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Research Article

Experimental investigation and numerical modelling of concrete with the optimum percentage of colloidal nano silica

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Abstract

This study investigates the effect of colloidal nano silica on the mechanical properties of concrete. An experimental investigation was conducted using two concrete mixes, with and without the use of 2.5% colloidal nano silica [Type CemSynXTX (30% of nano solids content)], to assess its effect on the mechanical properties of concrete. Additionally, a numerical model was developed using Abaqus software to simulate the behavior of a concrete prism. The experimental tests yielded an improvement in compressive strength by 10.7%, split tensile strength by 22.77%, and flexure strength by 12.69% in the concrete with the colloidal nano silica additive. The numerical analysis results demonstrated excellent agreement with the experimental results. This study bridges the gap between experimental investigation and numerical modelling of concrete made with the colloidal nano silica. Further, it proposes the optimum amount of colloidal nano silica required in concrete.

1. Introduction

Concrete is one of the principal and fundamental materials used in the construction industry all over the world [1]. Researchers are showing interest in finding better ways to augment and enhance its mechanical and durability properties. In recent times, researchers have explored supplementary cementitious materials to improve concrete stability. One such breakthrough in the science of construction was the application of nanotechnology in developing stronger, efficient, and long-lasting concrete.

The research and work of stalwarts Nori Taniguchi, K. Eric Drexler, and Richard P. Feynman paved the way for the use of nanotechnology across various disciplines [2]. This technological leap has extended into the civil engineering industry, where researchers began incorporating nanomaterials like nano-silica into cement-based systems to enhance the durability and performance of concrete [3]. Through nanotechnology, i.e., engineering at the nanoscale, researchers are able to tweak the molecular structure of concrete and, in turn, improve its material properties, such as increased volume stability, durability, and sustainability [4]. Nanoparticles occurring in nature during phenomena like volcanic eruptions are different from engineered nanoparticles. Engineered nanoparticles typically range between 1 and 100 nm in size and are characterized by their large surface area, which facilitates their chemical reactivity. These particles act as nuclei in the cement phases, which makes the cement more hydrated. They also strengthen the cement by acting as fillers and making the microstructure and interfacial transition zone (ITZ) denser, which reduces the number of pores [5]. Several nano-sized particles are used as nano-additives in concrete, and one commonly used among these nano-sized particles is nano-silica. Nano silica exists in two main forms: dry compressed grain and colloidal suspension. To evenly distribute dry nano-silica in concrete, a specific pre-mixing method is required to dissolve the

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nanoparticles in water or other liquid admixtures. Conversely, colloidal nano silica is ready to use in the form of nano silica, as it is manufactured as a suspension that is stabilized by a dispersive agent.

The results indicate that utilization of nano silica as a substitute for cement to achieve high-strength concrete was both excellent and economical, and it enabled the reduction of CO2 footprint in concrete production [6, 7]. Since nano silica has greater pozzolanic properties, it enables it to react with free lime during cement hydration; the reaction forms an additional C-S-H gel and enhances the strength, impermeability, and durability of concrete [8]. Previous research has delved into the application of nano-silica, examining diverse aspects of its mechanical and physical attributes.

Ehsani et al. investigated the effects of nano silica on the evolution of compressive strength and water absorption characteristics of cement paste and concrete containing fly ash [9]. According to their findings, early-age fly ash-based concrete containing nano silica had faster reactivity than concrete that did not, which improved the development of strength in both cement paste and concrete. Moreover, employing appropriate proportions of up to 5% nano silica alongside 15% fly ash, notably enhanced the interfacial transition zone (ITZ) in fly ash concrete while significantly reducing water absorption and the sorptivity coefficient of the concrete specimens. However, in a separate study, M. Berra et al. investigated the impact of nano silica incorporation on concrete workability; their study revealed that incorporating nano silica into the mix resulted in a reduction in workability [10]. Gedela et al. explored the impact and ideal dosage of colloidal silica on the compressive strength and workability of M20-grade concrete [11]. Their findings demonstrated a substantial increase in compressive strength along with a decrease in workability when colloidal silica was incorporated. According to their study, concrete with 2.5% colloidal silica exhibited the highest strength compared to mixtures with varying percentages of silica, ranging from 0% to 5%. Shih et al. examined the influence of nano silica on the properties of Portland cement composite [12]. Their results showed that compressive strength increased by about 43.8%, and the microstructure of Portland cement composite with nano silica evidently had a more solid, dense, and stable bonding framework.

