Journal of Structural Engineering and Geotechnics,

8 (1), 41-54, Winter 2018

Developing a Cost- Effective Approach for Enhancing the Rheological and Mechanical Behavior of High Strength Self-Compacting Concrete

Sahand Mardi[a] , Morteza Bastami*,[b]

[a]*Department of Civil Engineering, Qazvin Branch, Islamic Azad University, Qazvin, Iran*

[b]*Department of Structure, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran*

Received 13 October 2017, Accepted 02 March 2018

Abstract

Despite the numerous advantages of using concrete with high strength capacity, the brittle behavior of high strength concrete (HSC) and higher production cost has limited its use in the construction industry. This research aims to develop a cost- effective approach for production of high strength self- compacting concrete with desirable performance in either compressive or tensile loading condition. To reach this purpose, 18 mixtures were cast initially with different w/c, binder, and silica-fume percentage. The results show that it is possible to produce high strength self-compacting concrete economically without using any additives such as silica-fume. Afterward, an innovative reinforcing technique using hexagonal wire mesh (HWM) were introduced for enhancing the HSC performance. The results show that HWM is able to enhance HSM behavior in both tensile and compressive loading condition. Finally, an economic analysis was conducted and according to the analysis results, the optimum HWM properties are selected to produce HSC with desirable performance in the most efficient approach.

Keywords: *High Strength Concrete, Self-Compacting Concrete, Economic Analysis, Silica-Fume*

1. Introduction

The high strength concrete (HSC) definition has been changing always during the different era. In the 1950s, the concrete with 34 MPa was considered as high strength concrete. The committee 363 of American Concrete Institute (ACI) presented a new definition for HSC in 1992 that the concrete with the compressive strength of 41 MPa or higher would be considered as HSC[1]. In the last release of ACI committee 363 in 2010, the concrete with 55 MPa or higher compressive strength is considered as HSC[2]. There are two main reasons for this choice. Firstly, Careful production methods and curing are required to reach compressive strength higher than 50 MPa. Secondly, the behavioral changes in concrete with compressive strength higher than 50 MPa were recorded during the experimental tests in various researches which should be taken into account [2].

There are several methods to reach high strength in concrete. The first and primary method is to reduce the water to cement ratio [3-4]. This procedure will lead to a significant increase in compressive strength. The mentioned method is also cost-effective. Adding different pozzolanic additives are also another method to enhance the compressive strength of concrete. Pozzolans such as silica-fume are among the most common materials to increase the concrete strength[5-7]. Silica fume (SF) is a byproduct of producing ferrosilicon alloys or silicon metal. The silica-fume doesn't only enhance the mechanical behavior of concrete, but also improve the rheological performance of fresh concrete by reducing the bleeding in the fresh concrete.

The experimental investigation by Yang Ju et al. shows that silica fume increases the compressive strength significantly for different percentage of

---

*Corresponding Author Email address: m.bastami@iiees.ac.ir

silica fume substitution with cement but adding silica fume for more than 16% didn't increase the compressive strength. Adding 22% silica fume resulted in a slight decrease in compressive strength compared to the mixture with 16% silica fume [8]. Benaicha et al. investigated the effect of silica fume on fresh concrete. According to the obtained results, the use of pozzolans such as silica fume reduces the bleeding of concrete and therefore, the v-funnel time is longer compared to the control mixture. Moreover, the use of silica fume decreases the slump flow diameter values in general. The use of silica fume also decreases the H2/H1 value in L-box which is the result of silica fume performance in increasing the mixture viscosity [9]. The slump flow greater than 600 mm, H2/H1 greater than 0.8 in L-Box, V-funnel flow time equal to less than 14 seconds and segregation rate less than 15% are the standard values for self-compacting concrete according to the EFNARC [10] and AFGC [11].

