# Effect of Steel Fibers, Polypropylene Fibers and/ or Nanosilica on Mechanical Properties of Self-Consolidating Concrete

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## ABSTRACT

This research concerned studying the combined effect of using nano-silica and/ or hybrid fibers on key mechanical properties of self-consolidating concrete SCC. A comprehensive experimental work has been carried out, using steel fiber (SF) with volume fraction (0, 0.5% and 1.5%), polypropylene fiber (PPF) (0%, 0.05% and 0.15%) and $SiO_2$ nanoparticles (0%, 2% and 4%) by weight of powdered material (silica fume- Sf ) with constant w/c ratio (0.48) to produce eleven different mixtures and tested at different ages (7, 28 and 90 days).

Results showed that adding fibers adversely affect SCC workability and thus more dosage of super plasticizer (SP) should be added to stay within the standard limits. comparable to conventional concretes, the presence of steel fibers with SCC provide slight increase in compressive strength at 28 days, (up to 11%), while significant enhancement in tensile properties were observed (up to 24% and 32% for splitting and flexural strength respectively). Polypropylene or hybrid fibers however, provide lower enhancement compared with steel fibers. In contrast, implementation of nanosilica leads to significant improvement in concrete strengths particularly at 4% dosage. Combined effect of 4% nanosilica and 1.5% of steel fibers provide the superior hardening effect on the flexural performance compared with softening effect provided by other added dosages. Scanning Electron Micrograph (SEM) images confirm the matrix densification effect due to nanosilica adding. Flexural strength of SCCs without nanosilica was generally higher than splitting testing results. This fact does not change even with the presence of nanosilica and/ or fibers.

**Keywords:** Self-Consolidating Concrete (SCC); nanosilica; steel fibers; polypropylene fibers; compressive behavior; tensile behavior; SEM.

# تأثير الالياف الفولاذية والياف البولي بروبلين مع او بدون الحبيبات النانوية السليكية على الخواص الميكانيكية للخرسانة الذاتية الرص

**الخلاصة:**

تم دراسة التاثير المشترك لاستخدام الحبيبات النانوية السليكية مع او بدون الالياف المهجنة على الخواص الميكانيكية للخرسانة ذاتيـــة الرص. من اجل دراسة هذا التأثير تـــم القيام بفحوصات مختبرية باستخدام الالياف الفولاذيـــة بنسبـة ( 0 % و 0.5% و1.5% ) والالياف البولي بروبلين بنسبة ( 0% و0.05 % و 0.15.% ) وحبيبات النانو سليكا بنسبة (0% و2% و 4.% )2% ) كنسبة من وزن المواد الناعمة مع نسبة ثابتة من الماء الى السمنت (0.48) لانتاج احد عشر خلطة مختلفة ومفحوصة بمختلف الاعمار7 و 28 و 90 يوم.

النتائج اشارت الى حصول تأثير عكسي عند اضافة الالياف على القابلية التشغيلية الخرسانية لذا تطلب اضافة نسبة اكثر من المضاف الكيميائي الملدن المتفوق للثبات ضمن حدود المواصفات. ان اضافة الالياف الفولاذية الى

الخلطة الخرسانة ذاتية الرص ادى الى زيادة قليلة في مقاومة الانضغاط عند عمر28 يوم بمقدار11% بينما زيادة كبيرة في خواص الشد الى حوالي (24% و32%) لمقاومتي الانشطار والانثناء بالتتابع. اما الالياف البولي بروبلين او الخليط من الالياف يعطي تحسن اقل مما في حالة الالياف الفولاذية. بالمقارنة مع الالياف فان حبيبات $SiO_2$النانوسليكا تؤدي الى تحسن كبير في مقاومة الخرسانة خصوصا عند نسبة اضافة 4%. التأثير المشترك للحبيبات النانوية بنسبة 4% مع الالياف الفولاذية بنسبة 1.5% يعطي تاثير افضل على الخواص الصلبة. بالنسبة لفحص البنية المجهرية فيتوافق مع التأثير المكثف للتراكيب الداخلية للعجينة السمنتية نتيجة استخدام الحبيبات النانوية. كما لوحظ ان مقاومة الانثناء للخرسانة الذاتية الرص بدون المواد النانوية كانت اعلى من نتائج فحص مقاومة الانشطار. لذا هذه الحقيقة لا تتغيربوجود المواد النانوية مع او بدون الالياف.

## INTRODUCTION

Self- Consolidation Concrete (SCC) considered one of the most valuable evolutions in concrete technology for several decades .The necessity of this type of concrete was first predicted by Okamora [1]. R. Deeb et. Al [2] stated that SCC mix design is a negotiation between two contradictory objectives. On one hand, SCC should have high fluidity to ensure that it will fill the formwork under its own weight; on the other hand, it should be a cohesive mixture to prevent segregation during the flow. Therefore, utilizing fine materials has the ability to produce SCC with a cohesive nature results in an improved fresh and mechanical properties, with the nanotechnology advancement, nano materials were adopted to make it applicable in concrete mix designs to predict the physical, chemical and enhanced mechanical properties of concrete [3], A growing attract in recent years to the use of $SiO_2$ nano particles in concrete, they play a significant role in improving mechanical performance of concrete, they react with calcium hydroxide (CH) released during the hydration, form more hydration products and fill the available pores[4].