Givi et al. studied the effect of the size of SiO_2 nanoparticles on the characteristics of concrete [13]. The tests revealed that 15 nm of SiO_2 augmented early age strength, whereas 80 nm of SiO_2 enhanced the 90-day final strength. Du et al. examined the effect of colloidal nano silica on cement composite [14]. Their study showed that the colloidal nano silica accelerated the rate of hydration of cement composite and additionally improved the compressive strength of mortar through densifying pore structure. Atmaca et al. reported that the use of nano silica showed better results in normal concrete compared to lightweight concrete [15].
The Literature Review concludes that while there are several studies conducted on the mechanical and durability properties of concrete made with nano silica, there remains limited research in the mechanical and durability properties of concrete made with colloidal nano silica. In addition to this, there is limited research in the numerical investigation of concrete made with colloidal nano silica using FEM software. Hence, this study offers a combination of experimental and numerical investigation, comparison of mechanical properties of concrete with and without use of colloidal nano silica and simulating its behavior using Abaqus software.

2. Experimental Program

2.1 Materials

The following are the materials used in the study.

2.1.1 Cement

Ordinary Portland cement of grade 43 conforming to BIS is used in this study [16]. The cement exhibited a specific gravity of 3.12, a fineness modulus of 2.16, an initial setting time of 132 min, and a consistency of 29%.

2.1.2 Fine Aggregate

Sand procured from the local riverbed, having a fineness modulus of 2.26, a specific gravity of 2.6, and a bulk density of 1598 kg/m^3 is used as fine aggregate in this study. Sand is classified as Zone II as per BIS specifications [17].

2.1.3 Coarse Aggregate

Coarse aggregate with a particle size of 20 and 10 mm conforming to BIS specifications is used in this study [17]. Coarse aggregate exhibited the following properties: a specific gravity of 2.85, a bulk density of 1850 kg/m^3, and a fineness modulus of 7.05 for 20 mm aggregate. Similarly for 10 mm aggregate, the values of specific gravity, bulk density and fineness modulus are 2.70, 1563 kg/m3 and 7.1.

2.1.4 Colloidal Nano Silica

Colloidal nano silica of grade CemSynXTX with 30.0-32.0% active nano silica solids content with a purity of 99.99% in SiO_2 procured from Bee Chems Company, Kanpur, Uttar Pradesh, India, is used in this study. This particular nano silica exhibited a specific gravity ranging from 1.20 to 1.22 and maintains a pH value within the range of 9.0 to 10.0.

2.2 Mix Design

Two concrete mixes are prepared for the purpose of conducting experiments: one with 2.5% (by mass of cementitious materials) of colloidal nano silica as a partial replacement for cement and the other with 0% [18]. These mixes are given the notation of M3NS0% and M3NS2.5%, respectively. The quantities and proportions with which two types of concrete mixes are designed are detailed in Table 1.

Table 1. Mix proportions with and without colloidal nano silica

Mix Notation	Cement kg/m^3	Water cement ratio	Coarse aggregate kg/m^3	Fine aggregate kg/m^3	Super plasticizer %	Colloidal nano silica %
M3NS0%	400	0.43	1223	691	0.6	0
M3NS2.5%	397	0.43	1223	691	0.6	2.5

2.3 Specimens

To find the optimum content of colloidal nano silica to be used, concrete mixes are prepared initially with 0, 0.5, 1, 1.5, 2, 2.5 and 3% of dosage colloidal nano silica and tested for compressive strength. After performing a number of trials, concrete made with 2.5% of colloidal nano silica is found to be the optimum percentage of dosage from the results of the compressive strength tests.

Cubes of size 150 x 150 mm, cylinders with a diameter of 150 mm and a height of 300 mm and prisms measuring 100 mm × 100 mm × 500 mm are cast considering fixed optimum content of colloidal nano silica for determination of compressive strength, split tensile strength and flexure strength of concrete made with nano colloidal silica at 7 and 28 days of curing.

2.4 Slump

The target slump for concrete mix of M30 grade is 75 mm. To maintain consistent workability for concrete mix of M30 grade of concrete made without use of colloidal silica, several trial mixes are performed to adjust the dosage of superplasticizer. The values of slump decreased with the use of colloidal silica of type CemSynXTX for M30 grade concrete. The decrease is due to more water absorption by the nano particles as they have a large surface area. The initial slump measured for conventional concrete is found to be 95 mm. Whereas for the M3NS2.5% mix, it is 80 mm. The comparison of values of slump made with 2.5% of colloidal nano silica and conventional concrete i.e., with 0% of colloidal nano silica is shown in Fig.1

