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Impact of Different Curing Techniques on Some Mechanical Properties of Self-Compacting Concrete Containing Silica Fume

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Abstract – *The employment of self-compacting concrete SCC has extended worldwide due to its many advantages for the concrete production technology. On the other hand, the use of self-curing technique minimizes the consummation of curing water, which is an important issue especially in the areas with water scarcity. Therefore, the aim of this study is to use self-curing method with SCC. Firstly, the goal is to investigate the effect of cement replacement percentage with silica fume on some fresh and hardened properties of SCC and to specify the optimum one. For this purpose, mixes with four different percentages of silica fume (0%, 5%, 10%, 15%) have been considered. Secondly, the effect of applying self-curing using water soluble polyvinyl alcohol PVA in comparison with water curing and sealed curing on the mechanical properties of SCC has been investigated. For this goal the compressive, splitting tensile, and flexural tensile strengths of hardened SCC have been studied for the above mixes and for the three curing methods and two curing periods 28 and 60 days. The results show that the optimal percentage for silica fume that leads to maximum strength properties is 10% for all the curing techniques and periods. Furthermore, all the SCC mixes cured in water always give the highest strength values followed by those self-cured. Another important finding is that the self-curing using PVA shows an interesting result since it provides strength values close to the ones obtained from using water curing with a strength reduction less than 3% at age 28 days for the case of 10% silica fume.* ***Copyright © 2022 Praise Worthy Prize S.r.l. - All rights reserved.***

***Keywords**: Compressive Strength, Curing Techniques, Flexural Strength, Polyvinyl Alcohol, Self-Compacting Concrete, Self-Curing, Silica Fume, Splitting Tensile Strength*

Nomenclature

0%SF	Mix with 0% cement replacement by silica fume
5%SF	Mix with 5% cement replacement by silica fume
10%SF	Mix with 10% cement replacement by silica fume
15%SF	Mix with 15% cement replacement by silica fume
D	Mean value of two perpendicular diameters of the final spread concrete circle (slump flow test), mm
H_2/H_1	Blocking ratio which is resulted from measuring the concrete heights at the horizontal part of L-box apparatus: (H_1) at the beginning and (H_2) at the end
PVA	Water soluble polyvinyl alcohol
SCC	Self-Compacting Concrete
SP	Superplasticizer
T	Time in seconds recorded during the V-funnel test
$T50$	Elapsed time in seconds for flowing concrete to reach a spread circle of 50 cm diameter (slump flow test)

I. Introduction

Self-Compacting Concrete (or self-consolidating concrete) SCC is a special type of concrete that is flowable under its own gravity and can fully fill the formwork, even the places with congested reinforcement, without any compaction or vibration and without homogeneity defect due bleeding or segregation [1]. The SCC has three essential characteristics that distinguish it from other types of concrete. These characteristics are: filling (or flowing) ability, which reflects the SCC ability to flow through and fill the total space of the formwork, passing ability, which describes the ability of SCC to pass easily through the areas of dense reinforcement and other obstacles, and stability (resistance to segregation) that refers to the ability of SCC to keep its homogeneity during its placement and setting [2]-[3]. In order to reach these characteristics of SCC, three main categories of SCC mixes can be used. The first category is the powder type mixes in which a high content of powder (silica fume, fly ash, ground limestone fines, …..) is used, while the second one is the VMA type mixes that are characterized by a high dosage of Viscosity Modifying Agent (VMA), and the third type (combined type mixes) is a combination of the first two categories [4]. The SCC was originated in Japan at 1980s. However, the

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employment of SCC has extended worldwide due to its many advantages for the concrete production technology.

The main advantages of SCC are: less manpower (less labor cost), increasing productivity due less construction time, improving health and environment at the working site due to the reduction in noise levels, improving surface quality. Furthermore, SCC opens the possibilities for new structural elements that have not been feasible with the other types of concrete [5], [6]. Concrete strength is the result of chemical reactions between water and the cement compounds i.e. hydration of cement. The development in concrete properties with age continues as long as the cement has an internal moisture content above than 80% [7], [8]. Therefore, adequate curing plays an important role in the production of concrete with high quality since it can ensure the availability of water required for the cement hydration and eliminate problems related to the plastic shrinkage cracking [9]. Curing methods can be broadly classified into two main groups.