Singh et al. [5] clarified that the other reasons behind the strength gain concerning these two approaches: (a) Physical effect: by filling up the spaces between the cement particles. (b) Chemical effect: nanosilica has a pozzolanic activity which is much greater compared to silica fume (Sf) turns in considerable amount of C–S–H gel and more intensified micro structure. Kuo et al.[6], found out that nano particles which had a regular dispersion in the cement paste would accelerate the hydration process due to their high reactivity. However, Scrivener KL et al. [7], explained that depending on the test results, the fabrication route and characteristics of synthesis of $SiO_2$ nano particles (e.g., the reaction type and consuming time of the reaction for the sol–gel method). Whereas Ginebra et al. [8], expressed that the larger surface area of concrete powders the stronger electrostatic forces the more influential on cement kinetics and accelerator to the hydration evidently.

The employment of FRC combines the tensile and flexural mechanical benefits by the fibers addition as most gainful properties with the fiber addition can be achieved include toughness, impact strength, and energy absorption capacity [9]. One of the most common used fibers types are SF, make significant improvement in the tensile behavior of the concrete by arresting crack growth and controlling on the macro cracks initiate and propagate. In contrast with soft PPF the improvement in tensile behavior occurred by inhibiting microcracks growth [10]. Dawood et. al [11] outlined that the hybridization of various types of fibers play a significant roles in arresting both macro as well as micro size cracks, thus achieving the SCC or HPC. The hybrid fibers considered as a promising concept would further improve the composite rigidity, flexural toughness and improve the overall performances.

H. Oucief et al. [12] carried out a study deals with hybrid fiber (HF) to produce potentially better concrete performance than with single fiber effect, applied on SCC containing SF and PPF. An improvement of 15% in compressive strength, 53% flexural strength, and 62%-313% in toughness indices were determined for hybrid SCC composite compared to unreinforced SCC. The reason behind this fact was, for the unreinforced SCC, the material exhibits relative brittle behavior, the load declines rapidly with increase of midspan deflection after peak load. However, for the reinforced SCC, the decrease trends were much flatter.

In this study, two different types of fibers were applied in SCC (SF and PPF were partially replaced by coarse aggregate) to improve the tensile behavior, in addition to $SiO_2$ nano particles were added ( as partial replacement of 5% silica fume ) to the plain and fibrous mixes to investigate their influence on the fresh and key mechanical properties. Additionally, the porosity and densification of the hardened concrete microstructure of were analyzed by SEM techniques.

## Materials and Methods

The Ordinary Portland cement used in SCC mixtures that conforms the Iraqi specifications[13], the initial and final setting time were 1:58 hours and 5:15 hours respectively, and a compressive strength of 23.1 MPa at 3 days and 33.62 MPa at 28 days.

Silica fume (micro silica that conforms the ASTM C1240 [14]), $SiO_2$ nano particles as well as a fine filler limestone dust, with a very high fineness were used as an addition to the cement. The chemical compositions of ordinary Portland cement, $SiO_2$ nano particles, silica fume and the limestone powder were stated in Table 1.

The coarse aggregates used were with maximum size of (12.5 mm) and fine aggregates were natural sand with fineness modulus of 2.8 and maximum size of less than 5 mm. The grading curves conform to ASTM C33 [15] as plotted in Figure 1 A and B. The SF and PPF fibers were supplied by Sika Co., and their mechanical properties were presented in Table 2. Also (HRWRA) based on modified polycarboxylic ether (Glenium 54) has been adopted throughout this work, which conforms to ASTM C 494 Type F [16]. The technical description of this admixture is given in Table 3; w/c ratio of 0.48 was kept at constant rate. The mix design of the control mix was carried out following ACI 237 [17], the SF are added to the mixes according to the volumetric fractions of 0.5 and 1.5%, while PPF with (0.05% and 0.15%). Table 4 shows the details of concrete mixes.

**Table(1): Chemical composition of SCC fine materials**

| Constituent | Ordinary Portland Cement (%) | Silica fume (%) | $SiO_2$ nano particles (%) | Limestone powder |
|---|---|---|---|---|
| Lime | 61.52 | 0.90 | _ | 61.01 |
| Silica | 20.8 | 91.51 | 99.8 | 1.12 |
| Alumina | 6.4 | 0.73 | - | 0.64 |
| Iron oxide | 2.3 | 0.48 | - | 0.3 |
| Magnesia | 1.403 | --- | - | 0.31 |
| Sulphate | 2.5 | 0.97 | - | 0.15 |
| Sodium Oxide | 0.28 | 1.8 * | 1.38_ | - |
| Loss on ignition | 2.4 | 4.40 | ≤1.0 | 35.3 |

