. The plate and support were mesh using the volume sweep command. This ensures that the elements in the plates are the same width and length as the elements and nodes in the model concrete portions.

Loads and boundary conditions

For the model to be constrained and produce a unique solution, displacement boundary conditions are required. Boundary conditions must be introduced at points of symmetry

Fig. 21 Modelling of concrete

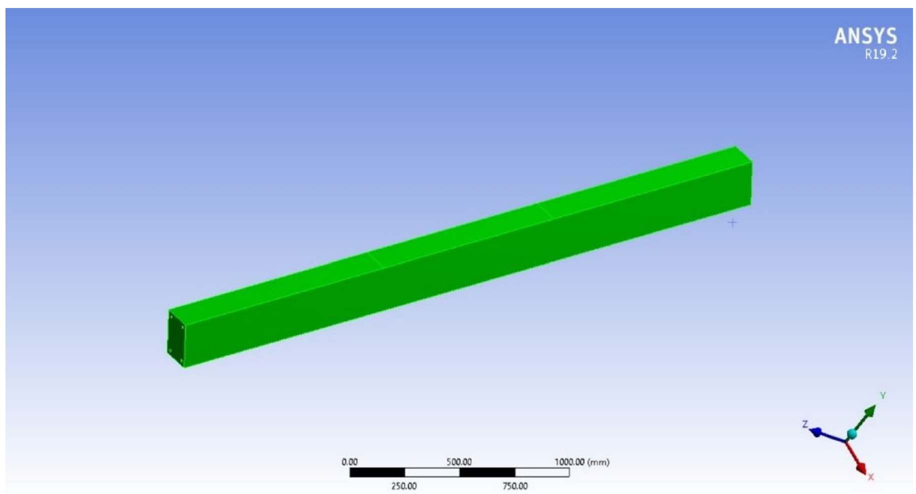
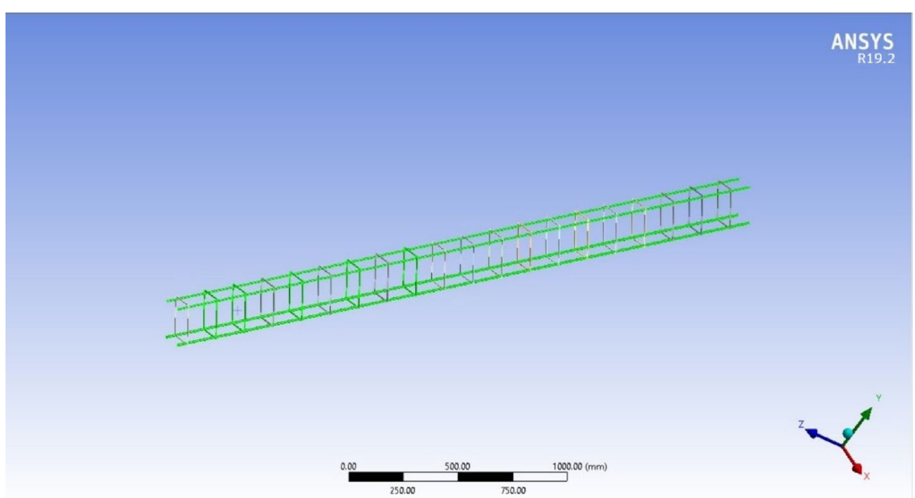