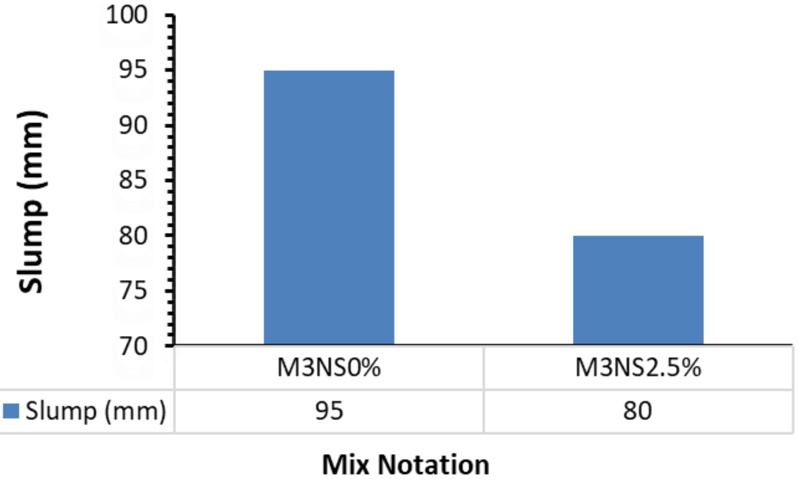

Fig.1 Comparison of slump values of both mixes

2.5 Strength Tests

2.5.1 Compressive Strength

The compressive strength of the concrete is determined by crushing the cubes of size 150 × 150 × 150 mm in a 3000 kN compression testing machine (CTM) at the ages 7 and 28 days for each mix. The average compressive strength of three cubes at various ages and a comparison of values of compressive strength of both mixes with age are shown in Fig. 1.

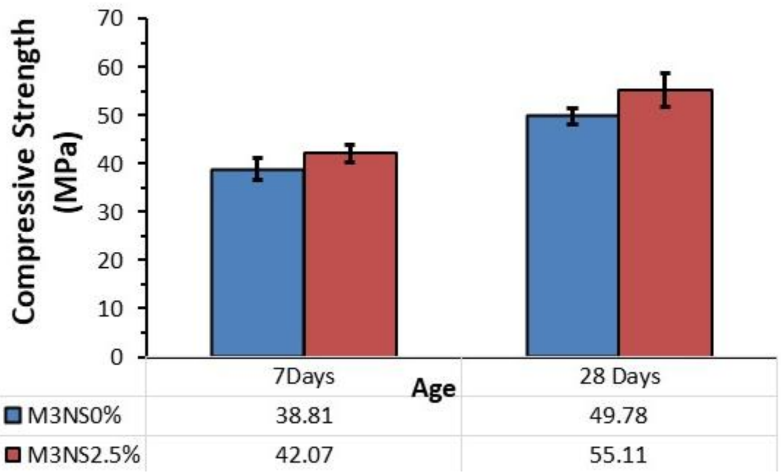

Fig. 2. Comparison of values of compressive strength of both mixes with the curing period

From Fig. 2 it can be noted that specimens containing colloidal silica exhibited higher compressive strength than the specimens without it. The increase in compressive strength of the cube specimens made with nano colloidal silica is due to the filling of voids with very fine colloidal silica and the pozzolanic reaction of nano silica.

2.5.2 Split Tensile Strength

The split tensile test is an indirect test to determine concrete's tensile strength by subjecting a concrete cylinder to compression in a 3000 kN compression testing machine (CTM) at the ages 7 and 28 days for each mix. The average value of split tensile strength of three cylinders for various curing days is shown in Fig. 3.

Similar to the values of compressive strength of both mixes, the values of split tensile strength are observed to have increased except at 7 days of the curing period for the mix made with colloidal silica. The increase in value of split tensile strength of the specimens made with colloidal nano silica is due to the filling of voids with very fine colloidal silica, making the concrete dense.

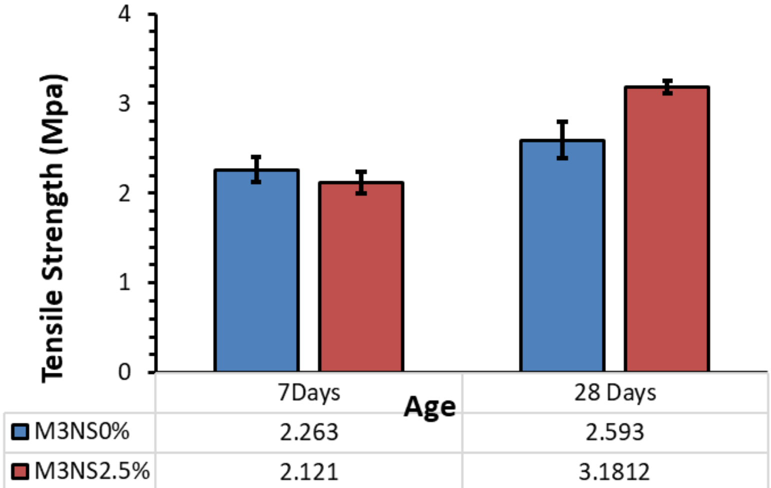

Fig. 3. Comparison of values of split tensile strength of both mixes with the curing period