* Includes Sodium and Potassium Oxide

**Table (2) Properties of the used SF and PPF**

| Property | Results of SF | Results of PPF |
|---|---|---|
| Description | Hooked end | Monofilament |
| Length | 30 mm | 12 mm |
| Diameter | 0.5 mm | 15 Mm |
| Aspect ratio ($l_f/d_f$) | 60 | 80 |
| Relative Density | 7840 kg / $m^3$ | 0.9 kg / $m^3$ |
| Ultimate Tensile Strength | 1180 MPa | 300-400 |

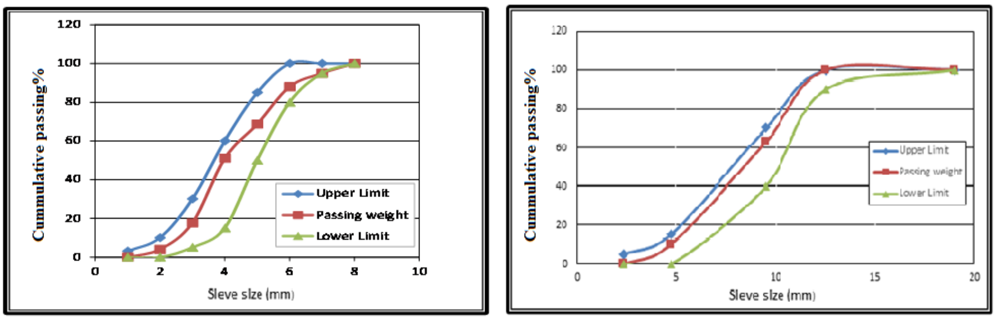
**Table (3) Technical description of Glenium 54**

| Basis | modified polycarboxylic ether |
|---|---|
| Appearance | Whitish to Straw coloured liquid |
| Relative density | 1.07 |
| PH | 5-8 |
| Storage | stored in original containers and at above 5$^o$C |
| Transport | Not classified as dangerous |
| Labeling | Not hazard label required |

**Table (4): Details of concrete mixes used in the present work***

| Group No. | Mix Descriptions | Cement(kg/m$^3$) | Sf (kg/m$^3$) | $NanoSiO_2$- N (kg/m$^3$) | LSP(kg/m$^3$) | Total powder(Kg/m$^3$) | Water (L/m$^3$) W/C= 0.48 | Crushed Gravel (kg/m$^3$) | Sand (kg / m$^3$) | Dosage of SP (L / m$^3$) | SF (kg/m$^3$) | PPF (kg/m$^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | SCC | 400 | 20 | 0 | 100 | 520 | 192 | 840 | 840 | 4 | 0 | 0 |
| | SCC-0.5SF | 400 | 20 | 0 | 100 | 520 | 192 | 798 | 840 | 4.5 | 42 | 0 |
| | SCC-0.05PPF | 400 | 20 | 0 | 100 | 520 | 192 | 839.5 | 840 | 5 | 0 | 0.5 |
| | SCC-0.5SF&0.05H | 400 | 20 | 0 | 100 | 520 | 192 | 797.5 | 840 | 7 | 42 | 0.5 |
| 2 | N2-SCC | 400 | 12 | 8 | 100 | 520 | 192 | 840 | 840 | 5 | 0 | 0 |
| | N2- SCC-0.5SF | 400 | 12 | 8 | 100 | 520 | 192 | 798 | 840 | 6 | 42 | 0 |
| | N2- SCC-0.05PPF | 400 | 12 | 8 | 100 | 520 | 192 | 839.5 | 840 | 6 | 0 | 0.5 |
| | N2-SCC-0.5SF& 0.05PPF | 400 | 12 | 8 | 100 | 520 | 192 | 797.5 | 840 | 8 | 42 | 0.5 |
| | N2-SCC-0.5SF& 0.15PPF | 400 | 12 | 8 | 100 | 520 | 192 | 796.5 | 840 | 14 | 42 | 1.5 |
| 3 | N4-SCC | 400 | 4 | 16 | 100 | 520 | 192 | 840 | 840 | 10 | 0 | 0 |
| | N4- SCC-1.5SF | 400 | 4 | 16 | 100 | 520 | 192 | 714 | 840 | 16 | 126 | 0.5 |

*SCC= self-consolidation concrete, N = $NanoSiO_2$, SF= Steel fiber, PPF= polypropylene fiber.




(A) Grading of fine aggregate (B) Grading of coarse aggregate

**Figure (1): Grading of aggregate (Limits of ASTM C33 Specifications).**

## Test Methods

### Fresh Concrete Properties

Efficient and consistence SCC has been considered on an importance scale, complying its fresh properties with the standards as well as guidelines, performing concrete laboratory, good practices and utilizing appropriate procedures in the mixing methods by following the standards results in SCC mixture with the required workability and conformity of the fresh tests with the specifications. The typical batching sequence that has been used to minimize balling of fine materials as below:

1. Adding the coarse aggregates to the mixer with more than 50% of mix water and mixing for 1minute.
2. After performing the dry mix for the powders (cement, limestone, silica fume and/or $SiO_2$ nano particles) followed by adding the fine aggregate to the previous ingredients and mixing for 1minute. As mentioned by other researchers[18] showed that nano materials was vigorously dry mixed with cement for 30 min or more to disperse nano particles with cement.
3. Adding remains water with 1/3 of superplasticizer and mix for $1^{1/4}$ minute after that adding the 2/3 of the leftover of superplasticizer dosage with $2^{3/4}$ minutes mix time.
4. The mixture is then discharged, tested and casted.

