Fresh and Hardened Properties of Nano Self-Compacting Concrete with Micro and Nano Silica

Mohammed H. Hameed¹, Zena K. Abbas² and Ali Hussein Ali Al- Ahmed²

¹ PhD, student Department of Civil Engineering, Baghdad University, Baghdad, Iraq
² Assist. Prof. Dr., Department of Civil Engineering, Baghdad University, Baghdad, Iraq
*Corresponding author e-mail: iraqcivilm@gmail.com

Abstract. Self-compacting concrete (SCC) has undergone a remarkable evolution recently based on the results from several studies that have indicated the chain of benefits SCC provides. Micro and nano materials used as mineral additives in SCC offer several high-performance properties, and this research studies the effects of micro silica (MS) (10%, used as a reference) and colloidal nano-silica (CNS) (2.5%, 5%, 7.5%, and 10%) on the fresh and hardened properties of SCC. All mixtures were estimated using flow, L-box, and V-funnel tests to examine workability and compressive strength, modulus of elasticity and tensile strength as hardened properties. The use of CNS increased the overall compressive strength compared to the reference mixture, with the average increase for 28 days being 41%. The discoveries of this work offer insight into the creation of volitional mineral admixtures for improving the toughness attributes of SCC, increasing enforcement, and offering a more maintainable and practical material.

1. Introduction
Since Okamura developed SCC, the material has seen a great deal of progress based on more research and it is still being developing due to its multiple advantages. SCC specifications allow for any corner of the mould to have proper filling with very tight reinforcement areas without insulation and perfusion, using the material’s own weight without the need for compression and vibration. In addition, SCC reduces the final cost and quality of the structural component as well as maintaining effective concrete properties [1], [2].

Among the various complementary cement materials used, it is widely agreed that silica fume (SF) is very effective in exaggerating the intensity and decreasing the permeability. The operational complications of adding SF for self-compacting concrete mixes (SCCs) are the leading obstacle to its use, as silica in the microscopic range is widely available and has proved as highly influential in improving the rigid properties of materials. However, in nanoparticle sizes ranging between 1 and 100 nanometres, silica (NS) may have even greater potential for concrete products [3].

Currently, nanotechnology is attracting a lot of attention from authors and scientists due to nanoparticles characteristic properties. There has been great consideration of nanomaterials and their potential implementations in the production of high performance, durable, and sustainable concrete due to the increased pozzolanic reactions produced, and NS is commercially available and can be delivered in the form of dry powders or colloids for ease of use. [4]
This paper study the behaviour of several SCCs with varying ratios of cement and NS. The properties studied are the rheologic (slump, flow time, V-funnel, L-box) and mechanical (pressure strength, split-tensile strength, and modulus of elasticity). A larger amount of compressive strength was acquired by aging NS for 28 days, and increases in pressure force not only depend on the amount of particles or the ratios used but also on the division of particles within the resulting mixture.

2. Properties of Construction Materials

2.1. Cement

In this paper Ordinary Portland cement (OPC) (Type-I) was used; this produced in Iraq under the trade name Tassloja. The properties of cement used in this paper are given in Tables (1) and (2), and all properties are identical with the Iraqi Specification (IS) No. 5/1984 [5]. All material testing was done at the Consulting Engineering Bureau (CEB) in the College of Engineering, University of Baghdad.

| Compounds | IS No.5/1984 |
|-----------|-------------|
| CaO       | 62.8        |
| SiO₂      | 21.44       |
| Al₂O₃     | 5.52        |
| Fe₂O₃     | 3.12        |
| MgO       | 2.9         |
| SO₃       | 2.47        |
| L.O.I     | 1.07        |
| I.R       | 0.68        |
| L.S.F     | 0.83        |

| Property                              | Test | IS Limits (I.O.S. 5/1984) |
|---------------------------------------|------|---------------------------|
| Fineness by air permeability method (Blaine), m²/kg | 298 m²/kg | ≥ 230 m²/kg |
| Initial Setting Time                  | 120 min | ≥ 45 min |
| Final setting time                    | 230 min | ≤ 6×10² min |
| Compressive Strength, MPa             | 3- day | 17.5 MPa |
|                                      | 7- day | 26.0 MPa |
|                                      | 3- day | 17.5 MPa |
|                                      | 7- day | 26.0 MPa |

2.2. Fine Aggregate

Normal sand was used this paper from an area in north Baghdad. The fine aggregate (FA) used in this paper had a maximum size of 4.75 mm with rounded particles and a 2.84 fineness modulus. Table (3) shows the grading of the FA. All results indicate that the FA sulphate content and grading are within the IS No. 45/1984 [6]. The sulphate content, absorption and specific gravity (SG) are shown in Table (4).