2.5.3 Flexural Strength

The flexural strength test is performed on a prism of size 100 mm × 100 mm × 500 mm. Load is applied on concrete specimens cured at the ages 7 and 28 days, considering the Third points loading condition at a rate of 0.7 N/mm2/min (rate of loading being 1.8 kN/min) in accordance with the guidelines of BIS [19]. The results obtained from the study are presented in Fig. 4.

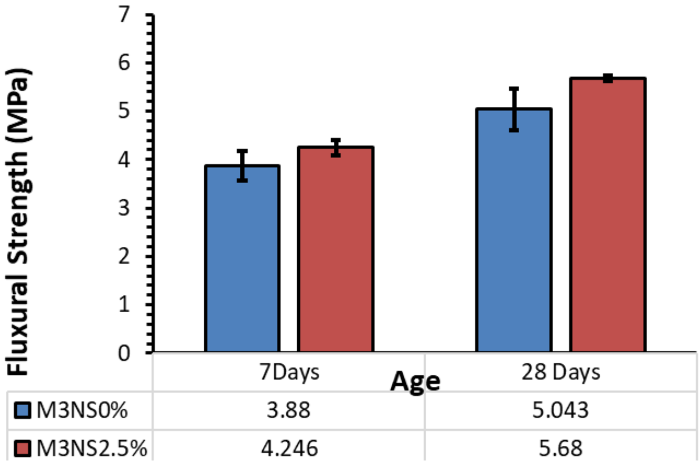

Fig. 4. Comparison of values of flexure strength of both mixes with the curing period

Fig .5. Testing of cube and cylinder

2.6 Uniaxial Compressive Strength of Cylinder

Standard practice requires that the Concrete Damaged Plasticity (CDP) model in Abaqus is calibrated based on uniaxial compression tests on concrete cylinders therefore the compressive strength of concrete cylinders is used instead of cubes. To determine the stress–strain response for the CDP model in Abaqus, uniaxial compression tests are conducted on concrete cylinders (150 mm diameter × 300 mm height) containing 2.5% colloidal nano-silica. Figure 6 illustrates the experimental setup for uniaxial compressive testing of concrete cylinders.

Fig. 6. Uniaxial compressive testing of cylinder

Three specimens are tested. These tests are carried out using a compression testing machine at a loading rate of 14 N/mm^2/min, in accordance with BIS [20]. Tests yielded an average compressive strength of 40.171 MPa and a modulus of elasticity of 19,240 MPa. The axial tensile strength f_t is estimated using the relation in accordance with the Fib Model Code 2010. $f_t=0.9\times f_{ct,sp}$, where $f_{ct,sp}$ is the experimentally measured split tensile strength. Based on the measured value of $f_{ct,sp}$= 3.18 MPa, the axial tensile strength was calculated as 2.86 MPa.

3. Numerical model

The numerical analysis of concrete made with 2.5% colloidal nano silica specimen is performed using Abaqus software, and the results obtained are compared with the experimental results. The purpose of modelling concrete elements using ABAQUS software is to simulate and study the behavior under different loading conditions, stress and failure mechanisms. This analytical modelling helps researchers understand the behavior of concrete elements under different loading conditions before construction.

3.1 Concrete Constitutive Model

The Concrete Damage plasticity model is used in this study to capture the nonlinear behavior of concrete made with 2.5% colloidal nano silica. The input parameters obtained from laboratory experiments and calibration are used to run the simulation and to understand the behavior of elements. Young's modulus, Poisson's ratio, density, and CDP parameters used in the study are presented in Table 2. Uniaxial compressive stress–strain data, obtained from experimental tests, and uniaxial tensile stress, estimated using the FIB Model Code 2010 have been used in this study to capture and study the non-linear response of prisms beyond the elastic limit. A stepwise approach followed in modelling the prism specimen, made with colloidal nano silica (M3NS2.5%) as numerical simulation using ABAQUS software, is given in the following sections.