In the present study the above procedure was followed. The total mix time takes 5 minutes. However, in case of SF mixes, the fibers are added after point 3 and mixed for 2 minutes to achieve homogenous distribution of fibers [19].

ACI 304 [20] suggests in synthetic fiber reinforcement (PPF), they can be added any time during the mixing process as long as at least 5 min of mixing occurs after the addition of the synthetic fibers.

### Hardened Concrete: Mechanical Properties

All specimens were tested at saturated surface dry condition and carried out according to BS 1881: Part 116 [21] for 100mm cubes compressive test, ASTM C496 [22] was followed for cylinder (100x20mm) splitting strength, ASTM C1609 [23]for prism(100x100x400mm) flexural strength and the chord modulus test was done according to ASTM C 469 [24]using cylinders (100x200mm). The porosity had determined following BS3921 (1985) [25] and finally SEM specimens were with dimensions (10x10x10mm).

## Results and Discussion

### Compressive Strength

After curing and testing the compressive specimens at 7, 28 and 90 days, they give an indication to an enhancement that occurred as a result of $SiO_2$ nano particles incorporation on all SCC mixes and the influence of the fiber introduction, which are presented in Table 5 and plotted in Figure 2.

Results from Figure 2 displayed that the increments were as a result of the higher gained bond between fibers/matrix interfaces for the SF mixes, whereas PPF bridge microcracks growth, consequently lead to higher strength of the composite. The reduction for HF due to the reduction in flowing ability and passing ability by the PPF incorporation results in higher amounts of air voids.

The behavior of $SiO_2$ nano particles was responsible for the enhancement in the strength due to acting as nucleus sites to tightly bond with C-S-H gel particles, results in more intensified microstructure.

**Table (5): Compressive test results for all specimens.**

| Group No. | Mixes Description | Compressive strength $f_{cu}$ (MPa) | | | Elastic modulus |
|---|---|---|---|---|---|
| | | 7 days | 28 days | 90 days | 28 days |
| 1 | SCC-Ref. | 32.9 | 41 | 50.6 | 31.06 |
| | SCC-SF | 36 | 45.5 | 58.9 | 32.76 |
| | SCC-PP | 33.4 | 41.6 | 51.9 | 30.12 |
| | SCC-H* | 31.2 | 38 | 48.8 | 28.82 |
| 2 | N2-SCC | 35.5 | 45.1 | 56.2 | 32.12 |
| | N2-SCC-SF | 41.9 | 53.2 | 69.5 | 35.32 |
| | N2-SCC-PP | 36.5 | 45.8 | 57.3 | 31.25 |
| | N2-SCC-H* | 33.2 | 39.2 | 50.8 | 29.86 |
| | N2- SCC H1* | 32.1 | 40.5 | 49.2 | 28.9 |
| 3 | N4-SCC | 45.1 | 57.8 | 72.2 | 37.12 |
| | N4-SCC-SF1 | 51.3 | 65.9 | 85.1 | 40.28 |

*Hybrid mix

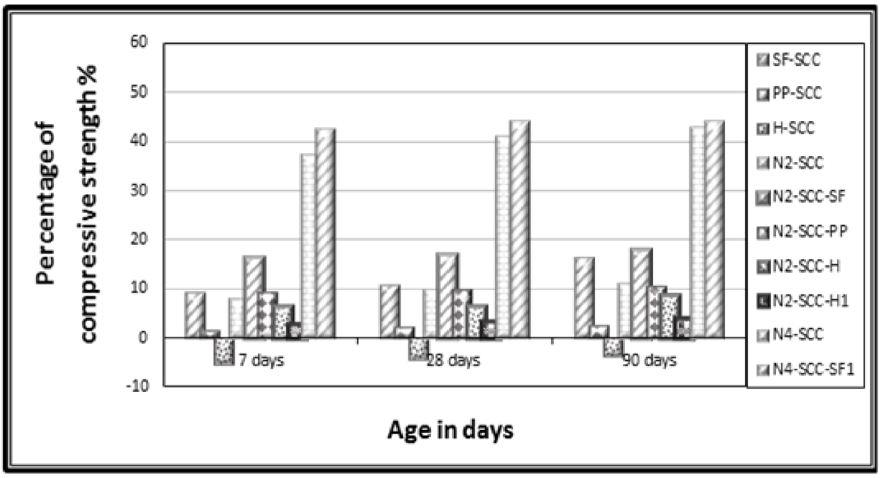



**Figure (2): Percentage of strength improvement for SCC mixes**

## Elastic Modulus

The increment in the SF elastic modulus mixes as illustrated in Table 5 and Figure 3 due to the fact that, they have higher stiffness results in improving the strength composite. On the other hand the reduction in PPF mixes case due to the lower elastic modulus and the weaker bond of this fiber. Also HF reduce the elastic modulus due to the fact that, the elastic modulus affected primarily by the same factors that affect its compressive strength, since the compressive strength of HF was reduced so it is expected to have a reduced elastic modulus due to the lower stiffness. The elastic modulus raise by nano particles introduction was due to the improved bond as a result of their higher pozzolanic effect and the higher surface area that improve the bond between fiber/matrix interfaces.