| Sieve Size | % Passing | IS No. 45/1984 for Zone(2) |
|------------|-----------|-----------------------------|
| 10 mm      | 100       | 100                         |
| 4.75 mm    | 92.56     | 90-100                      |
| 2.36 mm    | 76.69     | 75-100                      |
| 1.18 mm    | 62.44     | 55-90                       |
| 600 μm     | 45.47     | 35-59                       |
| 300 μm     | 15.72     | 8-30                        |
| 150 μm     | 2.2       | 0-10                        |
Table 4. Physical Properties of FA

| Physical properties | Results | IS No. 45/1984 for Zone(2) |
|---------------------|---------|-----------------------------|
| SG                  | 133/50  | -                           |
| Sulphate Content    | 0.18 %  | ≤ 1/2 %                     |
| Absorption          | 3/4 %   | -                           |

2.3. Coarse Aggregate

The coarse aggregate (CA) grading is shown in Table 5. The CA used has a 10 mm maximum size, and all outcomes indicate that the CA grading and sulphate content met the demands of IS No. 45/1984, as per Table 6.

Table 5. Grading of CA

| Sieve Size | % Passing | IS No. 45/1984 |
|------------|-----------|----------------|
| 14mm       | 100       | 100            |
| 10mm       | 92        | 85-100         |
| 5mm        | 12.5      | 0- (50/2)      |
| 2.36mm     | 1.7       | 0-5            |

Table 6. Physical Properties of CA

| Physical properties | % passing |
|---------------------|-----------|
| Test results        | IS No. 45/1984 |
| SG                  | 53/20     | --             |
| Sulphate content    | 0.07%     | ≤ (1/10)%      |
| absorption          | 0.62%     | --             |

2.4. Chemical admixture

Structuro 520 is differentiated from typical superplasticizers (SP) by supporting a single group ether chemical compound with long lateral chains. This greatly improves the dispersion of cement and combines the properties of water reduction, retention, and operability. This allows the production of high-performance concrete with improved operating efficiency. The properties of SP were taken from the manufacturer’s information sheet.

2.5. Mineral Admixtures

2.5.1 Micro-silica

The micro-silica, Mega Add MS(D) adapted to ASTM C 1240-15 [7], has a surface area of 15 m²/g and bulk density of 500-700 kg/m³. Table (7) shows the properties of the MS.
Table 7. Technical properties of MS

| PROPERTY                        | VALUE                                      |
|---------------------------------|--------------------------------------------|
| State                           | Sub-micron powder                          |
| Colour                          | Grey to medium grey powder                 |
| Specific Gravity                | 2.10 to 2.40                               |
| Bulk Density                    | 500 to 700 kg/m³                           |
| Silicon Dioxide (SiO₂)          | ≥ 85%                                      |
| Moisture Content (H₂O)          | ≤ 3%                                       |
| Loss on Ignition (LOI)          | ≤ 6%                                       |
| Specific Surface Area           | ≤ 15 m²/g                                  |
| Pozzolanic Activity Index, 7 days | ≥ 105% of control                       |
| Over size particles retained on 45-micron sieve | ≥ 10%                                     |

2.5.2. Nano-silica

The technical specifications of the nano-silica used are listed in Table 8. No strength activity index of NS is available, so the procedure followed in ASTM C 1240-15 was used and adapted from the recommendations of other authors (M. S. Nasr, 2006) [8] and R. T. Abdulkareem, 2015 [9]). The NS was created in the Islamic Republic of Iran.

Table 8. Technical specifications of NS

| Material appearance | liquid                                              |
|---------------------|-----------------------------------------------------|
| Colour %            | Slight blue and transparent                         |
| Chloride %          | < 1/10                                               |
| SiO₂ %              | 24.5                                                |
| pH                  | 9.5                                                 |
| Strength activity index % | 170                                             |

2.5.3. Limestone powder

Limestone powder (locally named Gubra) was employed as filler for SCC production in this research. To extend workability and early strength, as well as reducing the necessary compaction energy, the particle size must be consistent with EFNARC at less than 0.125 millimetres.

