Structural performance of nano-silica based blended CFST stub circular column

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Abstract. The objective of this study is to find the optimum percentage replacement of cement with the nano-silica in a concrete mix to improve the structural performance Concrete Filled Steel Tube (CFST) stub circular column under the axial compressive load. The CFST stub columns with circular cross-sectional area of conventional concrete mix (without nS) and nano-silica blended concrete mix (with nS-CFST) had been experimentally and numerically studied. The amorphous silica is a major component of the cementitious materials, and it reacts with the calcium hydroxide, which is comprised of the calcium silicate hydration. The addition of this nano-silica affects the different properties of the concrete and increases its performance. On the other hand, CFST is known for the composite behavior generated between the hollow tube of steel and a core constructed of concrete, which improves the collected performance of the member. In present study, the concrete mix of M25 had been modified with 4%, 6%, 8% and 10% of nano silica. The structural behavior of stub columns (with / without nS) are assessed under axial compressive load. Also, the CFST stub columns were then modelled into ABAQUS for finite element analysis. The nano-silica blended concrete in CFST stub columns showed an improved the structural performance than the conventional cement concrete stub circular CFST column.

1. Introduction
The partial replacement of cement with micro and nano-materials in a concrete mix is a common practice. It improves various properties of the concrete mix, which includes tensile strength, compressive strength, early age strength, etc. One of the most commonly used materials for partial replacement is nano-silica (nS). If a nano-silica is introduced in the concrete mix, it tends to increase its compressive, flexure and tensile strength [2]. The cement mortar mix which has nano-silica have more homogeneity binder, fewer pores, and more adhesion at interfacial zone [10]. Due to its ultrafine nature, the role of nano-silica is not limited to only the pozzolanic or filler effect, but it also increases the speed of kinetics of hydration [7]. It helps in improving the strength of the concrete by giving a boost to the generation of the nano-crystals of Calcium-Silicate-Hydrate (C-S-H) gel, and these nano-crystals occupy the nanopores as well as the micropores or voids that were left vacant in the cement-based concrete [2][5][8][10]. Nano-particles like nS, act as nuclei in the cement paste, as it has high activity, thus it...
promotes and accelerates the cement hydration process [2-3]. The percentage replacement of cement with the nano-silica to get maximum performance is highly dependent on the source of nano-particles, dispersing technique, w/c ratio, size of nano-silica etc. [11]. The compressive strength of the cement paste containing 5% silica was increased by 64% for 1 day, 39% for 7 days and 35% for 28 days in [1], it increased by 17.5% in 28 days in [3], it increased by 5% and 11% at 7 and 28 days at 0.55 water binder ratio in [6], and it increased by 45% in 7 days in [5]. The compressive strength of the concrete mix was reported to increase by 42% in 28 days when 6% of Nano-Silica was added in [4]. When w/b ratio of 0.55 was used then the increment in compressive strength of 77% and 87% was observed at 10% Nano-silica in [6]. In reference [9], when 2.5%, 5% and 7.5% cement content was replaced with nano-silica, then it gave maximum compressive strength at 5% replacement, which was corresponding to an increase 15%. Reference [10], tested the samples at 1%, 3%, 5%, 7% and 10% replacement of cement with 19nm nano-silica content, which in gave maximum compressive strength at 7% on 3.7 and 28 days with a maximum improvement of 55.7% at days. When there is an excess of nano-silica in the concrete mix, then the excess portion has no activation, and it takes the place of the cement in the form of an inert particle, which tends to decrease in the compressive strength [9-10].

Concrete-Filled-Steel-Tube or CFST comprises of a hollow steel section of required shape filled with plain concrete or concrete along with reinforcements. The steel tube in CFST acts as a permanent formwork that annihilates the use of temporary wooden formwork, which reduced the construction cost. This placement of the steel in the perimeter is considered as the most efficient use of the steel since the contribution in the moment of inertia and flexure capacity is maximum [12][16]. CFST is often used in high-rise buildings and sometimes low-rise industrial buildings that are exposed to robust loading or where efficient structural systems are required. Its composite action benefits both concrete and steel, as in this arrangement, the strength and ductility of the concrete core are improved because of the continuous confinement provided by the steel tube, whereas the local buckling of the steel tube is impeded by the concrete by avoiding tube to buckle inwards [16-17]. A lot of modifications to the CFST has been proposed in different studies to improve strength or get smaller cross-sections. Attaching circular stirrups along the surface of the column was a better alternative to increasing the thickness [13]. Sometimes another steel member is also inserted into the steel tube along with the concrete, and other cases are also used in studies. CFST columns with circular and square cross-sections are the most commonly used, followed by the hexagon, ellipse and other shapes. In short columns, confinement effects are observed to be more when compared with the slender columns under the axial loading [14].