## Tensile Behavior (Splitting and Flexural Strength)

In these tests both resultant mixes approximately similar as seen in Table 6 and Figure 4 A, B. Where, the incorporation of single and HF results in improving the split and flexure strength due to the arresting the macro-cracks as well as microcracks by SF and PPF, also using hooked end SF led to an improved bond, consequently, an improved mechanical properties.

As it was mentioned that the increment by the nano particles introduction was due to the filler effect, pozzolanic effect and the enormous surface area enhance the bond between fiber/matrix interface in addition to the growth restricting for both macro and microcracks.

**Flexural Toughness**

From test results in Figure 5 it seems the higher increment was with SF usage, due to the high strength that delay the fiber failure after first crack also the better bond was a major factor in this improvement due to the extra dense C-S-H gel obtained from silica fume addition. While the possibility of PPF to improve the toughness was lower as they are soft, thin fibers lose their strength rapidly, while HF improve it lower than SF due to the weaker bond as a result of the large amounts of entrapped air in the mix by PPF incorporation. The nano particles enhancement also due to the filler effect, pozzolanic effect and the large surface area of nano particles that enhance the bond between fiber/matrix interfaces.

**Porosity**

Test results exhibited a decrease in the porosity values with mono fibers (SF or PP) introduction as mentioned in Figure 6 by (3.8% and 2.7%), whereas a decrement by using HF of about (2.5%) in comparison with the SCC-Ref. mix, due to the efficient role of SF and PPF in growth arresting for both macro and microcracks, in addition to the action of superplasticizer to maintain the fresh parameters results in more uniform microstructure and a decrease in the porosity values.

Results of Group 2 fibrous mixes with $SiO_2$ nano particles make a further decrement about (4.1%, 2.9%, 2.5% and 1.9 compared with their counterpart mixes in Group1, due to the more intensified microstructure that improves the bond at the fiber/matrix interface. While N4-SCC-SF1 mix in Group3 have the highest drop among other nano-fibrous mixes about (16.4%) compared with SCC-SF mix, due to the higher amounts for both SF and $SiO_2$ nano particles, where nano particles accelerate the cement hydration significantly, consequently more hydration products that envelope the voids. Test results for N2-SCC mix and N4-SCC mixes diminished the porosity values by (2%, and 12.6%) at 28 days.

**Microstructure Properties**

The addition of nanosilica has modified the porosity of the cement paste and increased the average silicate chains by consumption of CH, Singh et al. [5] has reported that the CH content in the nanosilica incorporated cement paste reduced up to 62% at 28 days of the hydration process. This behavior is clearly evidence in N4-SCC microstructure in contrast with SCC-Ref. microstructure. With 20-μm scale, it is easy to recognize the microcracks of SCC-Ref. but it is difficult for N4-SCC even with smaller scale. The micro-cracks of SCC appear continuous as illustrated by arrows in Figure 7 (a & b), but in Figure 8 (a & b) the microcracks of N4-SCC appear intermittent or even invisible.

From Figure 7 and 8 (b, c & d) it can be seen plates of CH are made by its relative brightness, exhibiting a typical hexagonal habit. It can be seen very clearly in bright color, the ettringite (sulfate irons react with calcium aluminates), which clearly seen in Figure 7-d with magnification up to 2μm. SEM observation of silica fume appears all in form of typical agglomerates of round dark grains with a very small size, which can be seen by the magnification up to 2μm in Figure 7-c, but in N4-SCC mix it seems to be reacted by the combined action with nano particles to form additional C-S-H as illustrates in Figure 8 (c & d), where the arrows in Figure 8-a refer to $SiO_2$ nano particles agglomeration in cement paste of SCC through the fracture surface.

Table (6): Indirect tensile tests results for all SCC mixes

| Group No. | Mixes Description | Splitting strength $f_{sp}$ (MPa) | | Flexural strength $f_r$ (MPa) | |
|---|---|---|---|---|---|
| | | 7 days | 28 days | 7 days | 28 days |
| 1 | SCC-Ref. | 2.9 | 3.2 | 3.5 | 3 |
| | SCC-SF | 3.6 | 4.2 | 4.6 | 4 |
| | SCC-PP | 3.4 | 3.9 | 4 | 3.5 |
| | SCC-H | 3.5 | 4 | 4.3 | 3.7 |
| 2 | N2-SCC | 3.2 | 3.5 | 3.9 | 3.3 |
| | N2-SCC-SF | 4.4 | 5.3 | 6 | 4.9 |
| | N2-SCC-PP | 3.9 | 4.6 | 4.9 | 4 |
| | N2-SCC-H | 4.1 | 4.8 | 5.4 | 4.4 |
| | N2- SCC H1 | 4.2 | 4.9 | 5.5 | 4.5 |
| 3 | N4-SCC | 3.5 | 4 | 4.8 | 4 |
| | N4-SCC-SF1 | 6.4 | 7.8 | 11.3 | 9.2 |