Despite the several benefits of the high strength in concrete structures, the brittle and explosive behavior of HSC has limited its use in the elements which requires ductility to exhibit their performance. Therefore, researchers are always looking for new methods to reach a material with both strength and ductility at the same time [12–15]. Xue et al. conducted tests on seven HSC beams and two conventional normal strength concrete beams under cyclic loading conditions. Each specimen included different alternatives such as silica fume, polypropylene fibers, tendons and blast-furnace slags. The results show that the pinching effect is observable in beams with tendons (pre-stressed). Also, these beams behaved less ductile compared to normal beams. Blast-furnace slags and polypropylene fibers enhanced ductility of beams generally but increasing the reinforcement ratio caused less ductility in specimens. It was observed that both silica-fume and polypropylene fibers have little relation with HSC beams capacity [16]. A research was conducted on the confinement of ultra-high strength fiber RC columns by Shin et al. It was evaluated that micro steel fibers are able to be substituted instead of confining reinforcement efficiently [17]. Boulekbache et al. investigated steel fiber reinforced concrete flexural behavior under cyclic loading condition. In general, steel fiber enhances the flexural behavior of concrete but fibers are more effective in self-compacting concrete (SCC) because of better bonding condition between concrete components and fibers. Cyclic loading movement is irreversible, in order to define elastic limit conventionally. This loading procedure let to study the degree of reversibility (R), cyclic modulus (Ecyc) and cumulative energy. Reversible displacement of fiber reinforced concrete (FRC) in post cracking zone enhanced due to increase in fibers content and the corresponding aspect ratio. An identical trend was observed for the cumulative energy of FRC under cyclic loading except for the aspect ratio which indicated a slight influence [18]. Lampropoulos et al. investigated the ultra-high performance (strength) fiber reinforced concrete (UHPFRC) jacket effect on existing RC beams. UHPFRC jackets were placed in different positions: compressive side, tensile side and three sides (all sides except compressive one). Specimen with a jacket on tensile side recorded %31 increase in the ultimate moment while only %4 increase were observed for the specimen with a jacket on the compressive side. Three sides jacket increased the ultimate moment significantly by %53. The results also depict that three sides jacket caused a considerable decrease in ductility value of tested beam in comparison with other specimens [19].

Although various methods have been developed for achieving a ductile behavior in HSC elements, many of them don’t provide reliable strength and ductility at the same time. Moreover, some of the used methods are expensive, not efficient and even not practical in the construction industry. This research aims to develop an innovative reinforcing technique using Hexagonal Wire Mesh (HWM) as an inner jacket to enhance the HSC behavior. HWM is a low-cost and highly accessible material around the globe. HWM prepares a continual confinement that modifies HSC brittle behavior to a ductile and desirable one.

2. Experimental Program

2.1. Overview

An experimental program was designed to study the effect of hexagonal wire mesh (HWM) on the mechanical behavior of high strength concrete. First of all, it is necessary to find a proper mixture for the work which satisfies both required mechanical and rheological properties. Therefore, 18 mixtures were cast initially. The fresh concrete was made in the form of self-compacting concrete (SCC) in order to avoid possible difficulties during the casing of 300 mm x 150 mm cylinders jacketed with hexagonal wire mesh. Compressive strength at the age of 14 and 28 days, slump flow, j-ring, static segregation using column technique, V-funnel and L-box tests were conducted according to ASTM C39 [20] , ASTM C1611 [21], ASTM C1621 [22], ASTM C1610[23] and EFNARC[10] respectively. The desired mixture with most economic efficiency in term of compressive and appropriate rheology behavior was chosen and it remained constant for the next phases of the experimental program. After passing the initial phase, the effect of HWM on the mechanical behavior of high strength concrete was evaluated by conducting compressive and splitting tensile test on the standard concrete cylinder (300mm x 150mm).

2.2. Materials properties

The cement used was a type II Khamse™ according to ASTM C150 [24]. Limestone filler was used as the mineral additive. The Super-plasticizer was a Zhikava™ polycarboxylate-based admixture according to ASTM C494 [25] with the specific gravity of 1090 kg/m3. Coarse aggregates having the maximum particle size of 12.5 mm. Grading diagram of used aggregates is illustrated in Figure 1.

Three different type of hexagonal wire mesh (HWM) were used in this research. The difference is in the wire mesh opening nominal dimension, as in short, it is called mesh size. The smaller diameter of each wire mesh opening represents the nominal mesh size according to ASTM A975 [26]. The properties of used HWM are shown in Table 1.