3. Experimental program

3.1. Mixture proportioning

The concrete mixtures were consistent with ACI 237R-07 code [10] and EFNARC (2005) [11]. Table (9) shows details of these mixtures. A reference mix with 10% MS was cast for comparison with those with the addition of different percentages of CNS. SCC standard limitations for concrete mixtures’ attributes were retained. All compounds for this research were constant with only CNS or SP% contents changed by weight for NS and as a replacement weight by binder for SP%. The water substance of the NS hydrosols, SF slurry, and SP were all counted within the total water content. The slump range, from 677 to 730 mm, showed good workability in all mixtures. The varying water requirements of different blends was met by the utilisation of appropriate measures of SP. Five minutes in a pan mixer of 180 L capacity was used for all concrete mixtures, which were prepared following the procedure recommended by ACI 237R-07 and explained by Daczko (2012) [12].
3rd International Conference on Engineering Sciences
IOP Conf. Series: Materials Science and Engineering 671 (2020) 012079 doi:10.1088/1757-899X/671/1/012079

Table 9. Mixture proportions

| Mix designation | Cement (Kg/m³) | MS (Kg/m³) | LP (Kg/m³) | NS (Kg/m³) | FA (Kg/m³) | CA (Kg/m³) | Water (L/m³) | SP (l/100kg Cement) | W/P |
|-----------------|---------------|------------|------------|------------|------------|------------|--------------|---------------------|-----|
| SCC Ref.        | 400           | 40         | 50         | 0          | 820        | 840        | 180          | 1.1                 | 0.367 |
| SCC 2.5 % CNS   | 400           | 40         | 50         | 10         | 820        | 840        | 180          | 1.4                 | 0.36  |
| SCC 5 % CNS     | 400           | 40         | 50         | 20         | 820        | 840        | 180          | 1.9                 | 0.353 |
| SCC 7.5 % CNS   | 400           | 40         | 50         | 30         | 820        | 840        | 180          | 2.3                 | 0.346 |
| SCC 10 % CNS    | 400           | 40         | 50         | 40         | 820        | 840        | 180          | 2.8                 | 0.34  |

3.2. Preparation and Casting of Specimens

All mixtures had w/p ratios of 0.367 to 0.34 and constant cement content of 400 kg/m³. CNS additions of 2.5%, 5%, 7.5% and 10% as a partial weight of cement did not reduce the weight of cement. CNS begins as a clear liquid and changes to the cloudy substance (indicating agglomeration) when SP is added. CNS was mixed with water for 10 minutes by hand before being added to the concrete mixture 5 minutes later. All specimens were covered to reduce water evaporation during casting and lifted out of the moulds after 48h before being cured in a controlled environment following ASTM C 192 M-15, referenced at 28 days, as shown in Figure 1. Higher replacement levels did not affect workability as the increase in SP was at similar levels for all the mixtures. All the specimens were prepared in ASTM C 192, 15 30 (cm) cylinder moulds without vibration. Fifteen cylinder specimens were prepared for compressive strength testing at 28 days; fifteen were prepared for split-tensile strength examination; and fifteen samples were prepared for modulus of elasticity tests.

Figure 1. Specimens during curing

4. Result and discussion

4.1. Fresh properties

Table 10 and Figure 2 show the fresh properties for all mixtures. Fresh properties of a concrete mixture according to EFNARC include passing ability, filling ability and segregation strength as tested by slump, flow time, L-box and V-funnel. All SCC results showed good workability with regard to filling ability, and acceptable workability for passing ability. V-funnel time increased and slump flow decreased when CNS was used in mixtures, while little difference was noted in the L-box results.

Table 10. Mixture proportions

| Mix designation | Flow time (second) | Slump flow (mm) | V-funnel (second) | L-box (H2/H1) |
|-----------------|--------------------|----------------|------------------|---------------|
| SCC Ref.        | 3.4                | 730            | 8.5              | 0.98          |
| SCC 2.5 % CNS   | 3.1                | 694            | 9.4              | 0.96          |
| SCC 5 % CNS     | 2.8                | 687            | 10.2             | 0.92          |
| SCC 7.5 % CNS   | 3.4                | 684            | 11.3             | 0.88          |
| SCC 10 % CNS    | 3.8                | 677            | 12               | 0.81          |

Limits: 2.5 - 5.5, 650-800, 2-5, 0.8-1.0

Table 10 shows that increases in SP% content allowed the fresh concrete tests to remain within the European guideline limits. SP dosage is mostly dependent on the particle size compared with the rates of addition of mineral admixture. Increasing CNS content was related to the formation of new distinct
forms of flower-like crystals distributed in a complex form. The addition of CNS’s production of new phases of calcium silicate hydrates is due to the absence of calcium hydroxide and the presence of crystals in large quantities. This improvement is related to the development of various mechanical properties [13], [14] and [15].

4.2. Mechanical properties

4.2.1. Compressive strength

Table 11 shows the compressive resistance of all mixtures at 28 days. When adding CNS, the results show an increase in compressive resistance for all mixtures. Based on these results, SCCs with the added metals are higher than the reference concrete at 28 days. The mix of 10% CNS content shows the highest compressive strength of 59.91 MPa, suggesting that compressive resistance increases depending on the amount of metal added. This is due to hydration reactions and the pozzolanic reactions of added minerals.