Fig. 22 Modelling of steel rebar



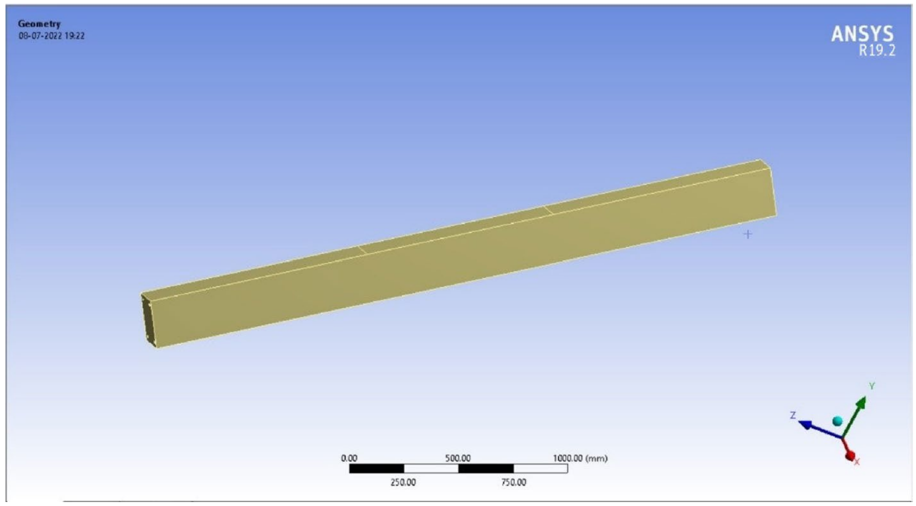


Fig. 23 3D Model of RC Beam

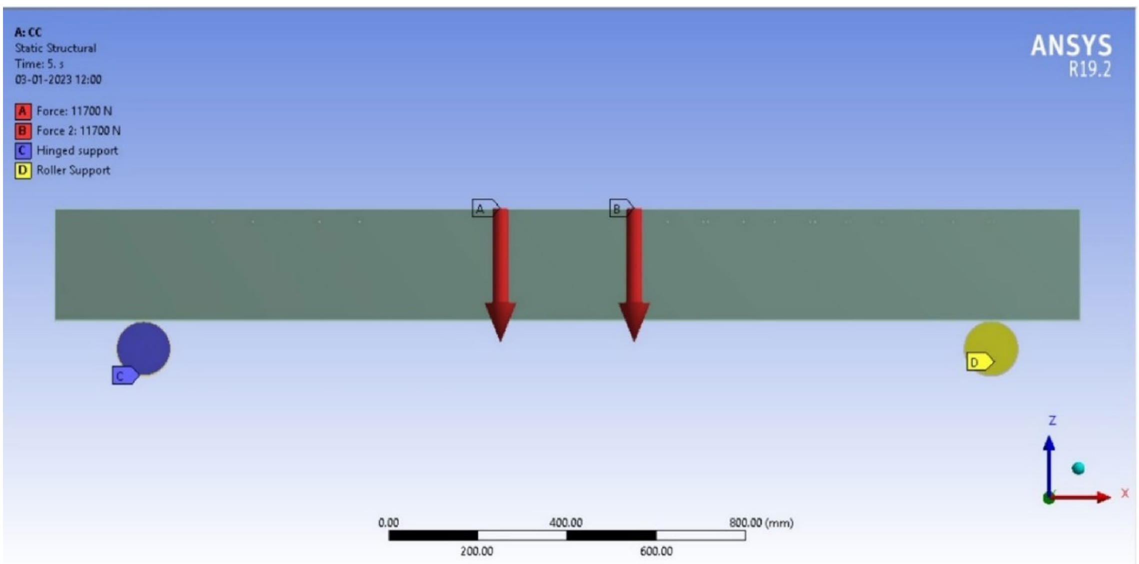


Fig. 24 Load and boundary conditions

where the supports and loadings are present in order to guarantee that the model behaves in almost the same manner as the experimental beam. In Fig. 24, loading and boundary conditions are depicted.

Deflection analysis

The results of the finite element analysis for the fibre-reinforced concrete with nanosilica and alccofine as CBS, NAS0, NAS1, NAS2, NAS3, and NAS4 are shown in Figs. 25, 26, 27, 28, 29, and 30. In this analysis, the final deflection obtained for each specimen was compared to the experimental values. All the specimens were analysed using ANSYS Workbench, and they showed results that were slightly higher when compared with experimental work. Table 14 compares the displacement acquired at the ultimate stage by experiment and numerical modelling. When compared to the reference specimen, the beam specimens NAS0, NAS1, NAS2, NAS3, and NAS4 indicated an increase of up to 3.45%, 19.84%, 21.95%, 23.17%, and 27.05%, respectively. It was observed that utilising 0.4% fibre-reinforced concrete could significantly improve strength and deformability. The increased fibre–matrix interfacial connection is mostly responsible for the improvement in flexural strength and deformability.

The experimental and analytical results of conventional concrete (NAS0, NAS1, NAS2, NAS3, and NAS4) are presented in Table 14. The maximum percentage error was also presented in Table 14. The percentage error for the results obtained through nonlinear finite element analysis varies