The first one involves the application of water frequently or continuously throughout the hydration process in form of water ponding, sprays, steam, covering with moist hessian (or burlap or cotton mats or sand or sawdust). The concept in the second group is to prevent the loss of water from concrete by covering the surface of fresh concrete with plastic sheets, reinforced paper, or by spraying (or applying) special curing compounds that form membranes covering the concrete surfaces, [10]-[13]. Another curing technique is the self-curing (or internal curing) in which the main concept is to preserve the concrete relative humidity necessary for the hydration process [14]. This can be achieved either by making the concrete able to reduce the water evaporation and as a result increasing its ability to retain water using chemical agents [15], or by making available additional internal water (not part of mixing water) using porous materials or physical water-absorbing materials [14]. Therefore, there are different materials that may be used for the purpose of the self-curing technique such as Shrinkage Reducing Admixture SRA, Super-Absorbent Polymers SAP, LightWeight Aggregate LWA, and superfine powders [16]-[19]. The use of self-curing involves many advantages compared to normal curing methods, including economical consummation of curing water which is an important issue especially in the areas with water shortage or scarcity, more efficient for high performance concrete or concrete with low w/c since the permeability of these concretes becomes rapidly low to permit the ingress of external curing water from concrete surface to the interior concrete layers, reducing autogenous shrinkage, curing water distributes somewhat uniformly through the whole concrete body and does not concentrate at the surface layer, more suitable for the concrete works in which the use of conventional curing methods is difficult like structural members at high altitude, vertical components, slope roofs [20], [21].

Many researchers [12], [20], [22]-[26] have studied the effect of curing regime on the mechanical properties of self-compacting concrete or self-compacting mortar and they have reported that the water curing regime can provide the maximum strength characteristics as compared to other methods. Madduru et al. [20] have investigated the efficiency of using different dosages of hydrophilic (PEG 4000: polyethylene glycol - 4000) and hydrophobic (LPW: Liquid Paraffin Wax) as internal curing agents on the mechanical properties of SCC as compared with normal water curing and no curing cases.

In comparison with water curing, the results indicate that the internal curing reduces the compressive strength, the splitting tensile strength and the flexural strength at age 28 days by 3.4%, 26.3% and 11.4% for PEG 4000 and 4.6%, 31.3% and 6.3% for LPW. Nandhini et al. [27] have studied the effect of water, internal using superabsorbent polymer, and Gunny bag curing methods on the compressive strength and splitting tensile strength of SCC. They have found out that at age 28 days the reduction in compressive and splitting tensile strengths due to the application of internal curing is about 10% and 20% respectively. Other researches [28], [29] have also reported that the compressive strength of self-cured concrete using curing agents is about 10% less than the one of normal water-cured concrete. Effect of using the internal curing chemicals (PEG 4000 and PEG 200) on the compressive strength of self-compacting mortar has been studied by Madduru et al. [25]. They have found out that there is about 6% reduction in compressive strength at age 28 days when using internal curing compared to the case of water curing. In order to protect the ecology, the use of eco-friendly construction procedures and materials becomes essential nowadays. As stated above, the use of each SCC and self-curing has a positive impact on the environment therefore the combination of them is aimed in the present study. Firstly, the goal is to investigate the effect of cement replacement percentage with silica fume on some fresh and hardened properties of SCC and to specify the optimum one, and secondly to study the effect of self-curing in comparison with other curing methods (water curing and sealed curing) on some mechanical properties of hardened SCC.

The rest of this paper has been developed to include three basic sections: experimental program, results and discussions, and conclusion. The first one demonstrates the experimental work that has been conducted in this study, which includes the materials properties, the mix proportions, the specimens' dimensions, and the performed tests. Thereafter, in the results and discussion section, the obtained results have been presented and discussed. Finally, some conclusions and recommendations have been given at the end of this article.

II. Experimental Program

The experimental work has been carried out in the laboratory of construction materials, department of civil engineering, college of engineering at the University of Babylon. The experimental program involves three subsections: materials used in this study, produced mixes and specimens, and the workability and the mechanical tests applied herein.

