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RESEARCH ARTICLE OPEN ACCESS

Experimental and analytical validation of stress-strain behaviour ofnano-silica admixed concrete

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Abstract:
This paper presents the stress-strain behavior of the nano-silica based concrete of M30 and M50 grade experimentally and was validated analytically using modified mathematical model proposed by Saenz. Colloidal nano-silica of size 60nm is mixed in the dosages of 1.0% and 0.5% by weight of powder in M30 and M50 grades of self-compacting concrete mixes. Nano silica-based SCC has shown improved stress values for the same strain levels compared to that of conventional SCC. The analytical equations for the stress-strain response of conventional and nano silica incorporated concrete mixes have been proposed in the form of $y = Ax / (1+Bx+Cx^2)$, both for ascending and descending portions of the curves with different set of values for constants.

Keywords: self-compacting concrete, nano-silica, EFNARC, stress-strain, nanomaterials

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I. Introduction

A dense microstructure is of great importance in concrete for several reasons.A dense microstructure enhances the strength and durability of concrete. When the concrete has a higher density, it provides better resistance against external forces, such as compressive loads, shear forces, and impacts. It also reduces the risk of cracking, which can compromise the structural integrity of the concrete [1]. A denser microstructure also improves the concrete's resistance to chemical attacks, such as those caused by aggressive substances like chloride ions or sulfates.A dense microstructure in concrete significantly reduces its permeability. This means that the movement of liquids, gases, and other substances through the concrete is restricted [2]. This is particularly important in applications where the ingress of water, moisture, or harmful chemicals needs to be minimized, such as in water-retaining structures, underground constructions, or marine environments. Reduced permeability helps to maintain the concrete's long-term durability and protect embedded reinforcement from corrosion.Concrete with a dense microstructure is better able to withstand freeze-thaw cycles. When water penetrates the concrete and subsequently freezes, it expands, exerting internal pressure[3]. If the concrete has interconnected pores or voids, the expansion of freezing water can cause damage, leading to cracking, spalling, or deterioration [4]. A dense microstructure reduces the presence of voids, limiting the space available for water to enter and freeze, thereby enhancing the concrete's freeze-thaw resistance.Certain aggressive chemicals, such as acids or alkalis, can attack the cementitious matrix of concrete, causing deterioration and weakening the material [5]. A dense microstructure provides a barrier against the ingress of these chemicals, reducing the rate at which they can penetrate and react with the concrete. This improves the concrete's resistance to chemical attacks and extends its service life in aggressive environments [6].A denser microstructure promotes better bond strength between the concrete matrix and the embedded reinforcement, such as steel bars [7]. The reduced presence of voids and improved contact between the concrete and reinforcement increases the load transfer efficiency [8]. This is crucial for the structural integrity of the concrete, as it ensures that the reinforcement effectively resists tensile and shear forces [9].

To achieve a dense microstructure in concrete, several factors should be considered during the mix design and construction processes [10]. These include selecting appropriate aggregates, optimizing the water-cement ratio, ensuring proper compaction, using high-quality cement and supplementary cementitious materials, and employing effective curing techniques. Additionally, the use of additives and admixtures, such as pozzolans or silica fume, can further improve the density and microstructure of the concrete [11-16].

Objective of the work

The aim of this study is to determine the stress-strain behavior of M30 and M50 grade nanosilica based concrete experimentally and to validate proposed stress-strain mathematical model against the experimental stress-strain values. Finally, modulus of elasticity and toughness were evaluated from the stress-strain curves.

II. Methodology

1. Materials

Self-compacting concrete: Self-compacting concrete (SCC) is a specialized type of concrete that can flow and compact under its own weight without the need for mechanical vibration. It is highly fluid and can easily fill complex formwork, congested reinforcement, and narrow gaps. SCC is known for its excellent workability, high durability, and improved aesthetic appearance.SCC has a high slump flow, typically between 600 and 800 mm, which allows it to easily flow and fill even the most intricate formwork. It can pass through narrow gaps and around congested reinforcement without segregation or blockage.SCC is capable of self-leveling due to its high deformability and low viscosity. Once placed, it can settle and distribute itself evenly within the formwork, achieving a smooth and uniform surface finish without the need for external vibration.SCC exhibits superior workability, making it easy to handle, place, and finish. Despite its high fluidity, it maintains its cohesiveness and does not segregate, ensuring uniform distribution of aggregates and other constituents.SCC typically exhibits improved durability properties compared to conventional concrete. The high density and low porosity of SCC reduce permeability, making it less susceptible to moisture ingress, chemical attack, and freeze-thaw damage. It also provides better resistance to abrasion and improves long-term structural performance.It's important to note that the design and production of SCC require careful consideration of the mix proportions, particle grading, viscosity modifiers, and admixtures to achieve the desired flowability and performance characteristics. Proper testing, trial mixes, and quality control measures should be employed to ensure the successful implementation of SCC in construction projects.