Table 2. Input parameters for concrete damaged plasticity (CDP) model

Young's modulus [MPa]	Poisson's ratio	Mass density [kg/m^3]	Dilation angle	Eccentricity	f_{b0}/f_{c0}	K	Viscosity parameter
19240	0.18	2.4E−09	40	0.1	1.16	0.6667	0.00007
Uniaxial compressive strength ($\hat{f}c$)				Uniaxial tensile strength (f_t)			
40.171				2.86			

3.2 Geometry Creation

A plain concrete prism of size 100 mm × 100 mm × 500 mm is modelled as a 3D deformable body using Abaqus software. To replicate the loading and support system as that of the experimental investigation, additional components such as cylindrical rollers with dimensions of 25 mm in diameter are created along with the prism model.

3.2 Material Definition

Concrete material is defined using Concrete Damage Plasticity with input parameters listed in Table 2. Steel rollers are assigned as an elastic model with the Young's modulus of 200000 MPa and Poisson's ratio of 0.3.

3.3 Assembly

Assembling of both elements is carried out after modelling as that of the flexural test arrangement as per the codal provisions of BIS [19]. The prism model created using Abaqus as that of the Thirds point loading arrangement for the flexural test is shown in Fig. 7.

3.4 Interaction

Surface to surface contact is defined between rollers and a concrete prism. The loading and supportive rollers are assigned as rigid body constraints. The friction coefficient between the concrete specimen and the steel rollers is considered as 0.25 for tangential behaviors, with "hard" normal behavior.

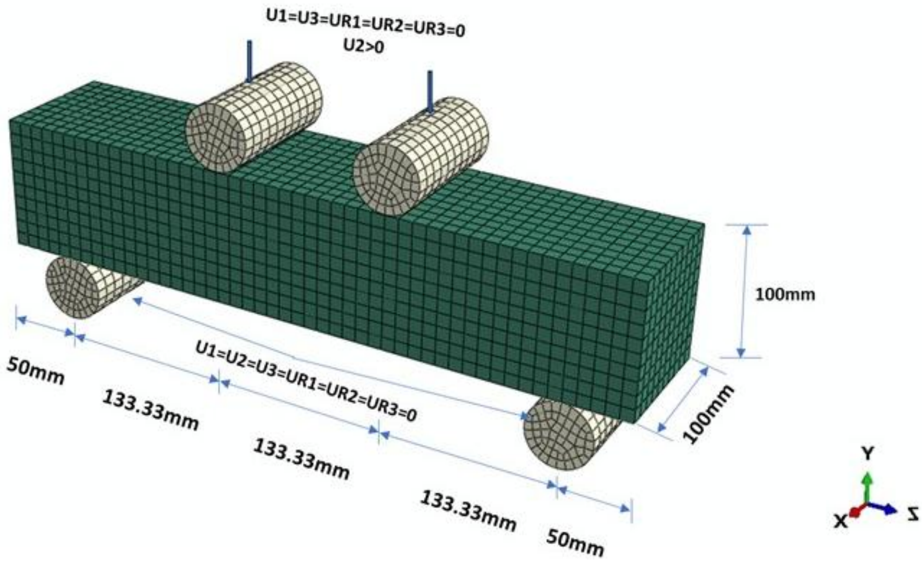

Fig. 7. Thirds point loading arrangement for flexure test in Abaqus

3.5 Meshing

The optimum mesh size is considered to be 10 mm after performing number of trials to get optimum values i.e., a suitable balance between accuracy and computational efficiency. The element used is an 8-noded linear brick element (C3D8R) with reduced integration as shown in Fig. 8. This element is a linear solid element which is used for modelling solids with non-linear behavior. The "R" stands for the reduced integration, which makes the simulations faster. The element has 3 degrees of freedom per node (displacement in X, Y, and Z directions).

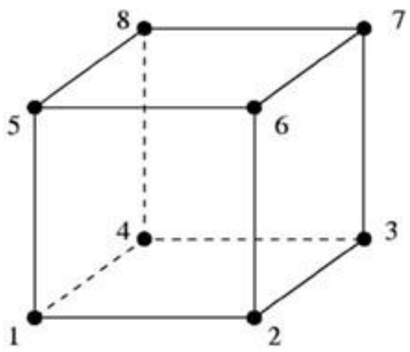

Fig. 8. Eight-node brick element with reduced integration (C3D8R)

3.6 Step Definition

A static general step is defined for nonlinear analysis. NLGEOM is enabled to account for geometric nonlinearity.