II.1. *Materials*

Ordinary Portland cement (commercial mark is Kufa) conforming to Iraqi Standard Specification No. 5 [30] has been used in this research. In order to produce SCC, micro silica fume conforming to ASTM C 1240 [31] has been also used as a partial replacement of cement content. Table I provides the chemical properties of cement and silica fume adopted in this study as given by the manufacturer. Regarding the aggregate used herein, a natural clean and free from impurities river sand with fineness modulus of 2.6 and specific gravity of 2.55 has been used as a fine aggregate and the coarse aggregate has been a rounded gravel with a maximum size of 12.5 mm and specific gravity of 2.6. Two types of chemical admixtures have been used in this work. In order to obtain the required workability of fresh concrete, the first admixture has been a superplasticizer SP agent commercially known as Visco-Creat5930-L. The second admixture has been a polyvinyl alcohol PVA, which is a type of water-soluble polymer as used for self-curing.

II.2. *Mixes and Test Specimens*

The SCC mixes have been designed according to the European guidelines for self-compacting concrete [32].

In order to study the effect of silica fume on the properties of SCC, four mixes have been prepared. The variable in these mixes has been the percentage of replacement of cement by silica fume while the other mix compounds have remained fixed as given in Table II. The first mix has been without silica fume i.e. the control mix while for the other three concrete mixes the percentage of replacement of cement by silica fume has been 5%, 10%, and 15% respectively. As shown in Table II, the superplasticizer SP percentage has been 1.3% by weight of cement. In fact, this percentage has been selected after several trials in order to achieve the desired workability.

After the preparation of each mix, three types of specimens have been casted: cubes of dimensions 150×150×150 mm for the compressive strength test, cylinders having the dimensions of 100×200 mm for the splitting test, and prisms with the dimensions of 100×100×400 mm for the flexural test. In order to investigate the effect of curing methods, three curing techniques have been applied in this study.

TABLE I
CHEMICAL COMPOSITION OF CEMENT AND SILICA FUME

Oxide	% By weight	
	Cement	Silica fume
SiO_2	20.34	91.45
Al_2O_3	5.56	0.03
Fe_2O_3	3.36	0.25
CaO	61.37	0.55
MgO	2.97	0.09
SO_3	2.33	0.29
LOI	3.17	3.15

TABLE II
MIX PROPORTION OF SELF-COMPACTING CONCRETE

Mix type	Cement kg/m³	Silica fume kg/m³	W/B	Sand kg/m³	Gravel kg/m³	SP %
0%SF	500	0	0.36	780	830	1.3
5%SF	475	25	0.36	780	830	1.3
10%SF	450	50	0.36	780	830	1.3
15%SF	425	75	0.36	780	830	1.3

These are:

- Water curing, in which the samples have been cured in a water tank at 20° C for the whole period before application of the mechanical test;
- Sealed curing, in which the samples have been covered by aluminum papers in order to prevent water evaporation and have been stored in the laboratory until the mechanical test;
- Self-curing; in this technique, the PVA has been added to the mixing water with a percentage of 0.75% by weight of cement in order to increase the water retention ability of concrete and reducing the amount of the evaporated water.

II.3. *Performed Tests*

The testing program has been performed into two stages. The first one has involved the testing of fresh concrete while the second one has included the mechanical tests of hardened concrete. Regarding the testing of fresh concrete, three tests (slump flow and T50, V-funnel, and L-box) have been performed for each mix in order to investigate the fresh concrete characteristics of SCC i.e. filling ability, passing ability, and resistance to segregation. The filling ability of SCC mixture has been assessed using slump flow and V-funnel tests following the testing procedures described in EN 12350-8 [33] and EN 12350-9 [34] respectively. L-box test that evaluates the passing ability of SCC has been performed in according with EN 12350-10 [35]. However, the resistance to segregation of SCC mixes has been examined visually during the slump flow test in accordance with ACI 237R-7 [2]. Regarding the testing of hardened concrete, three mechanical tests have been carried out. The compressive strength test has been applied on the cube samples in accordance to BS.1881: Part 116 [36], Figure 1. The cylinder samples have been tested following the procedure detailed in ASTM C 496 [37] in order to calculate the splitting tensile strength of SCC. The third mechanical test has been the flexural strength test that has been devoted to find the flexural tensile strength of the hardened SCC. This test has been performed on the prism samples following the test method explained in ASTM C78 [38], Figure 2.

III. Results and Discussion

This section outlines and discusses the results obtained from the tests carried out on both fresh and hardened SCC. For clarity, it is subdivided into two subsections according to the measured properties of SCC.