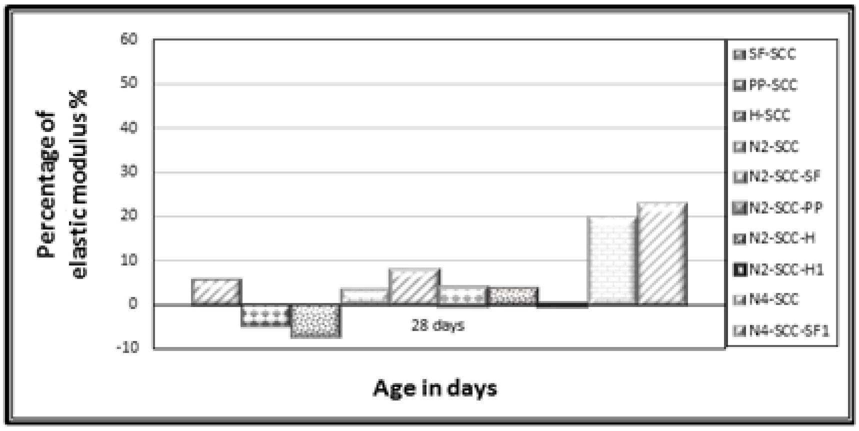
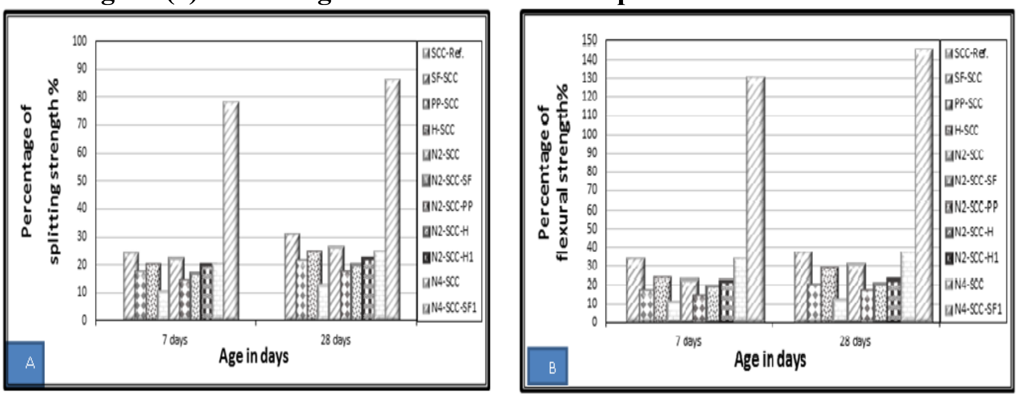



Figure (3) Percentage of elastic modulus improvement for SCC mixes.




(A) Splitting strength (B) flexural strength.

Figure (4): Percentage of strength improvement for SCC mixes.