Nano-silica: Nano-silica, also known as nano-sized silica or silica nanoparticles, refers to extremely fine particles of silicon dioxide (SiO2) with sizes typically ranging from 1 to 100 nanometers. It is derived from the controlled synthesis or processing of silica precursors. Nano-silica exhibits unique properties and has various applications across different industries, including construction, electronics, healthcare, and materials science.

2. Mix Design

Self-compacting concrete (SCC) mix design involves selecting the appropriate proportions of materials to achieve the desired properties and performance of SCC. Several methods and guidelines are available for SCC mix design. The European Federation of National Associations representing producers and applicators of specialist building products for concrete (EFNARC) provides guidelines for SCC mix design. The EFNARC method focuses on the optimization of the paste volume and aggregate grading to achieve the required workability and performance.These are commonly used tests to assess the flowability and passing ability of SCC. The results of these tests can provide valuable data for mix design optimization. The V-Funnel test measures the time it takes for SCC to flow through a funnel, while the L-Box test evaluates the passing ability of SCC through narrow gaps.The Nan-Su method, developed by Professor Hajime Okamura, is another widely used approach for SCC mix design. It involves a systematic process of selecting the optimal combination of materials based on target workability, strength, and durability requirements. The Nan-Su method emphasizes the use of viscosity-modifying admixtures to control the rheological properties of SCC.SCC mix design often involves conducting trial batches to validate the selected proportions and adjust the mix to achieve the desired properties. These trials may include adjusting the amounts of admixtures, fine aggregates, or cementitious materials to fine-tune the SCC mix.

3. Stress-strain Behavior

Cylinders of standard size 150 x 300 mm are cast, cured for 28 days and tested in uni- axial compression under strain control as per IS: 516-1999 to understand the stress- strain behavior.

From the experimental values of stresses and strains, average stress-strain curve for each grade are plotted, taking the average values of the results of the three cylinders.

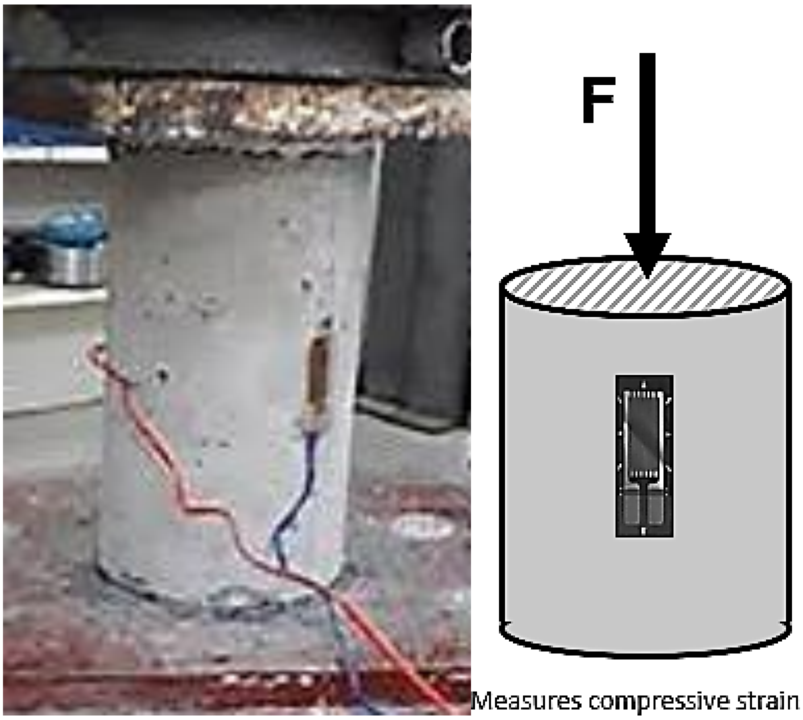

Fig.1 - Test setup for stress-strain measurements

Analytical stress- strain curves- proposed Mathematical Model

In order to study the stress-strain behavior of nanosilica concrete, one of the most important steps is to establish appropriate analytic stress-strain models that capture the real (observable) behavior. The better the stress-strain model, the more reliable is the estimate of strength and deformation behavior of concrete structural members. Appropriate analytic stress-strain mathematical model is developed that can capture the real (observable) stress-strain behavior of nanosilica concrete. This can be done by utilizing the best attributes of earlier models and proposing a stress-strain model that can well represent the overall stress-strain behavior of nanosilica concrete. After obtaining the stress-strain behavior of conventional and nanosilica concrete experimentally, empirical equations are developed to represent uni-axial stress-strain behavior of conventional and nanosilica concrete mixes are calculated and compared with experimental values.