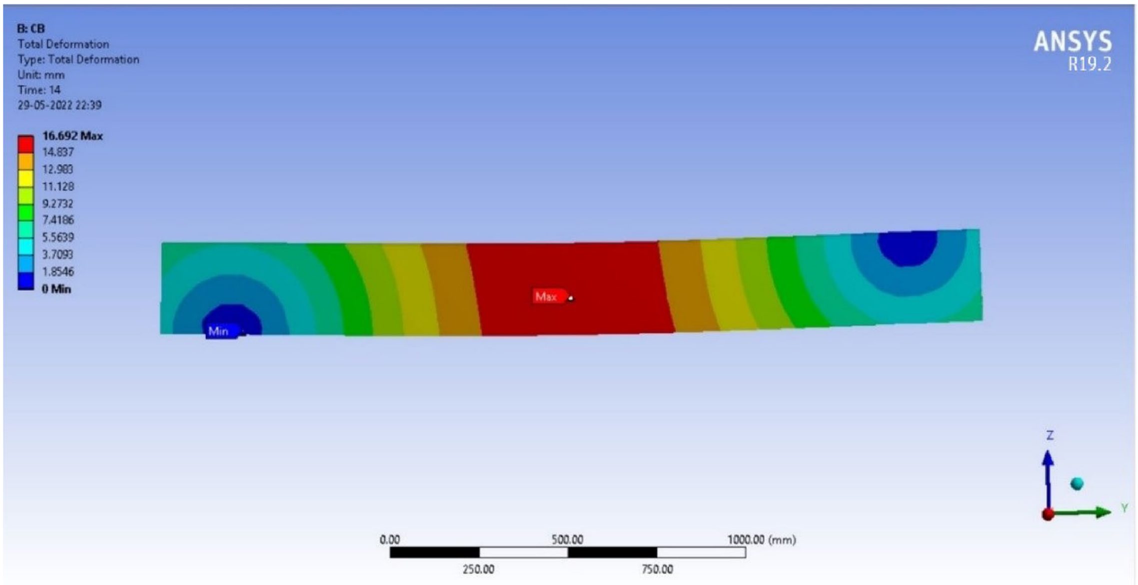


Fig. 25 Ultimate deflection profile of conventional beam

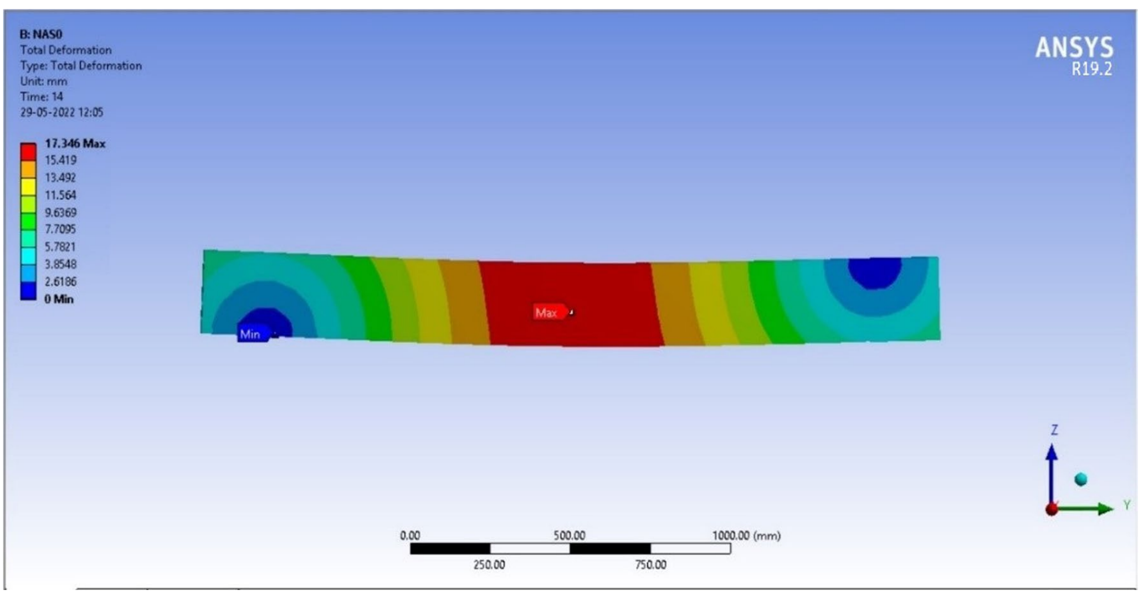


Fig. 26 Ultimate deflection profile of NAS0

from 1.35 to 9.67%. The ultimate deflections of finite element analysis are shown in Figs. 25, 26, 27, 28, 29, and 30. The force–displacement response obtained through analytical modelling for all specimens is presented in Figs. 31, 32, 33, 34, 35, and 36. Through it, it can be seen from the results that the experimental and numerical solutions are in reasonably good agreement, satisfying the validity of the numerical model adopted for the purpose.

Conclusions

In this study, the effect of polypropylene fibres at varying percentages (0, 0.1%, 0.2%, 0.3%, and 0.4%) with 15% alccofine and 1% nanosilica is attempted. Through this work, the authors hoped to offer a comparative picture of how polypropylene fibre can be efficiently employed to improve the qualities of M25-grade concrete, even when alccofine