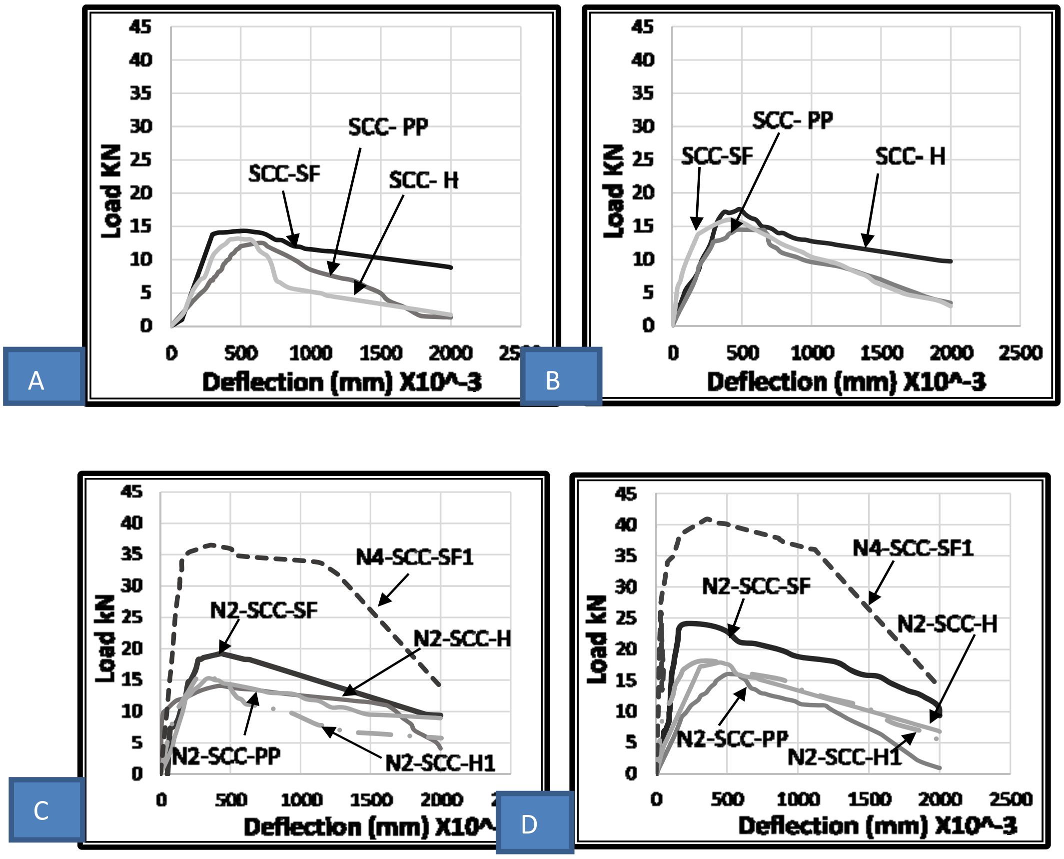



Figure (5): Comparison between Load –Deflection at 7 and28 days (A), (B): for fibrous mixes. (C) and (D): for nano-fibrous mixes.