Fig. 1. Compressive strength test

Fig. 2. Flexural tensile strength test

III.1. Properties of Fresh SCC

The results of testing fresh SCC properties are given in Table III. Regarding the slump flow test, two types of measurements have been recorded: D, which is the mean value of two perpendicular diameters of the final spread concrete circle and $T50$, which is the elapsed time for flowing concrete to reach a spread circle of 50 cm diameter. From these results, it can be seen that the average diameter D decreases while the time $T50$ increases as the silica fume percentage changes from 0% to 15%. In order to interpret these results, it is necessary to keep in mind that D measures the flow distance that concrete can travel horizontally and freely, i.e. without any obstacles, due to its own weight in order to fill a formwork and $T50$ represents the flow rate that is related to the viscosity of SCC mixture [2]. Consequently, smaller D and higher $T50$ values highlight that the fresh concrete has less filling capacity and higher viscosity as the silica fume increases. Nevertheless, these results are still within the typical range for the acceptance of SCC as specified by EFNARC [1] i.e. ($650 \text{ mm} \leq D \leq 800 \text{ mm}$) and ($2 \text{ s} \leq T50 \leq 5 \text{ s}$). Furthermore, from the visual inspection of the concrete spread throughout the slump flow test, there have been no signs of segregation and as a result the SCC property of resistance to segregation has been valid for all the mixes considered in this study.

TABLE III
RESULTS OF ASSESSING THE PROPERTIES OF FRESH SCC

Mix type	Slump flow D (mm)	Slump flow T50cm (s)	V-funnel T (s)	L-box H_2/H_1
0%SF	750	3	7	0.96
5%SF	730	3.5	8	0.93
10%SF	710	4.1	9.5	0.88
15%SF	680	4.4	10.7	0.85

Table III also provides the V-funnel flow time T recorded from the V-funnel test that is used to evaluate the filling ability and viscosity of SCC [34]. The interpretation of these T values confirms the above observation about the increase in viscosity and the decrease in filling ability as the silica fume percentage increases.

Even so, these values remain within the range ($6 \text{ s} \leq T \leq 12 \text{ s}$) that is accepted for the typical mixes of SCC according to EFNARC [1]. In order to assess the ability of SCC to flow and pass through reinforcements without any problem of segregation or blocking [4] the L-box test has been carried out.

The measured values from this test have been the blocking ratio (H_2/H_1). The H_2/H_1 values given in Table III decrease as the silica fume increases but remain within the recommended range stated by EFNARC [1] i.e. ($0.8 \leq H_2/H_1 \leq 1.0$). In order to understand these results, it is necessary to know that if the flow of SCC occurs freely like water then the value of H_2/H_1 will equal 1.0 [2]. Therefore, H_2/H_1 value closer to 1.0 indicates higher passing ability. Hence, the results of this test can tell that the presence of silica fume reduces the ability to pass of SCC. In summary, the tests performed on the fresh SCC in order to assess its characteristics show a reduction in these properties as the silica fume percentage raises. However, for all the mixes considered in this work, the SCC characteristics satisfy the acceptance criteria recommended by EFNARC.

III.2. Properties of Hardened SCC

Three mechanical tests have been carried out on samples in order to assess three properties of hardened concrete; these are compressive strength, splitting tensile strength and flexural tensile strength. These mechanical properties have been measured for specimens having different curing methods (water curing, sealed curing, and self-curing) and for two curing periods 28 and 60 days.

III.2.1. Compressive Strength

Table IV provides the results of compressive strength for all the mixes and for the three curing techniques and the two curing durations, while Figures 3 and 4 illustrate graphically these results for 28 and 60 days curing periods respectively. These results clearly show an increase in compressive strength as the silica fume percentage increases and the maximum values obtained at the percentage of 10%. Thereafter the results exhibit a trend of decreasing compressive strength.