In this study is focused on the structural properties of the conventional and nano silica modified blended CFST stub columns. To discuss it more straightforwardly, this study is conducted in three different phases. The first phase is about testing the standard M25 concrete mix along with the concrete in which there is a replacement of different percentages of cement with the colloidal nano-silica (nS). For this purpose, cubes and cylindrical specimens are cast and tested for its axial compressive strength. In Phase 2, the standard concrete mix and nano-silica blended concrete mixes are then used as core materials in the steel tubes with a circular cross-section to form nano-silica blended CFST or as termed in this study “nS-CFST”. In Phase 3, numerical models are developed for the nS-CFST specimens from Phase 2.

2. Experimental details
A concrete of M25 grade has been taken as a reference concrete mix for this study. The basic ingredients of the present study are Portland Pozzolana Cement of 43-grade, mild steel tube of a circular cross-sectional area, and nano-silica of particle size of 8-15nm and pH of 9-10. The amount of cement replaced with nS is 4%, 6%, 8%, and 10% by its weight. All the related values of the design mix containing the amount of cement, fine aggregate, coarse aggregate, and water are mentioned in table 1. This concrete mix and nano-silica blended concrete mix is used to cast specimens in the form of cubes of sides 150mm and cylinders of diameter 150mm and height 300mm, which are tested for axial compressive strength. This testing of cubes and cylinders are covered in the Phase 1.
Table 1. Design mix values for the different percentages of nano-silica.

| Parameter with its value for 1m³ volume |
|----------------------------------------|
| Cement (kg) | nS (kg) | % of nS | Water (litre) | Fine Aggregate (kg) | Coarse Aggregate (kg) | w/b Ratio |
|-------------|---------|---------|--------------|---------------------|----------------------|-----------|
| 395         | 0       | 0       | 219          | 675                 | 1100                 | 0.48      |
| 379.2       | 15.8    | 4       | 219          | 675                 | 1100                 | 0.48      |
| 371.3       | 23.7    | 6       | 219          | 675                 | 1100                 | 0.48      |
| 363.4       | 31.6    | 8       | 219          | 675                 | 1100                 | 0.48      |
| 355.5       | 39.5    | 10      | 219          | 675                 | 1100                 | 0.48      |

In Phase 2, the nano-Silica blended CFST or nS-CFST are tested along with the standard CFST specimens. They have the core of the mixes represented in table 1 from the Phase 1. The tube sections selected for analysis is the circular cross-sectional shapes. These specimens are also tested for axial compressive load, and their behaviors are noted down. After phase 2, the numerical models of nS-CFST specimens are developed to study the behavior under compressive. The finite element numerical techniques are used for the analysis of behavior of the modelled stub columns under axial compressive load. The finite element software used for the modelling of specimens is ABAQUS, in which steel tube is modeled using S4R elements as they are known to give accurate results for steel members, whereas the concrete core is modeled utilizing the three-dimensional eight-node solid (C3D8R) element. The bottom end of the sample is kept fixed and the compressive load is applied from the top cross-sectional area. The load is applied with the kinematic coupling using the modified RIKS method. This method is available within the software library and it is considered very accurate. The non-linear geometry parameter is also included to incorporate large displacements in the analysis. The load in the modified RIKS method is proportionally applied in several load increments. In this, the equilibrium iteration is performed in every load increment and the equipoise path is traced in the space of load-displacement.

3. Results

The cubes and cylinders of nano-silica blended specimens and control specimens from Phase 1 are tested under the axial compressive load using the universal testing machine, in which the displacement is incremented with time, and corresponding loads are noted. The specimens are tested at 14 and 28 days under axial compressive load and the output of the testing is mentioned in table 2. Based on the output of the compressive test, it can be inferred that the increase of strength through colloidal nano-silica was very significant. The observations were almost the same in both cubical and cylindrical specimens. It gave the maximum improvement of 44.7% in compressive strength when 6% of cement was replaced by nS. The compressive strength decreased slightly at 8% replacement, and a significant drop can be observed in the case of a 10% replacement. This highest increase in compressive stress of 36% was observed at 6% of nS.

The nS-CFST specimens and standard CFST specimen of the circular cross-sectional area that are tested in Phase 2 reflected almost the same behavior. The optimum percentage of nano-silica in nS-CFST specimens are observed when 6% of the cement was replaced by the nano-silica by mass. The stress developed at 8% was almost similar to the stress at 6%. Although, when the replacement of cement with nS is increased to 10%, there is a very extreme drop that can be observed in the nS-CFST specimens. The values of maximum stresses generated by the circular nS-CFST specimens as well as the standard specimen can be observed in in Fig. 1 - 5 and also in table 3. The table clearly shows a huge drop in stress values at 10% replacement of nano-Silica. The stress-strain behavior of the specimens throughout the loading duration can be observed in the graphs represented in Fig. 1 - 9.
Table 2. Compressive strength of nano-silica blended concrete.