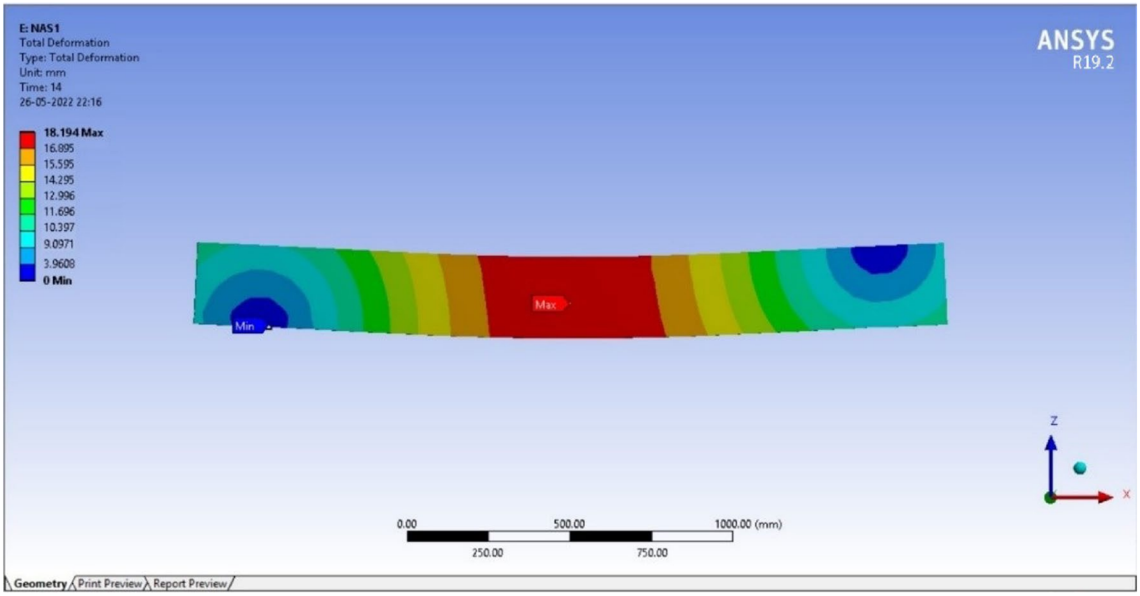


Fig. 27 Ultimate deflection profile of NAS1

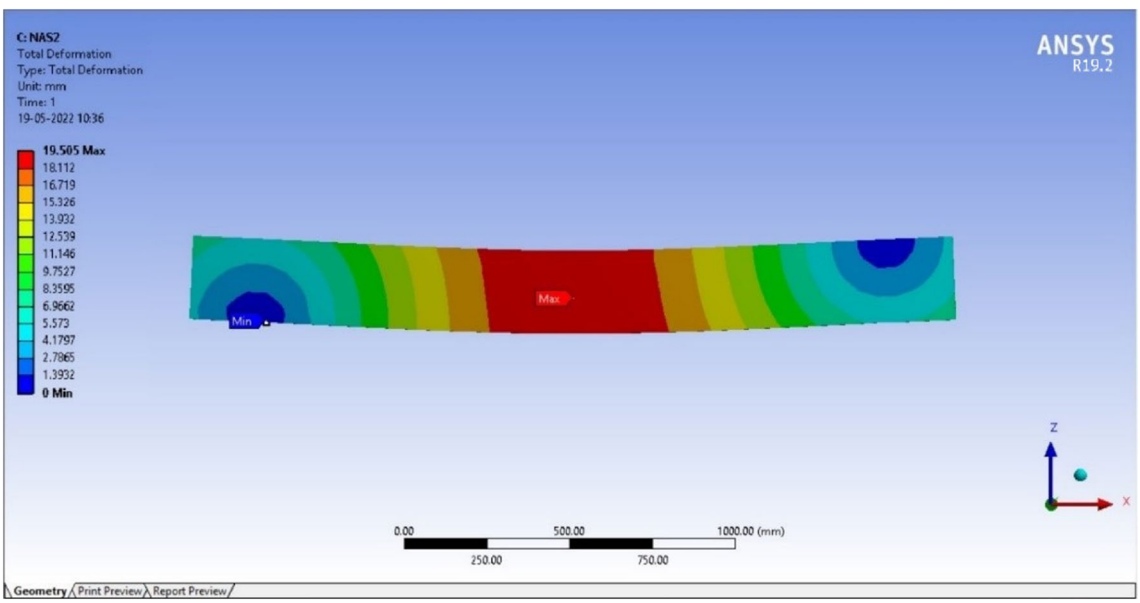


Fig. 28 Ultimate deflection profile of NAS2

and nanosilica are also used to partially replace cement. The reader learns a lot about the best ways to use alccofine and nanosilica in concrete, as well as how polypropylene fibre works to increase the properties of concrete. As a result, researchers and practitioners now have access to information about quality, both with and without the use of fibres. Based on the results obtained through the experiment, the following conclusions are drawn:

The addition of 0.4% of the volume fraction of polypropylene fibres resulted in an increase of 29.35% in the strength capacity of concrete beams incorporated with 15% of alccofine and 1% of nanosilica.

The beams with 0.4% volume fractions of polypropylene fibres exhibited a reduction of 35.81% in deflection compared to the concrete beams incorporated with 15% alccofine and 1% nanosilica.