Many models were developed for the stress-strain behavior prediction of concrete by many researchers. Some relevant models are considered below:

1) Desayi’s and Krishnan’s model (1964)
2) Modified Saenz Model (1964)
3) Hognestad Model (1955)
4) Wang *et al*, Model (1978)
5) Carriera and Chu Model (1985)

Of all the above stress-strain models, simplified and the modified single variable polynomial equations based on modified Saenz’s model that fits with the developed normalized stress-strain curves seems to be valid for both ascending and descending portions of the curve. The developed equations for ascending and descending portions of analytical stress-strain curve are in the form of

$$y = Ax/(1+BxCx^2)$$

and

$$y = Dx/\ (1+Ex+Fx^2)$$

where y is the stress at any level ; x is the corresponding strain at that level; A, B, C are the constants for ascending portion and D, E, F are the constants for descending portion of analytical stress-strain curve. Similarly, the equations for ascending and descending portions of non-dimensional stress-strain curve (normalized) are in the form of

$$f / fo = A^1(\varepsilon/ \varepsilon_o) / (1+ B^1(\varepsilon/ \varepsilon_o) + C^1 (\varepsilon / \varepsilon_o)^2)$$

and

$$f / fo = D^1 (\varepsilon / \varepsilon_o) + / (1+ E^1 (\varepsilon / \varepsilon_o) + F^1(\varepsilon / \varepsilon_o)^2)$$

A^1, B^1, C^1 are the constants for ascending portion and D^1, E^1, F^1 are the constants for descending portion of non-dimensional stress-strain curve. f / fo is normalized stress (stress ratio) and $\varepsilon / \varepsilon_o$is the normalized strain (strain ratio).

Constants are evaluated based on the boundary conditions of normalized stress- strain curves for both conventional and nanosilica concrete.

Boundary conditions for ascending and descending portions of stress-strain curves are,

(1) At the origin the ratio of stresses and strains are zero
i.*e.* at $(\varepsilon / \varepsilon_o) = 0, (f / fo) = 0$

(2) The strain ratio $(\varepsilon / \varepsilon_o)$ and stress ratio at the peak of the non-dimensional stress- strain curve is unity.
i.*e*at $(\varepsilon / \varepsilon_o) = 1, (f / fo) = 1$

(3) The slope of non-dimensional stress-strain curve at the peak is zero
i.*e*at $(\varepsilon / \varepsilon_o) = 1.0, d(f / fo) / d(\varepsilon / \varepsilon_o) = 0$

(4) At 85% stress ratio, the corresponding values of strain ratio is recorded
i.*e*at $(f / fo) = 0.85, (\varepsilon / \varepsilon_o)$=strain ratio corresponding to 0.85 stress ratio

where fo - peak stress and ε_o - strain at peak stress; f and ε corresponds to stress and strain values at any other point.

Boundary conditions (1), (2) and (3) are for determining the constants A^1, B^1, C^1 in the ascending portion of the normalized stress-strain curve and (2), (3) and (4) are for determining the constants D^1, E^1, F^1 in the descending portion of the curve. Corresponding A, B, C constants for ascending portion and D, E, F constants for descending portion of analytical stress-strain curve are then evaluated using equations

$$A = A^1 (f_o / \varepsilon_o),\ B = B^1 (1/\varepsilon_o) \text{ and } C = C^1 (1/\varepsilon_o)^2$$

and

$$D = D^1 (f_o / \varepsilon_o),\ E = E^1 (1/\varepsilon_o) \text{ and } F = F^1 (1/\varepsilon_o)^2$$

III. Test Results and Discussions

Based on the mix design principles of Nan Su and EFNARC, the quantity of materials that are obtained for M30 and M50 grades are listed below in table 1.