3.7 Boundary Conditions and Loading

The support rollers are completely fixed through their reference points, preventing all translations and rotations. The loading rollers are initially fixed through their reference points and later released in the Y-direction to allow free displacement during loading.

4. Results and Discussions

For validation purposes, finite element analysis has been carried out on the prism modelled using ABAQUS software considering CDP parameters, and the results obtained are compared well with the experimental measured values presented in Table 3.

Table 3. Values of deflection obtained from both analysis for peak ultimate load.

Description	Experimental		FEA	
	Peak Load, P (kN)	Deflection, **Δ** (mm)	Peak Load, P (kN)	Deflection, **Δ** (mm)
Prism	14.2	0.19	14.27	0.16

4.1. Deflection

Deflection of the prism model obtained from finite element analysis is shown in Fig. 9. The deflection is observed to be maximum at midspan of the prism from both analyses. The maximum deflection obtained from experimental analysis is 0.19 mm against a maximum load of 14.2 kN.

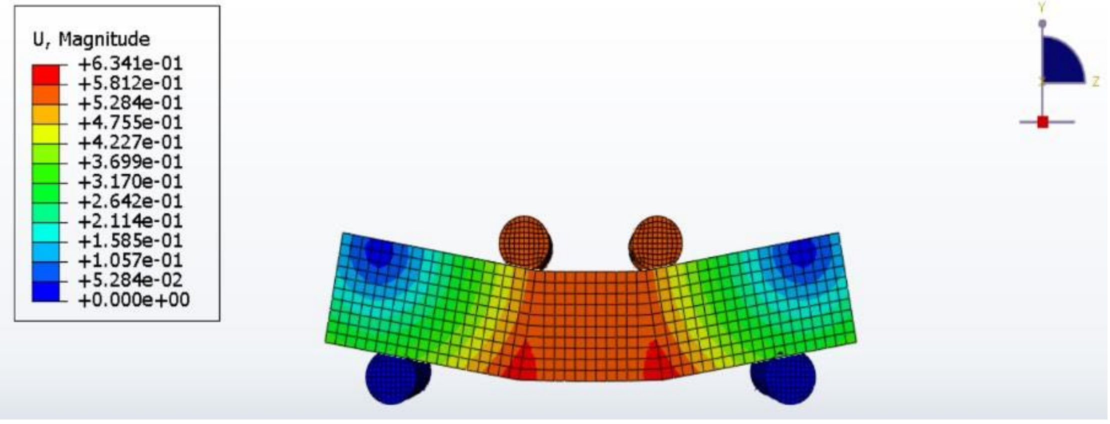

Fig. 9. Deflection of prism from finite element analysis

Whereas for analytical analysis performed by ABAQUS software, the value is 0.16 mm for the corresponding maximum load of 14.27 kN. However, a deflection of 0.5 and 0.63 are observed under a post-peak load of 1.8 and 1.83 kN in experimental investigation and analytical analysis, respectively. The key factor contributing to this discrepancy is the CDP model's reliance on simplified material parameters, which do not fully account for the heterogeneous nature of concrete. There has not been much difference in values of deflection from both studies. This indicates that the ABAQUS software can be used to simulate experimental studies to study the various parameters using CDP model parameters.

4.2 Stress

Figs. 10 and 11 show the stress distribution in terms of von Mises stress and the maximum principal stress of prisms. The maximum von Mises stress observed in the prism analyzed by ABAQUS software by performing FE analysis is 10.12 MPa. Whereas the maximum principal stress observed is 2.627 MPa.