For this reason, many researchers believe that the strength of pressure depends not only on the particle size and quantity of the mineral mix but also on the particle size distribution of materials used for the preparation of concrete [16].

**Table 11. Compressive strength of Mixtures**

| Mix designation | Compressive Strength (MPa) | Increase % |
|-----------------|----------------------------|------------|
| SCC Ref.        | 40.45                      | -          |
| SCC 2.5% CNS    | 52.31                      | 29.32      |
| SCC 5% CNS      | 56.96                      | 40.82      |
| SCC 7.5% CNS    | 58.98                      | 45.8       |
| SCC 10% CNS     | 59.91                      | 48.1       |

**Figure 2.** Relationship between slump flow and CNS% (a), Relationship between V-funnel time and CNS% (b) and Relationship between L-box and silica percentages CNS% (c)
4.2.2. Splitting tensile strength

Figure 4 and Table 12 shows the results of split-tensile strength determined at 28 days. All concrete mixtures show enhancement in split tensile strength compared to the reference mixture at 28 days. The important distinction suggests that additions increase durability based on the percentage of the additive. A blend with additions may also have additional fineness due to varying particle sizes where, as in this work, the supplementary materials are additional to the reference mixture.

Table 12. Split-tensile strength of mixtures

| Mix designation | Split Tensile Strength (MPa) | 28 days | Increase % |
|-----------------|-----------------------------|---------|------------|
| SCC Ref.        | 4.56                        | 0       | 0          |
| SCC 2.5% CNS    | 5.32                        | 16.67   |
| SCC 5% CNS      | 5.45                        | 19.52   |
| SCC 7.5% CNS    | 6.05                        | 32.68   |
| SCC 10% CNS     | 6.15                        | 34.87   |

Figure 4. Averages of Split tensile strengths at 28 days (a) and Improvement rates in splitting strengths at 28 days (b)

4.2.3. Modulus of elasticity

In this paper, modulus of elasticity tests were carried out on all SCCs as cylindrical specimens of 15 cm x 30 cm; measurements of the static modulus of elasticity were then made according to ASTM C469-02 technique (0.4 fc’), to avoid damage to the testing device and its parts. Thus, all specimens were tested up to approximately 40% of ultimate compression strength. The results are seen in Table 13 and Figure 5 SCCs with ternary mixtures of CNS showed lower values than the reference mixture.
This makes it clear that the utilisation of CNS generates a small increase in the coefficient of elasticity; however, 10% CNS develops the largest value of the modulus of elasticity (36.7 GPa). To better perceive the result of a various dose of CNS on SCCs, the obtained results are represented in Figure 5 as a percentage of the reference SCC. Among the CNS dosages used, 2.5% provided the best comparative modulus of elasticity.

| Table 13. Modulus of elasticity of concrete mixtures |
|-----------------------------------------------------|
| Mix designation | Modulus of Elasticity (GPa) | Different in Modulus of Elasticity % |
|-----------------|-----------------------------|-------------------------------------|
| SCC Ref.        | 35.03                       | -                                   |
| SCC 2.5% CNS    | 37.52                       | 7.1                                 |
| SCC 5% CNS      | 35.5                        | 1.3                                 |
| SCC 7.5% CNS    | 36.2                        | 3.34                                |
| SCC 10% CNS     | 36.7                        | 4.77                                 |

Figure 5. Averages of Modulus of Elasticity at 28 days (a) and Improvement rates in modulus of elasticity at 28 days (b)

5. Conclusions

Fresh properties:
1. The results show the addition of SP dose is generally associated with the particle size rather than the addition by weight for the mineral admixture. Using CNS during this study rather than the powder type used elsewhere did not alter this.
2. Inducing CNS within mixes causes a reduction in slump flow values of 730 to 677 mm, and a rise in V-funnel time of 8.5 to 12 second. For L-box results however, only small distinction was detected within the results.
3. Such additions, to have an impact, require signification quantities of SP because of its minor particle size and its corresponding large surface area.

Mechanical properties:
1. Concretes made from cement proportion replacements of 2.5%, 5%, 7.5%, and 10% CNS have considerably increased compressive strength levels (29.32%, 40.82%, 45.8%, and 48.1% improvements, respectively) compared to the reference sample. The improvement in strength level is dependent on the replacement percentage.
2. Concretes made from higher cement proportion replacements, from 2.5% to 10% CNS have increases in tensile strength levels of between 16.67% to 34.87% compared to the reference sample. This development may be a result of the additional fineness generated by the completely different particle sizes.
3. Optimum modulus of elasticity is achieved at 2.5% CNS dosage. Unlike compression strength, this behaviour shows high sensitively to CNS additions.
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