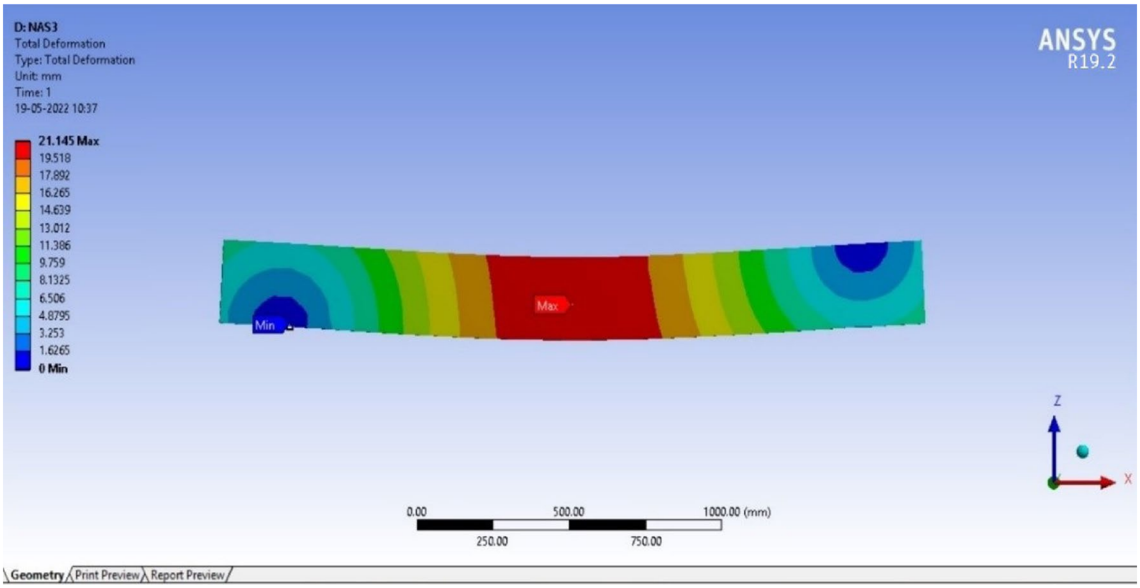


Fig. 29 Ultimate deflection profile of NAS3

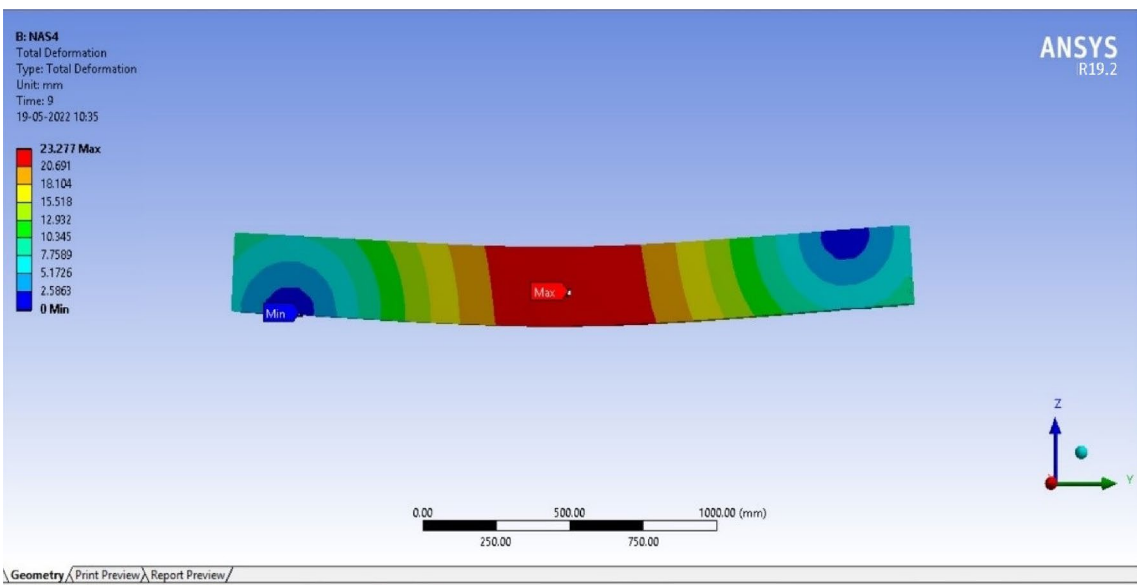


Fig. 30 Ultimate deflection profile of NAS4

Table 14 Comparison of experimental and analytical values

Beam	Ultimate load (kN)	Experimental ultimate deflection (mm)	Analytical ultimate deflection (mm)	% of error
CBS	50.00	15.22	16.692	9.67
NAS0	52.25	16.84	17.346	3.0
NAS1	55.75	17.95	18.194	1.35
NAS2	57.50	18.77	19.505	3.91
NAS3	60.50	20.65	21.145	2.40
NAS4	65.00	22.87	23.277	1.77

An increase in energy ductility of 8.87% and deflection ductility of 3.37% has been observed in beams with 0.4% of polypropylene fibres.

An increase in energy ductility of 8.87% and deflection ductility of 3.37% has been observed in beams with 0.4% of polypropylene fibres.