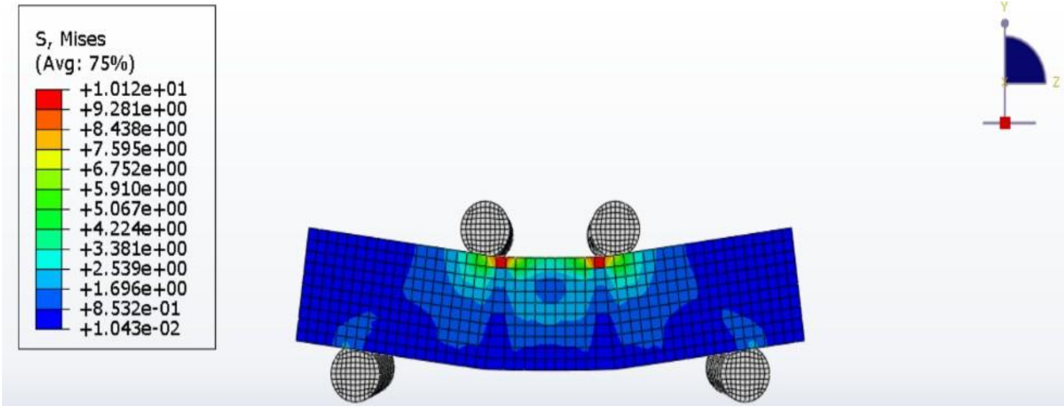

Fig. 10 Maximum von mises stress observed in prism

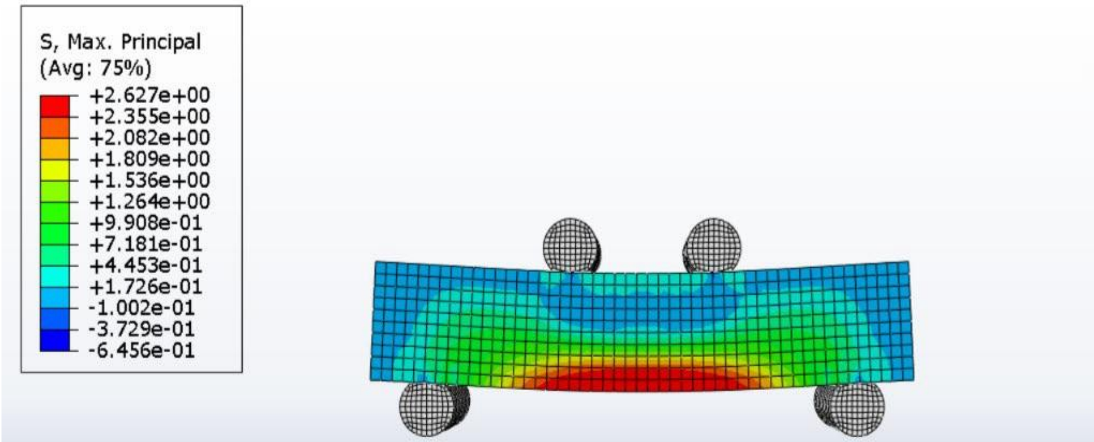

Fig. 11. Maximum principal stress observed in prism at the first crack load

4.3 Load-Deflection Behavior

The load–deflection response of prism specimens is evaluated by performing experimental and FE analysis using Abaqus software under the Third points loading conditions and compared the results. The deformations observed in both the analyses for corresponding maximum loads are presented in Table. 3. The load deflection curves obtained from both analyses are shown in Fig. 12.

The curves obtained from both analyses exhibited linear elastic behavior where the load increases proportionally with deflection, reflecting the beam's stiffness under elastic conditions. The curves transformed into a nonlinear phase as the beam approaches its maximum load-carrying capacity. A deflection of 0.19 mm is observed at a peak load of 14.20 kN for the experimental investigation, while, for FE analysis the deflection observed is 0.16 mm at a maximum load of 14.27 kN. Following the peak, the load decreased to 1.83 kN at a deflection of 0.63 mm in FE analysis, while for experimental analysis load dropped to 1.8 kN at a deflection of 0.5 mm. From Fig. 9, it is observed that, the curves observed for both analyses are more or less the same, indicating close agreement with the values. This shows that the FE analysis can be used to study the load deflection behavior of prism specimens more effectively using the concrete damage plasticity model as an element. This close agreement indicates that the Abaqus model accurately captures overall load deflection behavior.

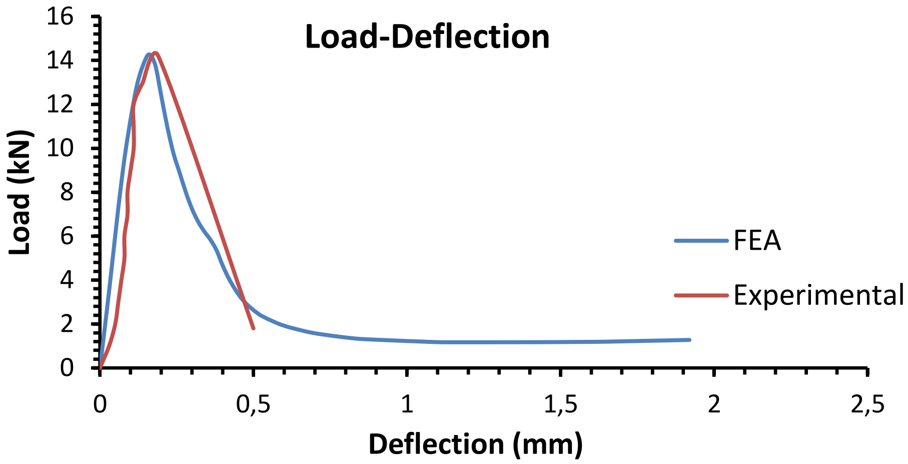

Fig. 12 Comparison of load deflection curves of prism made with colloidal silica obtained from FEA and experimental investigation