Table 1- Quantities of materials forM30 and M50 grades of SCC

Material	M30 SCC without Nano silica kg/m^3	M30 SCC with Nano silica (1% bwp) kg/m^3	M50 SCC without Nano silica (5% MS bwp) kg/m3	M50 SCC with Nano silica (0.5% bwp) kg/m3
Cement	230	160	290	240
Pozzolana (fly ash)	158.9	228.9	257	257
Fine aggregate (FA)	995	995	891	891
Coarse aggregate (CA)	705	705	738	738
SP	3.91L	5.84 L	3.4 L	9.43 L
Water(W)	234.93L	234.93L	231.23 L	231.23 L

Fresh properties of SCC

The following table 2 presents the fresh properties of the Self-Compacting Concrete mixesbased on EFNARC guidelines.

Table 2- Fresh properties as per EFNARC guidelines

Tests Conducted	SCC		
	Conventional	M30 Gradewith 1%NS added	M50 Gradewith 0.5%NS added
Slump flow	721mm	653mm	657mm
J ring	1.2mm	2.9mm	5.2mm
V funnel	12sec	8sec	11
L box	0.9	0.8	0.82

Stress -strain curves

Figure 1 presents the stress-strain curves of the M30 and M50 grade SCC mixes blended with various dosages of nanosilica by weight of powder. Experimentally obtained stress values in the strain-controlled environment are plotted to depict the stress strain relations of nanosilica based SCC mixes. From the stress-strain curves, peak stress values and their corresponding strains are determined and tabulated in table 3.

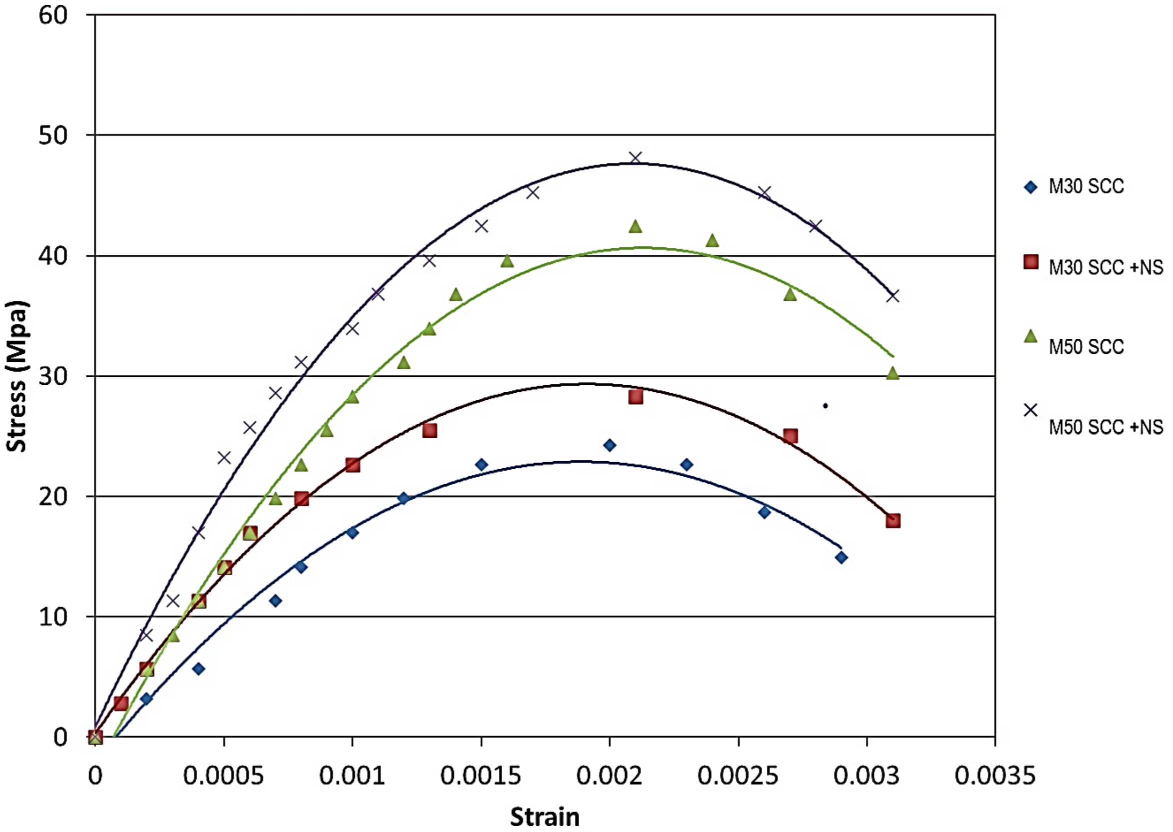

Fig.1 - Experimental stress-strain curves

Table 3- Peak stress values and their corresponding strains

Grade of Concrete	Plain SCC		Nano silica-based SCC	
	Peak Stress f_o MPa	Corresponding strain at peak stress	Peak Stress f_o MPa	Corresponding strain at peak stress
M30	24.25	0.0020	28.31	0.0021
M50	42.46	0.0021	48.12	0.0021