| Days | % nS | Stress (MPa) Cube | Stress (MPa) Cylinder |
|------|------|-------------------|----------------------|
|      | 0%   | 23.07             | 18.53                |
|      | 4%   | 27.32             | 22.97                |
|      | 6%   | 32.23             | 27.68                |
|      | 8%   | 31.83             | 26.14                |
|      | 10%  | 28.17             | 23.90                |
| 14   | 0%   | 26.52             | 21.3                 |
|      | 4%   | 30.25             | 25.71                |
|      | 6%   | 36.19             | 30.76                |
|      | 8%   | 34.82             | 29.17                |
|      | 10%  | 31.24             | 26.55                |
| 28   | 6%   |                   |                      |
|      | 8%   |                   |                      |

Results from Phase 1 and Phase 2 show a collective outcome that once the amount of colloidal nano-silica crosses a certain percentage, there will be a huge drop in the stress values. This satisfies for both the phases. Reference [9,10] discusses the same behavior, as when there is an excess of nS in the concrete mix, the nS particles left after the reaction acts as the inert particles which reduce the performance of the specimen. Through the stress-strain graphs of nS-CFST presented in fig. 1 - 4, it is inferred that even after the nS-CFST specimens have reached its maximum value or the ultimate strength, there is a very large plastic region, which is one of the normal behaviors observed in the CFST members, as it is known to delay the failure of the members.
8% nS-CFST

Figure 4. Stress-strain curves of nS-CFST with 8% replacement.

10% nS-CFST

Figure 5. Stress-strain curve of nS-CFST with 10% replacement.

Figure 6. The behavior of circular nS-CFST under the axial compressive load for (a) 4% nS Test Specimen, (b) 4% nS FEA Model.

Figure 7. The behavior of circular nS-CFST under the axial compressive load for (a) 6% nS Test Specimen, (b) 6% nS FEA Model.
Reference [12][18] explains how the cross-sectional areas have an effect on the stresses of the nS-CFST specimens as well. For this, the term “confinement factor” is used, and the formula used for the calculation of this factor is: \( \zeta = \frac{f_s A_s}{f_c A_c} \) In this, \( f_s \) stands for the strength of steel, whereas \( f_c \) stands for strength of concrete, and \( A_c \) and \( A_s \) stands for the cross-sectional area of the concrete and steel respectively. As the name stands, it expresses the confinement effect on the concrete core generated by the steel tube. Higher the effect, better the performance of the member. So, the confinement factor for the experimental test specimens is also calculated and represented in a graph given in Fig. 10. The higher values of confining factors for specimens nS-CFST from the graph explains the better confinement effect. This can be used to compare nS-CFST of different cross-sectional areas. It can also be observed from Fig. 1-5 and table 3, that the increase in compressive strength of specimen was around 28% at 6%, which gave the best performance.

### Table 3. Compressive Stress Developed In nS-CFST Stub Columns.

| % nS | Maximum Stress (MPa) in nS-CFST |
|------|---------------------------------|
| 0    | 40.86                           |
| 4    | 48.52                           |
| 6    | 52.67                           |
| 8    | 50.28                           |
| 10   | 42.21                           |

In Phase 3, the numerical models are successfully developed for the experimental nS-CFST specimens and standard CFST. Similar behavior can be observed in all the numerical models. The results of the stress-strain graphs obtained from the numerical models and experimental specimens are represented together in fig. 1-5. The output values show almost the same behavior as that of the
specimens. The deformed profile of the numerical models is almost same to the experimental specimen, which can be observed in Fig.6-9, which validates the model.

![Confinement Factor](image)

**Figure 10.** Confinement factors for nS-CFST specimens.

4. Conclusions

The study observes the effects of partial replacement of cement with the nano-silica (nS) in M25 mix and nS-CFST stub columns. The numerical models were also developed in the study. The following conclusions can be drawn from the study:

- The blended concrete mix 6% of nano-silica showed better strength than all other nano-silica based blended concrete mix and control cement mix.
- A similar trend could be seen in nS-CFST stub columns, the optimum amount of nano-silica in nano-silica blended concrete and CFST was observed at 6%, although the 8% also gave quite good results.
- A significant reduction in the compressive strength in the case of both nS blended concrete and nS-CFST specimen with more than 6% of nano-silica in the mix, which shows the optimum dosage of nS plays an important role and the drastic decrease in strength after that dosage.
- A numerical model for the nS-CFST was successfully developed, which shows approximately the same results given by the experimental specimens.

The conclusions describe the improvement of the performance of the blended concrete mix and nS-CFST corresponding to the percentage replacement of concrete with nano-silica. It could also be seen from the stress-strain curves that the nS-CFST models acted in a very ductile manner, which shows its ability to delay the ultimate failure.

5. References

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