An increase of 68.75% in number of cracks, a decrease of 26.08% in crack width, and a change of 41.66% in the spacing of cracks have been observed in beams with a 0.4% volume fraction of polypropylene fibres incorporated with 15% of alccofine and 1% of nanosilica.

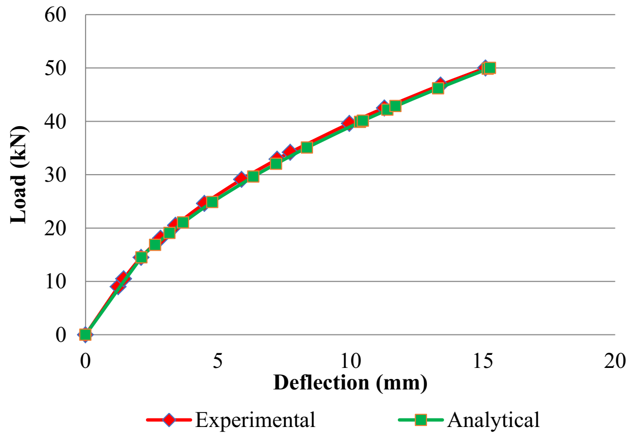


Fig. 31 Force–displacement plot—exp versus FEA—CC beam

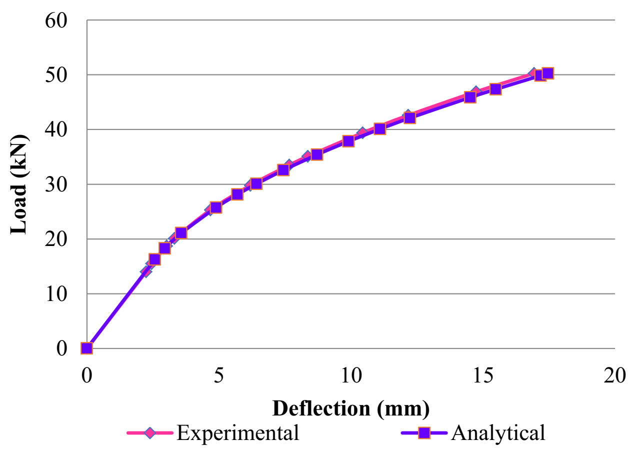


Fig. 32 Force–displacement plot—exp versus FEA—NAS0 beam

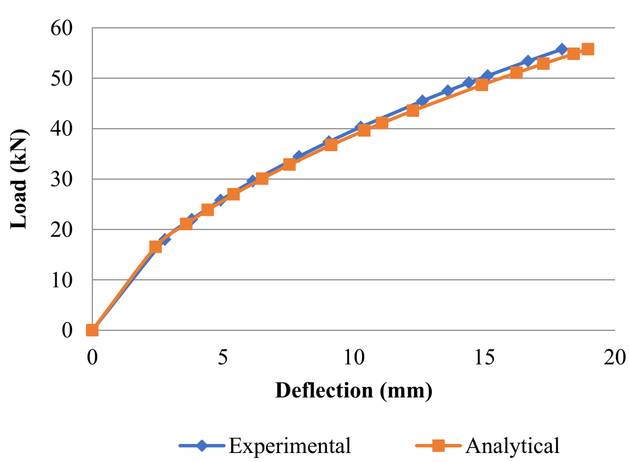


Fig. 33 Force–displacement plot—exp versus FEA—NAS1 beam

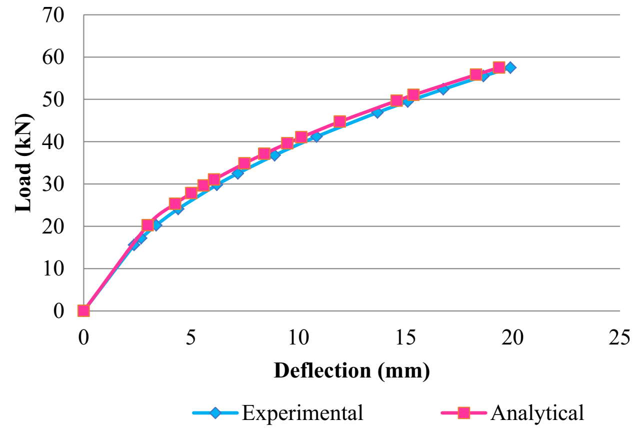


Fig. 34 Force–displacement plot—exp versus FEA—NAS2 beam

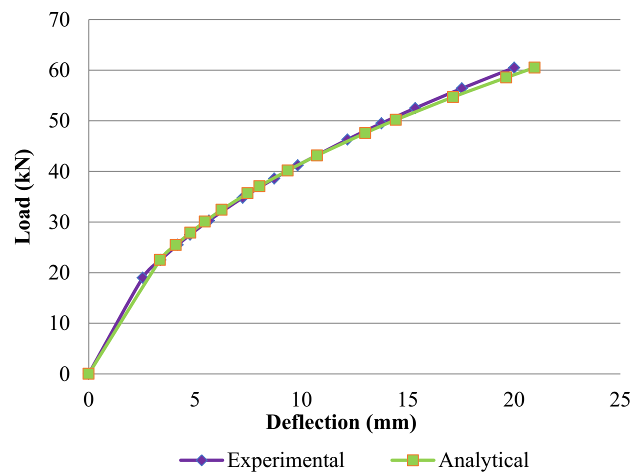


Fig. 35 Force–displacement plot—exp versus FEA—NAS3 beam

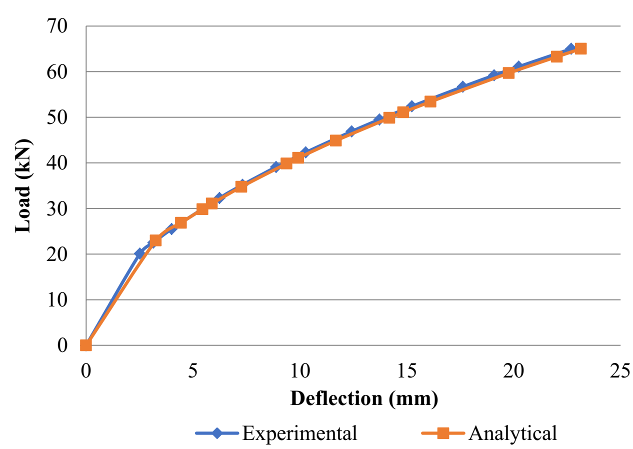


Fig. 36 Force–displacement plot—exp versus FEA—NAS4 beam

An increase in energy capacity of 79.86% has been observed in beams with 0.4% polypropylene fibres.
The results obtained from finite element analysis showed better convergence with experimental values.

This experimentation helps the researchers and practitioners in developing new green concrete, but still a lot of work needs to be done towards the investigation of different grades of concrete to understand the use of fibres in varying percentages. Similarly, the researchers may extend this work to determine the optimal use of alccofine, nanosilica, and fibres by using mathematical optimisation or simulation modelling. The authors believe that their research attempt will open up new avenues of research and applications for both researchers and practitioners.

Acknowledgements The study is part of the research conducted by the first author towards a PhD dissertation.

Author contributions The formulation of the problems, the selection of the materials, the design of the experiments, the method of testing, the selection of the analysis tools, and the preparation of the manuscript were all done by the authors. The final manuscript was read and approved by all authors.

Funding The authors declare that no funds, Grants, or other support were received during the preparation of this manuscript.

Declarations

Conflict of interest No potential conflict of interest was reported by the authors.

Ethical approval Not applicable.

Informed consent Not applicable.