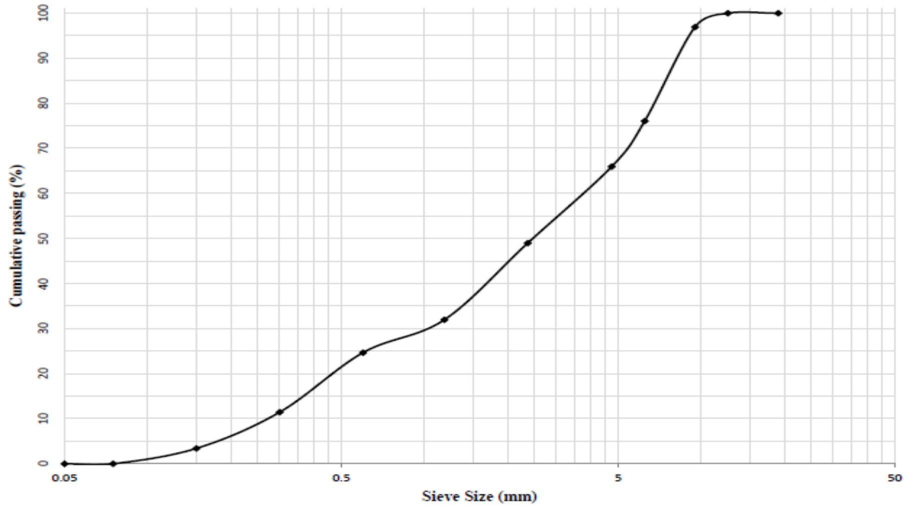


Figure1. Grading diagram of aggregates.

Table 1. Hexagonal wire mesh properties

Code	Mesh opening diameter (mm)	Wire diameter (mm)	Weight per square meter (Kg/m2)	Normalized Cost
G2	20	0.4	0.144	0.67
G4	40	0.8	0.374	0.71
G5	50	1.9	1.135	1

Table 2. The tested mixtures by trial and error method

Mixture Code	Binder (kg/m^3)	W/C	% SF	% Gravel	% Sand	% Filler	% SP	Strength (MPa)
(1)	450	0.4	0	28	60	12	1.8	42.48
(2)	450	0.4	5	28	60	12	1.8	51.02
(3)	450	0.4	10	28	60	12	1.8	59.6
(4)	450	0.4	15	28	60	12	1.8	67.38
(5)	450	0.4	20	28	60	12	1.8	63.68
(6)	500	0.4	0	28	60	12	1.8	45.16
(7)	500	0.4	5	28	60	12	1.8	55.81
(8)	500	0.4	10	28	60	12	1.8	66.54
(9)	500	0.4	15	28	60	12	1.8	71.12
(10)	500	0.37	10	28	60	12	1.8	69.16
(11)	500	0.37	15	28	60	12	1.8	75.88
(12)	500	0.35	10	28	60	12	1.8	72.45
(13)	500	0.35	15	28	60	12	1.8	78.22
(14)	500	0.32	5	28	60	12	1.8	65.35
(15)	550	0.39	0	28	60	12	1.8	50.69
(16)	550	0.35	0	28	60	12	1.8	60.11
(17)	550	0.35	5	28	60	12	1.8	70.06
(18)	550	0.39	5	28	60	12	1.8	63.25

2.3. Mixture design

The desired mixture was determined by trial and error method. First of all, the desired mixture shall have proper rheology behavior. Afterward, the mixture shall satisfy the required compressive strength to be considered as HSC. Finally, the chosen mixture shall be efficient in terms of being most economical mixture. The tested mixtures are shown in Table 2.

2.4. Rheology Test

The slump flow test was conducted for all specimens according to EFNARC and ASTM C1611 [21]. Two perpendicular flow diameter were measured and averaged as slump flow test result. After choosing the desired mixture with proper rheology and mechanical behavior, the extra rheology tests will be conducted including j-ring, L-box, V-funnel, and static segregation test using columns technique on the chosen mixture to verify its rheological behavior in any possible condition. the rheology test methods are depicted in Figure 2.