Modulus of Elasticity and Toughness

The relationship between stress and strain is important in understanding the basic elastic behavior of concrete in hardened state. From the plotted Stress-Strain curves, modulus of elasticity and modulus of toughness for conventional and nanosilica concrete can be calculated. Modulus of elasticity will indicate the elastic behaviour of the material whereas toughness gives the ability of a material to counteract crack propagation by dissipating deformation energy. Modulus of elasticity can be evaluated from the slope of the stress-strain curve whereas toughness (amount of energy absorbed by the specimen under loading) can be determined by measuring the area (i.e., by taking the integral) underneath the stress-strain curve. Modulus of toughness is the energy needed to completely fracture the material (the total area up to fracture).

Table 4 - Modulus of Elasticity and Toughness

Grade of Concrete	Modulus of Toughness (MPa)		Secant Modulus Of Elasticity (GPa)	
	Plain SCC	Nanosilica-based SCC	Plain SCC	Nanosilica-based SCC
M30	0.035	0.044	22.4	27.2
M50	0.066	0.075	32.2	36.7

Development of Analytical stress-strain relations

Constants and empirical analytical equations giving the complete stress-strain behavior are developed for conventional and nanosilica concretes and are tabulated in table 5

Table 5 -Constants for ascending and descending portions of non-dimensional stress-strain curve

Grade of Concrete	SCC					
	Ascending portion Constants			Descending portion constants		
	A	B	C	D	E	F
M30	13338	-450	250000	16975	-300	250000
M50	28092	-286	226757	51807	129	226757
	Nano silica-based SCC					
M30	49685	755	250000	23639	-165	250000
M50	40830	14	226757	42616	-62	226757

Calculation of Theoretical Stresses

Theoretical stresses have been calculated using proposed empirical equations for Plain SCC and Nano silica-based SCC mixes which are derived from modified Saenz's model in the form of

For Ascending portion of the curve: $y = Ax/(1+BxCx^2)$and

For Descending portion of the curve: $y = Dx/(1+Ex+Fx^2)$

Where y is the stress at any level; x is the corresponding strain at that level.

From the stress-strain values of Plain SCC and Nano silica-based SCC grades the corresponding normalized stress-strain values are calculated by dividing each stress value by the peak stress and dividing each strain value by strain at peak stress.After an appropriate model for predicting stress- strain behaviour is selected, empirical equations are developed in the form of $y = Ax/(1+Bx+Cx^2)$ for ascending and descending portions of Plain SCC and Nano silica-based SCC mixes for various grades of concrete in terms of unknown constants.Constants are computed based on the boundary conditions. Theoretical values of stresses are calculated at different values of strains in Plain SCC and Nano silica-based SCC based on the developed empirical equations. These theoretical stress-strain curves are compared with experimental stress-strain curves and found that theoretical stress-strain curves have shown good correlation with experimental stress-strain curves for all grades of Plain SCC and Nano silica-based SCC validating the proposed model adopted to study the stress-strain behavior of plain SCC and nano silica-based SCC.

IV. Conclusions

From the observations made from stress-strain curves, the following conclusions are drawn:

1. Nano silica-based SCC has shown improved stress values for the same strain levels compared to that of conventional SCC. The strain at peak stress is slightly higher, and the slope of the descending part is steeper due to the decrease in the extent of internal micro cracking in Nano silica-based SCC
2. The analytical equations for the stress-strain response of conventional and nano silica incorporated concrete mixes have been proposed in the form of $y = Ax / (1+Bx+Cx^2)$, both for ascending and descending portions of the curves with different set of values for constants.
3. The results show that the above proposed model was validated against the experimental data and gave good predictions for both ascending and descending branches; it also demonstrates satisfactorily the effect of nano silica on the stress–strain curve.

4. The results show that the proposed model provides a good simulation to the experimental stress–strain curves. The stress-strain curves obtained in the experiment for different grades of Nano silica-based SCC exhibit a similar trend as that of stress-strain curves developed from the empirical equations of modified Saenz model. So Saenz mathematical model of second degree polynomial was successfully evaluated and validated for nano silica incorporated concrete to be better fit to predict the stress-strain behavior Nano silica based SCC

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