TABLE IV
COMPRESSIVE STRENGTH OF SCC (IN MPa) FOR DIFFERENT CURING METHODS AND FOR TWO CURING DURATIONS 28 & 60 DAYS

Mix type	Water curing		Sealed curing		Self-curing	
	28 days	60 days	28 days	60 days	28 days	60 days
0%SF	48.00	50.56	45.48	47.68	47.36	49.00
5%SF	55.32	60.00	52.93	56.99	54.35	58.90
10%SF	59.95	64.52	57.09	61.68	58.38	63.57
15%SF	55.68	60.20	53.07	57.23	54.60	59.00

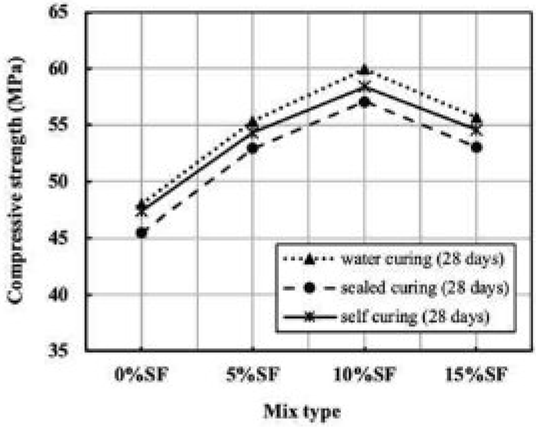

Fig. 3. Compressive strength of SCC (in MPa) for different curing methods and for curing duration of 28 days

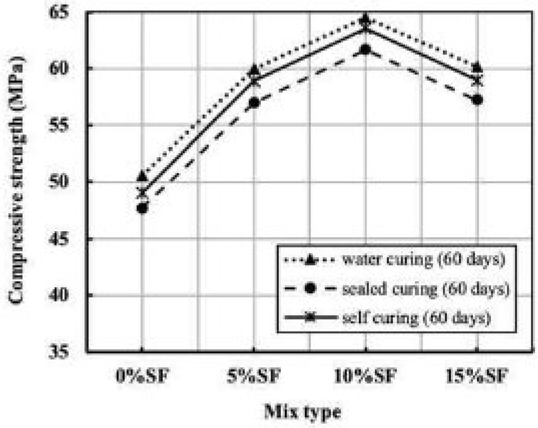

Fig. 4. Compressive strength of SCC (in MPa) for different curing methods and for curing duration of 60 days

This finding is true for the three curing methods and the two curing periods. In comparison to the mix without silica fume (control mix), the increase in compressive strength at the age of 28 days for the mix with 10% silica fume is about 24.9%, 25.5%, and 23.2% when using water curing, sealed curing and self-curing methods respectively. The positive effect of silica fume on the compressive strength is due its pozzolanic activity. In other words, due to the further production of C-S-H condensed gel as a result of the reaction of silica fume having extreme fine particles and higher surface area with $Ca(OH)_2$ released from the hydration process of Portland cement. Regarding the effect of curing method, from Table IV and Figures 3 and 4, it can be noticed that the highest compressive strength values have been obtained from water cured specimens followed by the self-cured specimens then sealed cured specimens at both ages of 28 and 60 days. The lowering in compressive strength at age 28 days due to the use of self-curing instead of water curing has been 1.3%, 1.8%, 2.6%, and 1.9% for mixes containing micro silica fume as a replacement percentage of 0%, 5%,10%, and 15% respectively. This finding is not surprising since, as stated in the introduction, many researchers have reported the superiority of water curing technique.

However, the interesting issue here is the small amounts of reduction in compressive strength when applying the self-curing if one compares the present results with that reported by other researchers [20], [27]-[29]. This finding may be due to use of the self-curing agent PVA in this study in contrast to the cited works in which other self-curing agents were utilized. Concerning the effect of using sealed curing method as compared to water curing method, the reduction in compressive strength at age 28 days has been 5.3%, 4.3%, 4.8%, and 4.7% for mixes containing micro silica fume as a replacement percentage of 0%, 5%, 10%, and 15% respectively which are higher than the corresponding values for the case of self-curing. A similar trend of results has been obtained when the curing period has been extended to 60 days but of course with a gain in strength due to the continuation of hydration process, Table IV and Figure 4. The reduction in compressive strength when applying self-curing as compared to water curing has been 3.2%, 1.8%, 1.5%, and 2.0% for mixes with micro silica fume as a replacement percentage of 0%, 5%,10%, and 15% respectively.

III.2.2. Splitting Tensile Strength

The results of the splitting tensile strength for all the mixes and for the three curing techniques are given in Table V for both curing durations (28 and 60 days) and plotted on Figures 5 and 6 for the curing period of 28 and 60 days respectively. These results clearly indicate that 10% silica fume is the optimum replacement percentage of cement weight in order to obtain the highest values of splitting tensile strength for each curing technique.