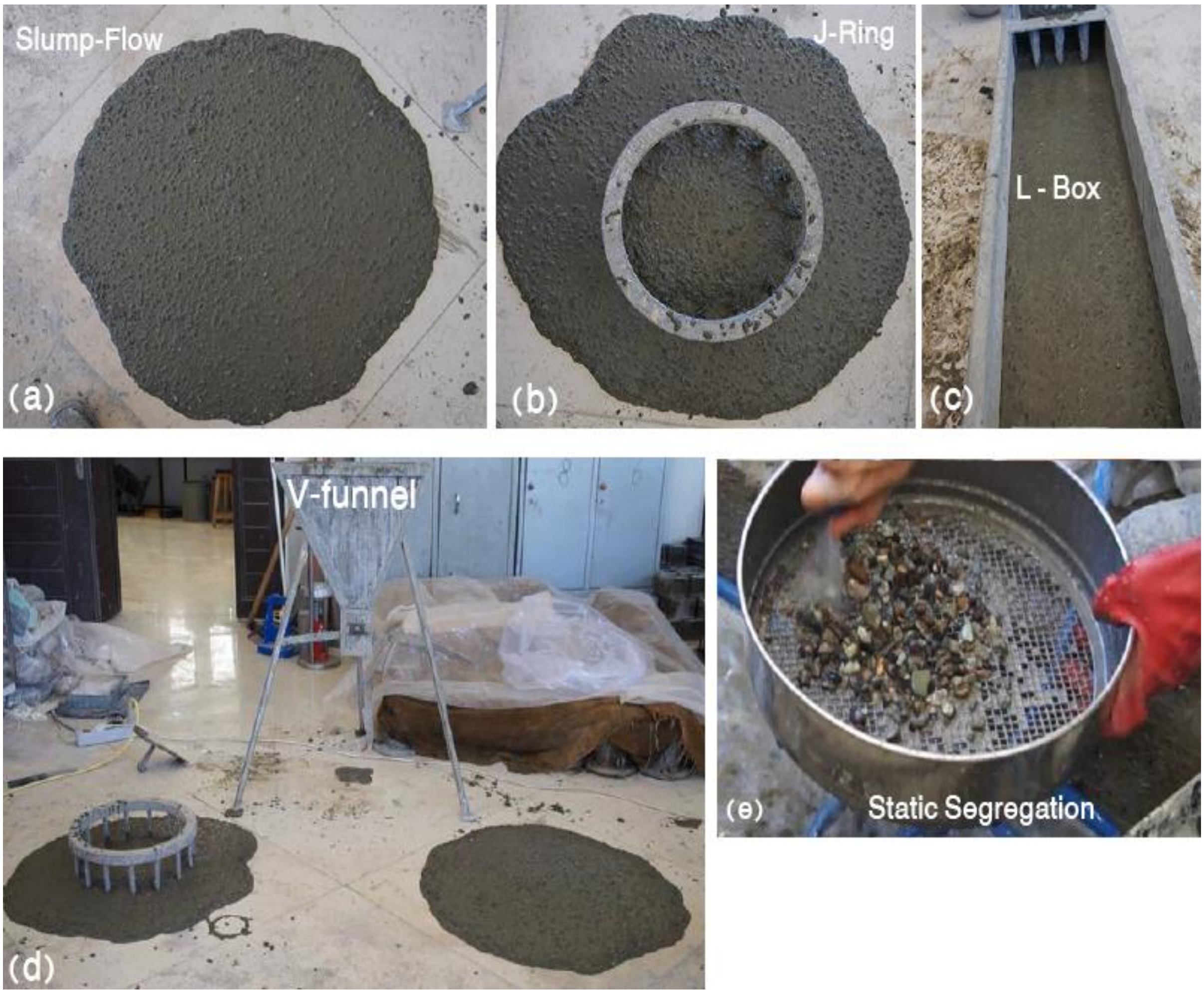
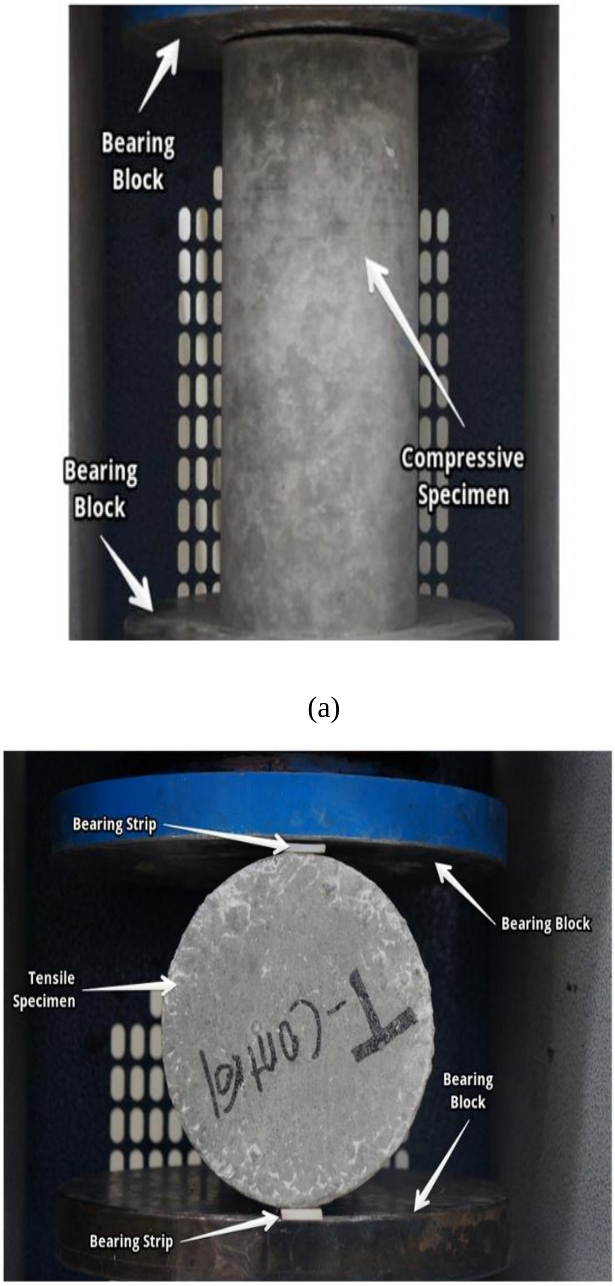