References

1. Bentur A, Mindess S (2006) Fibre reinforced cementitious composites, 2nd edn. Taylor and Francis
2. Fallah S, Nematzadeh M (2017) Mechanical properties and durability of high-strength concrete containing macro-polymeric and polypropylene fibres with nano-silica and silica fume. Constr Build Mater 132:170–187
3. Thomas J, Ramaswamy A (2007) Mechanical properties of steel fiber-reinforced concrete. J Mater Civ Eng 19:385–392. https://doi.org/10.1061/(ASCE)0899-1561(2007)19:5(385)
4. Mashrei MA, Sultan AA, Mahdi AM (2018) Effects of polypropylene fibres on compressive and flexural strength of concrete material. Int J Civ Eng Technol 9(11):2208–2217
5. SintoJacoba SKK, Mendeza JM, George KE (2010) Reinforcing effect of nanosilica on polypropylene-nylon fibre composite. Mater Sci Eng 168:245–249
6. Chowdary A, Chaithra N, Chethan K (2017) A study on impact of polypropylene (Recron 3s) fibres on compressive and tensile strength of concrete. Int J Innov Res Sci Technol 4(3)
7. Larisaa U, Solbona L, Sergei B (2017) Fibre-reinforced concrete with mineral fibres and nanosilica. Proc Eng 195:147–154
8. Narasimha Reddy P, AhmedNaqash J (2019) Development of high early strength in concrete incorporating alccofine and non-chloride accelerator. SN Appl Sci 1:755. https://doi.org/10.1007/s42452-019-0790-z
9. RajeshKumar S, Samanta AK, SinghaRoy DK (2015) An experimental study on the mechanical properties of alccofine based high-grade concrete. Int J Multidiscip Res Dev 2(10):218–224
10. Karthick MS, Chandrasekaran P, Nirmalkumar K, Raghunathan M (2020) Effects of mineral admixtures in mechanical behaviour of high-performance concrete. Int J Adv Sci Technol 29(03):8031–8038
11. Sumathi A, Gowdham K, Saravana Raja Mohan K (2018) Strength and durability studies on alccofine concrete with micro steel Fibres. Roman J Mater 48(1):58–63
12. Upadhyay SP, Jamnu MA (2014) Effect on compressive strength of high-performance concrete incorporating alccofine and flyash. J Int Acad Res Multidiscip 2:125–130
13. Upadhyay SP, Jamnu MA (2014) Effect on compressive strength of high-performance concrete incorporating alccofine and flyash. J Int Acad Res Multidiscip 2(2):125–130
14. Boobalan SC, Aswin Srivatsav V, Mohamed Thanseer Nisath A, Pratheesh Babu A, Gayathri V (2021) A comprehensive review on strength properties for making Alccofine based high performance concrete. Mater Today Proc 45:4810–4812
15. Li LG, Zheng JY, Zhu J, Kwan AKH (2018) Combined usage of micro-silica and nano-silica in concrete: SP demand, cementing efficiencies and synergistic effect. Constr Build Mater 168:622–632
16. Senff L, Hotza D, Repette WL, Ferreira VM, Labrincha JA (2010) Mortars with nano-SiO_2 and micro-SiO_2 investigated by experimental design. Constr Build Mater 24:1432–1437
17. Tanveer Hussain S, Gopala Krishna Sastry KVS (2014) Study of strength properties of concrete by using micro silica and nano silica. Int J Res Eng Technol eISSN: 2319-1163/pISSN: 2321-7308, 03(10)
18. Beigi MH, Berenjian J, Omran OL, NikandIman AS, Nikbin M (2013) An experimental survey on combined effects of fibres and nanosilica on the mechanical, rheological, and durability properties of self-compacting concrete. Mater Des 50:1019–1029
19. Dheyaaldin MH, Mosaberpanah MA, Alzeebaree R (2022) Performance of fiber-reinforced alkali-activated mortar with/without nano silica and nano alumina. Sustainability 14(5):2527. https://doi.org/10.3390/su14052527
20. Harish B, Dakshinamurthy NR, Sridhar M, Jagannadha Rao K (2022) A study on mechanical properties of high strength concrete with alccofine as partial replacement of cement. Mater Today Proc 52:1201–1210. https://doi.org/10.1016/j.matpr.2021.11.037
21. Jayswal S, Mungule M (2022) A comparative assessment of strength and fracture performance of alccofine and fly ash blended high performance concrete. Mater Today Proc 65:1200–1204. https://doi.org/10.1016/j.matpr.2022.04.177
22. Jelodar HN, Hojatkashani A, Madandoust R, Akbarpour A, Hosseini A (2022) Experimental investigation on the mechanical characteristics of cement-based mortar containing nano-silica, micro-silica and PVA fiber. Processes 10:1814. https://doi.org/10.3390/pr10091814
23. Shameer KM, Jayaaruna SS, Raghunath PN, Suguna K (2021) An experimental study on properties of ternary blended steel fibre reinforced concrete. Int Trans J Eng Manag Appl Sci Technol 12(11):1–14. https://doi.org/10.14456/ITJEMAST.2021.213
24. Murthi P, Poongodi K, Awoyera PO, Gobinath R, Saravanan R (2020) Enhancing the strength properties of high-performance concrete using ternary blended cement: OPC, nano-silica, bagasse ash. SILICON 12:1949–1956. https://doi.org/10.1007/s12633-019-00324-0

25. Swetha A, Suguna K, Raghunath PN (2022) Strength and durability studies on steel fibre reinforced ternary blended concrete containing nano silica and zeolite. Civ Eng Arch 10(6):2306–2321. https://doi.org/10.13189/cea.2022.100606
26. Ahmed TW, Aljubory NH, Zidan RS (2020) Properties and performance of polypropylene fibre reinforced concrete: a review. Tikrit J Eng Sci 27(2):82–97. https://doi.org/10.25130/tjes.27.2.10
27. Hemavathi S, Kumaran A, Sindhu R (2019) An experimental investigation on properties of concrete by using silica fume and glass fibre as admixture. Mater Today Proc. https://doi.org/10.1016/j.matpr.2019.06.558
28. Sankar B, Ramadoss P (2022) Experimental and statistical investigations on alccofine based ternary blended high performance concrete. Int J Eng Trans B Appl 35(08):1629–1640. https://doi.org/10.5829/ije.2022.35.08b.19
29. IS 12269:2013 Ordinary Portland cement 53 Grade, Bureau of Indian Standards, New Delhi, India
30. IS 383:2016 Coarse and fine aggregate for concrete specification, Bureau of Indian Standards, New Delhi, India
31. ASTM C1116 Standard Specification for Fiber-Reinforced Concrete and Shotcrete, American Society for Testing Materials
32. ASTM C494—Standard Specification for Chemical Admixtures for Concrete, American Society for Testing Materials
33. IS 516:2004 Methods of Tests for Strength of Concrete, Bureau of Indian Standards, New Delhi, India
34. IS 10262:2019 Concrete Mix Proportioning - Guidelines, Bureau of Indian Standards, New Delhi, India