From data in Table V or Figures 5 and 6, it can be noticed that the water curing technique is the best one and it leads to maximum splitting tensile strengths at both ages 28 and 60 days followed by self-curing then sealed curing techniques. The use of self-curing instead of water curing has caused a drooping in splitting tensile strength at age 28 days of 2.0%, 3.6%, 2.3%, and 3.6% for mixes containing silica fume as a replacement percentage of 0%, 5%, 10%, and 15% respectively.

TABLE V
SPLITTING TENSILE STRENGTH OF SCC (IN MPa) FOR DIFFERENT CURING METHODS AND FOR TWO CURING DURATIONS 28 & 60 DAYS

Mix type	Water curing		Sealed curing		Self-curing	
	28 days	60 days	28 days	60 days	28 days	60 days
0%SF	3.45	3.60	3.22	3.34	3.38	3.50
5%SF	3.88	4.04	3.62	3.82	3.74	4.00
10%SF	4.28	4.56	4.03	4.26	4.18	4.41
15%SF	3.92	4.13	3.64	3.85	3.78	3.98

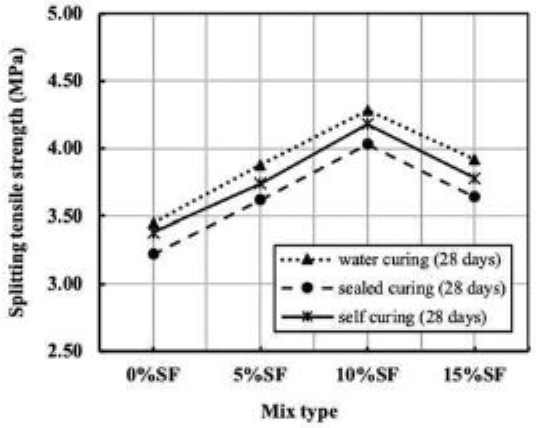

Fig. 5. Splitting tensile strength of SCC (in MPa) for different curing methods and for curing duration of 28 days

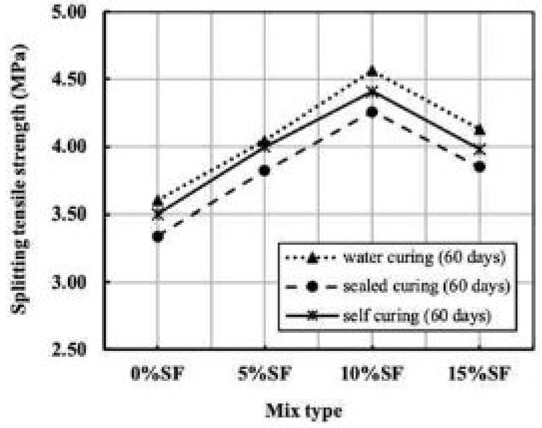

Fig. 6. Splitting tensile strength of SCC (in MPa) for different curing methods and for curing duration of 60 days

These amounts of reduction are very small in comparison with that reported by other researches [20], [27] in which the reduction has been more than 20%.

Therefore, it seems that the use of PVA as a self-curing agent is more efficient than the agents used in the cited previous works (polyethylene glycol - 4000, liquid paraffin wax, and superabsorbent polymer). For the case of sealed curing, the reduction has been 6.7%, 6.7%, 5.8%, and 7.1% for mixes with silica fume as a replacement percentage of 0%, 5%, 10%, and 15% respectively.

III.2.3. Flexural Tensile Strength

The prism specimens have been tested using the two points load method in order to calculate the flexural strength. Table VI shows these results for all the mixes and the three curing techniques and for both curing durations 28 and 60 days. Moreover, Figures 7 and 8 demonstrate graphically these results for curing period 28 and 60 days respectively. It can be seen that these results reveal an identical trend as for compressive strength and splitting tensile strength in which the best percentage of cement replacement by silica fume is 10% whatever the curing regime.