Figure 2. Rheological test methods (a) slump-flow (b) J-ring (c) L-box (d) V-funnel (e) static segregation test using column technique.

2.5. Mechanical Test

After determining the proper mixture, twenty-four cylinders with the dimension of 300 mm x 150 mm were cast using three different types of hexagonal wire mesh (HWM) along with the control specimen without HWM. The HWM were shaped resembling a cylinder with 20 mm concrete cover for each side. Compressive strength, tensile splitting strength test was performed on the specimens to evaluate the effects of HWM on HSC as shown in Figure 3. Since HWM tends to participate in bearing loads for high deflections, therefore, the specimens are loaded several times until they experience a total failure. In the compressive and tensile test, each specimen is loaded until it reaches the maximum loading capacity. when the load drops to 20% of maximum load, the loading process is stopped and the machine will go into the unloading condition. Afterward, the specimen is loaded again with an identical procedure and it will be repeated several times until the specimen collapses completely. The number of applied cycles and maximum load in each cycle is recorded and it iscompared to the condition of control specimen. After evaluating the results, an economic analysis will be executed to find the most optimal HWM type in enhancing the behavior of high strength concrete.



(a)

(b)

Figure 3. Setup for (a) Compressive strength and (b) Tensile strength test methods.

The specimens are named by three characters. The first character implies the test method (Tensile test: T and Compressive test: C). The second and third characters imply the HWM type according to Table 1. For example, TG2 means the cylinder specimen reinforced with HWM with mesh opening size of 20 mm under tensile loading condition.