4.4 Crack Pattern

The crack patterns observed from both analyses are shown in Figs. 13 and 14. Cracks are observed at the middle of the prism in both analyses, indicating flexure cracks. The crack pattern observed in the prism from the FE analysis is in good agreement with the crack pattern obtained from the experimental investigation for a mesh size of 10 mm. The crack is observed at a distance of 14 mm from the nearest support in the experimental investigation. The same has been observed in the FE analysis.

Fig.13. Crack pattern observed in prism made with colloidal silica from experimental investigation

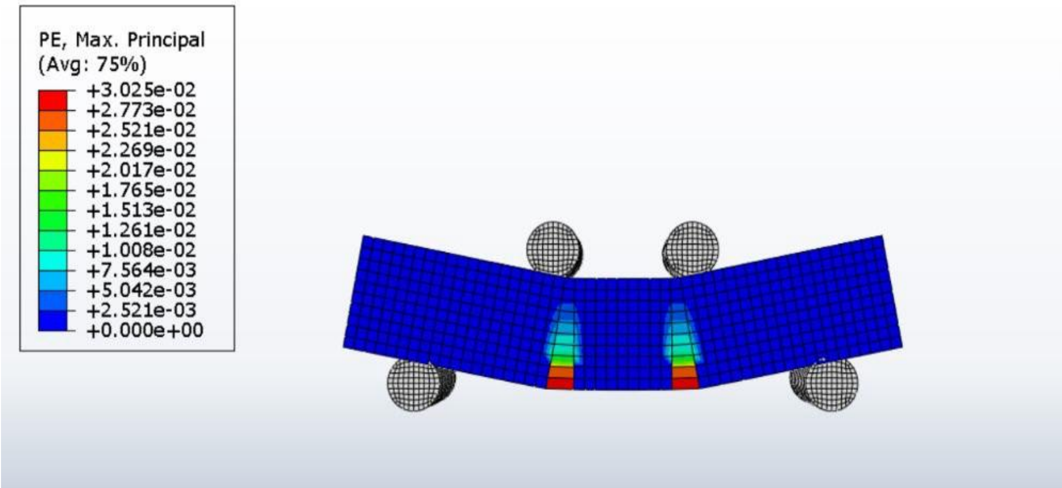

Fig. 14 Crack pattern observed in prism made with colloidal silica from FEA

5. Conclusion

- Enhanced mechanical properties in concrete with colloidal nano silica: The results of the experiment demonstrate that incorporating colloidal nano silica improved the mechanical properties of concrete, with an increase of 10.7% in compressive strength, 22.7% in split tensile strain and 12.69% in flexural strength, compared to the controlled specimen which did not contain any percentage of colloidal nano silica. These enhancements prove colloidal nano silica to be a high-performance additive in concrete production.

- Mechanism driving strength improvement: The significant strength gain is due to the dual role of colloidal nano silica. Firstly, it acts as a micro filler, which intensifies the concrete matrix, leading to a more compacted microstructure. Secondly, its pozzolanic reactivity, which results in the formation of a CSH gel, further strengthens the cementitious matrix and improves overall durability.

- Effective numerical modelling with Abaqus: Numerical simulation using Abaqus software and the CDP model accurately captured the load deflection behavior and failure mechanism of a concrete prism specimen. These simulated results matched the experimental findings, which demonstrates the capability of the model to accurately predict the structural response of a concrete prism under a load.

- Validation of load deflection response: The experimental analysis recorded a maximum deflection of 0.19 mm under a 14.2 kN load, while the Abaqus simulation predicted a deflection of 0.16 mm at a load of 14.27 kN. This close similarity indicates the accuracy of the CDP model in simulating the behavior of colloidal nano silica modified concrete.

- Practical implications: These findings from the experimentations suggest that colloidal nano silica is an effective additive for enhancing the mechanical properties in concrete, suitable in the construction of high-performance structural applications. Furthermore, Abaqus proves to be a robust tool for predicting the behavior of such modified concrete, assisting engineers in optimizing designs and reducing experimental costs.

6. Future Research Directions

The results of this study pave the way for further research in the optimization of nano silica dosage and exploration of long-term durability. The validated Abaqus model, in this study, can be extended to simulate complex structural elements, thus aiding the broader adoption of nano silica in concrete technology.

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