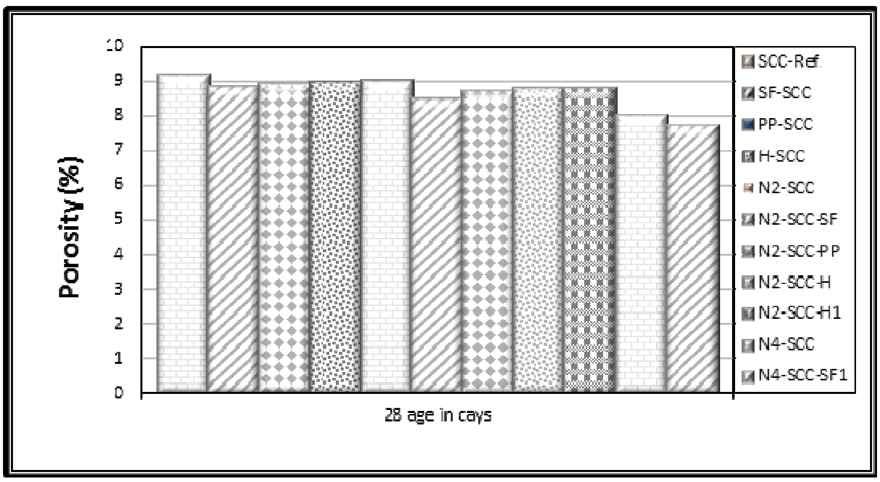



Figure (6): Porosity test results for all SCC mixes

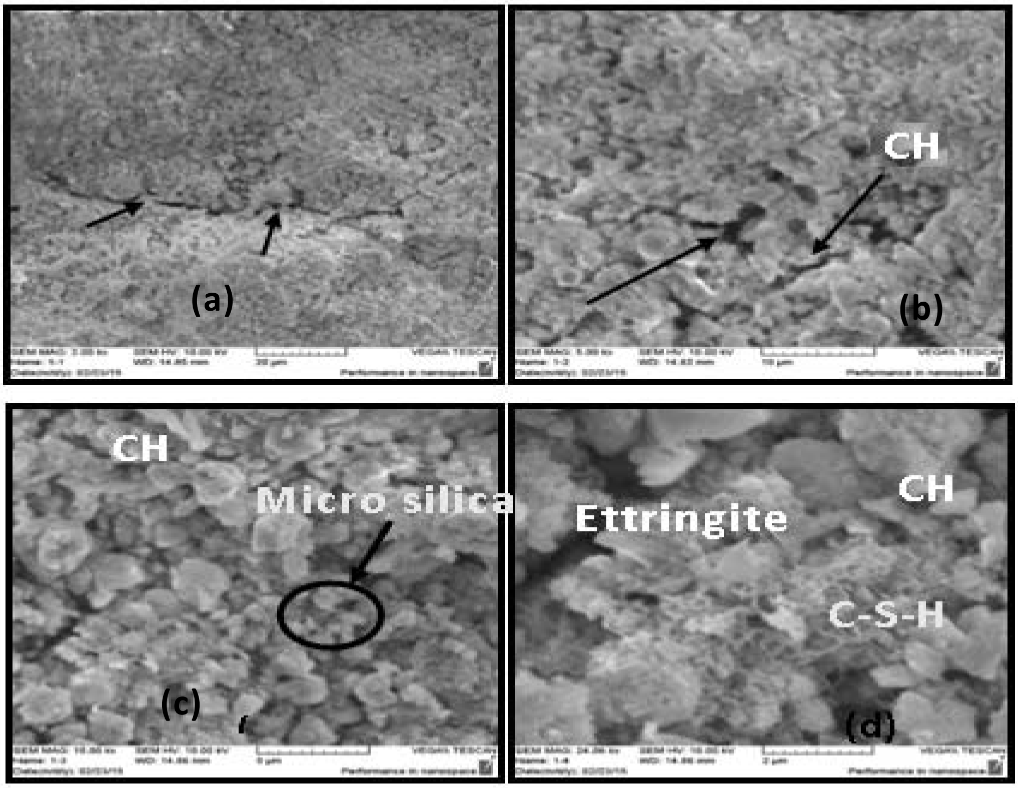



**Figure (7): SEM micrograph of microstructure-hydrated for SCC-Ref. at 28 days with different scales.**

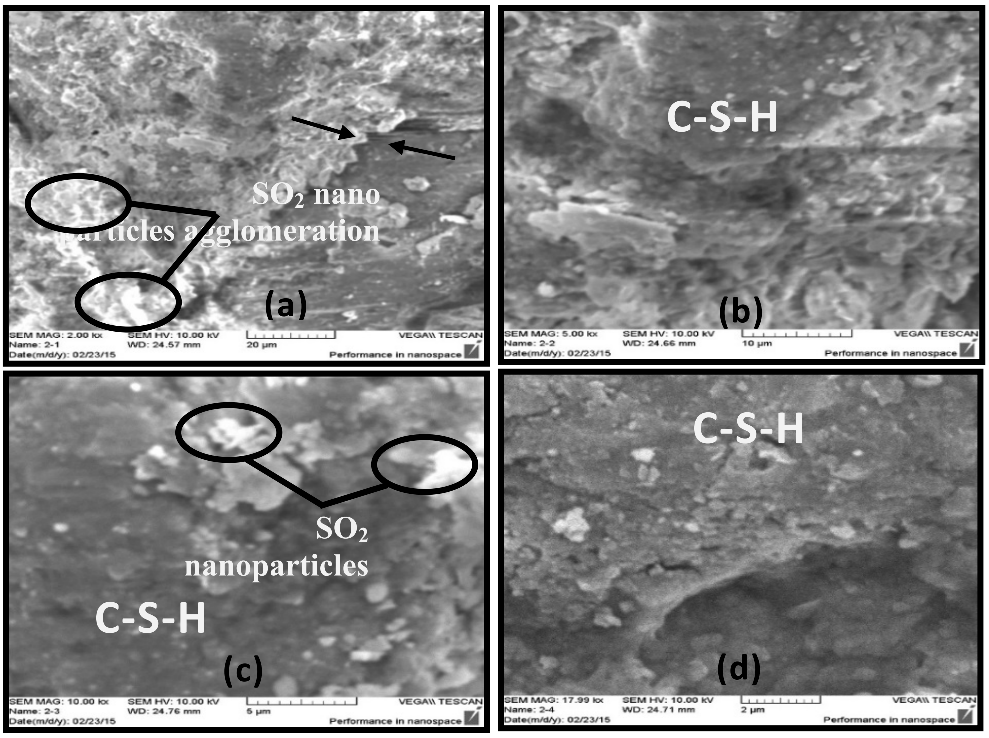



**Figure (8): SEM micrograph of microstructure-hydrated for N4-SCC mix at 28 days with different scales.**

## CONCLUSIONS

Based on the experimental work results in this investigation, the following conclusions can be drawn:

1. The compressive strength of SCC improved with $SiO_2$ nano particles incorporation at 7, 28 and 90 days, this improvement was more pronounced under the combined effect of SF and $SiO_2$ nano particles at 4% nano particles and 1.5% SF for N4-SCC-SF1 mix.
2. Modulus of elasticity increased by using $SiO_2$ nano particles, regardless the used fiber type. At 28 days of curing the percentage of increasing was 22.9% for N4-SCC-SF1, the rate of increment depend on fiber situation either single or in combination, where a decrement in the elastic modulus was observed with mixes having PPF and HF as compared with the reference mix, but this drop was surpassed by $SiO_2$ nano particles incorporation when compared with their counterpart mixes, but the PPF and the HF with and without nano particles still having lower elastic modulus in comparison with the reference mixes, this observation show that the contribution of these fibers to SCC mixes was not positive.
3. All tensile and flexural strengths are improved with time especially under the combined influence for both $SiO_2$ nano particles and SF. The maximum percentages of enhancing splitting and flexural tensile strengths were more evident in N4-SCC-SF1. However, the rates of gain in strengths were more pronounced in flexure tensile strengths.
4. Because of using the special polycarboxylate superplasticizer, mineral admixtures (micro and nano) and different fibers, SCC mixes achieve paste with porosity decreased up to 16.4% for the same mix at 28 days of curing.
5. SEM micrographs show that the SCC mix containing $SiO_2$ nano particles appear more homogeneous, denser, less pore volume and less roughness fracture surface than the concrete with silica fume only.

This study demonstrates the beneficial combined effect of fibers and nano-silica on key hardened properties of SCCs. The limited understanding regarding the factors influence such combined effect may lead to reduce field and practical utilities of FR-SCC, and hence provide more insight would be useful for the engineers that utilize SCC in different structural applications and projects.

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