3. Results and Discussions

3.1. Fresh Concrete

The slump flow test result for each mixture is shown in Table 3 and Figure 4. According to the results, the binder volume has a direct relation with spread diameter of slump flow. The comparison of slump flow diameter between the mixtures with different volume of binder values (cement and SF) shows that as the binder increases, the flow diameter will increase generally. This procedure can be seen in the comparison between (1) to (9) mixtures. Different SF substitution percentage with cement also affects the slump flow spread value. The substitution of SF with cement up to 10% leads to an increase in slump flow spread as the higher volume of the binder with very fine particles are spreading. However, the usage of SF for more than 10% leads to a decrease in slump flow diameter. The high volume usage of SF increases the homogeneous of mixtures and decreases the concrete bleeding by consuming a high bulk of water. Therefore, the spreading flow decreases as the results. This procedure is more remarkable in the mixtures with low W/C ratio and high binder volume. For the mixtures with high W/C ratio and low binder volume, more than 15% SF substitution leads to an identical phenomenon as high volume of free water is available to be absorbed by silica fume fine particles.

Table 3. Slump Flow test results.

Mixture Code	Slump flow (mm)
(1)	660
(2)	680
(3)	720
(4)	655
(5)	680
(6)	725
(7)	735
(8)	725
(9)	750
(10)	735
(11)	700
(12)	700
(13)	650
(14)	665
(15)	740
(16)	750
(17)	700
(18)	740

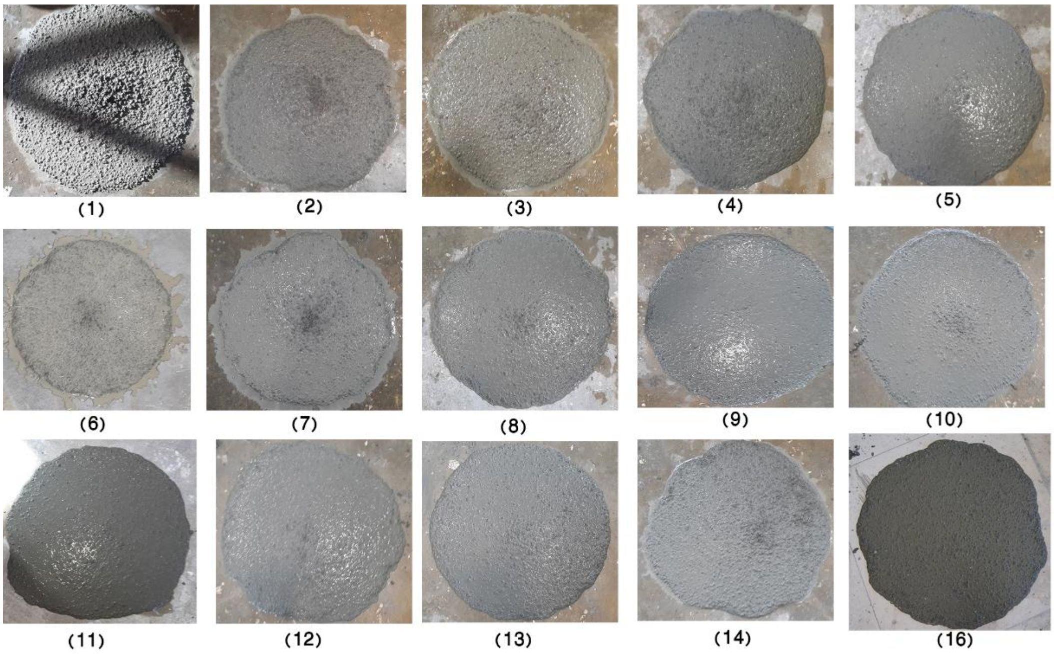


Figure 4. Slump flow test results.