TABLE VI
FLEXURAL TENSILE STRENGTH OF SCC (IN MPa) FOR DIFFERENT CURING METHODS AND FOR TWO CURING DURATIONS 28 & 60 DAYS

Mix type	Water curing		Sealed curing		Self-curing	
	28 days	60 days	28 days	60 days	28 days	60 days
0%SF	5.92	6.28	5.58	5.85	5.78	6.15
5%SF	6.53	6.98	6.15	6.58	6.50	6.72
10%SF	7.34	7.85	6.96	7.45	7.22	7.76
15%SF	6.90	7.42	6.54	7.00	6.76	7.30

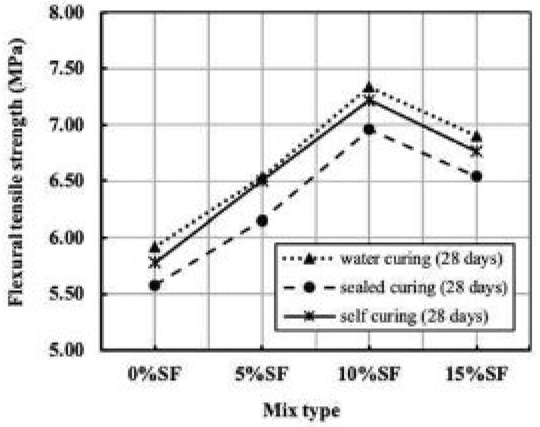

Fig. 7. Flexural tensile strength of SCC (in MPa) for different curing methods and for curing duration of 28 days

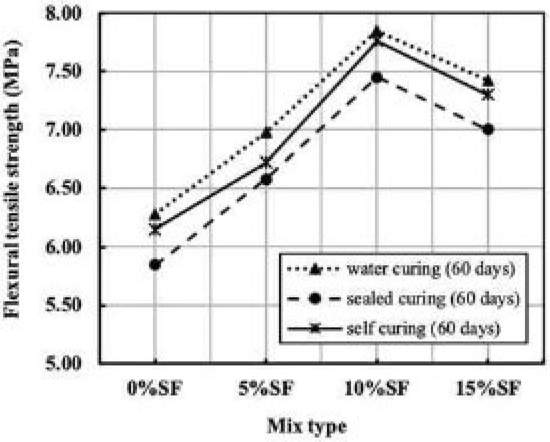

Fig. 8. Flexural tensile strength of SCC (in MPa) for different curing methods and for curing duration of 60 days

Furthermore, the water curing is the best one followed by the self-curing then the sealed curing methods. At the age of 28 days, the flexural strength of SCC internally cured using PVA is lower than that normally water cured samples by 2.4%, 0.5%, 1.6%, and 2.0% for mixes containing micro silica fume as a replacement percentage of 0%, 5%, 10%, and 15% respectively. Similar to the cases of compressive and splitting tensile strengths, the obtained reduction in flexural strength has been less than the one reported by [20], which highlights the capacity of PVA as a self-curing agent. Regarding situation when applying the sealed curing method as compared to water curing, the flexural strength of SCC is reduced by 5.7%, 5.8%, 5.2%, and 5.2% for mixes having micro silica fume with a percentage of 0%, 5%, 10%, and 15% respectively.

IV. Conclusion

In this paper, the effect of three curing regimes (water curing, sealed curing and self-curing using PVA) on the strength characteristics of hardened SCC (compressive strength, splitting tensile strength and flexural tensile strength) has been studied. In addition, the effect of containing silica fume as a partial replacement by weight of cement (0%, 5%, 10%, and 15%) on the fresh and hardened properties of SCC has been investigated. Based on the results of this study, the following findings can be concluded:

- Increasing the silica fume replacement percentage from 0% to 15% reduces the filling and passing abilities and increases the viscosity of fresh SCC; however for all the mixes considered in this work, the fresh SCC characteristics satisfy the acceptance criteria recommended by EFNARC;
- The tested mechanical properties of hardened SCC (compressive strength, splitting tensile strength, flexural tensile strength) improve when silica fume content raises until a replacement percentage of 10%; thereafter, these properties exhibit a decrease in their values. Therefore, the optimal percentage for silica fume is 10%;
- Based on the strength values obtained from the mechanical tests, the water curing is the best curing regime followed by the self-curing then the sealed curing;
- Self-curing using water soluble polyvinyl alcohol PVA shows an interesting result since it provides strength values close to that obtained from using water curing with a strength reduction less than 3% at age 28 days for the case of 10% silica fume while the strength reduction due to the use of the sealed curing is about 6%.

Due to many benefits of using SCC and due to the significant impact of using self-curing on the consummation of water specially with the recent water lacking problem in Iraq and based on the obtained results, it is strongly recommended to use the SCC and self-curing for the concrete production in Iraq.

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