3.2. Hardened Concrete

The compressive strength of mixtures is determined after 28 days of wet curing in the temperature of 20 ± 1. The results are presented in Table 4. The obtained compressive strength ranged between 40 to 80 MPa. The results show that decreasing the W/C ratio is the most efficient way to increase the compressive strength. However, the usage of silica-fume provides the possibility of reaching higher compressive strength. The comparison between mixtures (1) to (9) shows that the use of higher binder volume, results in higher compressive strength. It is remarkable that up to 15% SF substitution with cement, increases the compressive strength. However, high volume substitutions (20%) results in a slight decrease in compressive strength compared to 15% substitutions. The results show that it is possible to make high strength concrete with desired strength (higher than 55 MPa) without using any additives including silica-fume and by only decreasing the W/C ratio. For example, the (3), (16), and (18) mixtures provided roughly identical compressive strength while silica fume is used in the (3) and (18) mixtures and (16) mixture doesn't have any additives. The use of silica-fume increases the cost of concrete production while it is possible to cast concrete with an identical mechanical performance with low cost.

Table 4. Compressive strength test results

Mixture Code	28 Days Compressive Strength(MPa)
(1)	42.48
(2)	51.02
(3)	59.6
(4)	67.38
(5)	63.68
(6)	45.16
(7)	55.81
(8)	66.54
(9)	71.12
(10)	69.16
(11)	75.88
(12)	72.45
(13)	78.22
(14)	65.35
(15)	50.69
(16)	60.11
(17)	70.06
(18)	63.25

Table 5. Rheology properties of the selected mixture

Test name	Test method	Measured values				
Slump-flow	ASTM C1611	Averaged flow diameter (mm) 750		T-500 (sec) 6.5		
J-ring	ASTM C1621	Averaged flow diameter (mm) 715		T-500 (sec) 10.12		
V-funnel	EFNARC	Time [sec] 19.3				
L-box	EFNARC	H1 (mm) 76	H2 (mm) 72	Passing ability (%) 94.74	T200 (sec) 4.96	T400 (sec) 9.53
Static segregation using column mold	ASTM C1610	Concrete Segregation % 0				

3.3. Verifying the Rheological Performance

The mixture (16) by providing the desired compressive strength (60.11 MPa) is considered as HSC according to ACI 363 [2] recommendations (compressive strength shall be higher or equal to 55 MPa). This mixture also by having the slump flow spread of 750 mm shows the desirable rheological behavior according to the EFNARC [10] and AFGC [11] recommendations. Therefore, the mixture (16) is chosen as the desirable mixture with proper rheological and mechanical behavior. This mixture is also most efficient from economic point of view since it doesn’t require any additives and can be cast easily with already used materials in the construction field.

After selection of the desired mixture, extra rheological tests were conducted to verify the rheological performance from different aspects including passing ability, filling ability and workability. Therefore, J-ring, L-box, V-funnel, and static segregation test using column technique were performed as illustrated in Figure 2. The test results are presented in the Table 5. The measured values are correctly at defined ranges in literature. Therefore, the chosen mixture can be used in the next phases of the experimental program.

3.4. HWM Effects on the Compressive Behavior of HSC

Tests were conducted on cylinder compression specimens as mentioned in the experimental program. Un-reinforced specimens experienced sudden explosive failure after reaching the maximum load capacity in the first loading. However, reinforced specimens have shown more ductile behavior in compression and not only resulted in a slight increase of loading capacity but also increased the number of loading cycles. Sudden explosive failure was avoided in the specimens reinforced with HWM which is the result of extra confinement in such a composite material. Compressive test results are shown in Figure 5. It is determined for the HWM with stronger wires (thicker wires), the numbers of applied cycles are increased. Moreover, the mentioned specimens endure higher compressive strength at each loading cycle. It is remarkable that the strength deterioration in each cycle has a direct relationship with wire diameter. As the diameter of the wires becomes larger, the less drop in compressive strength was recorded in an identical cycle. It was determined that HWM could keep damaged aggregates together and avoided aggregates or concrete big pieces to be thrown. Figure 6-shows the status of CG4 specimens at the final loading stage. It can be seen HWM were deformed and wires were yielded. Figure 6-b shows CG5 specimen after removing the concrete cover, to see what happened inside the specimen. It was observed that although the concrete inside the core was damaged and aggregates were crushed at final loading stage but HWM was able to keep concrete components together and avoided the total collapse of the composite which is very appropriate behavior in seismic zones especially to reduce the induced human fatality.

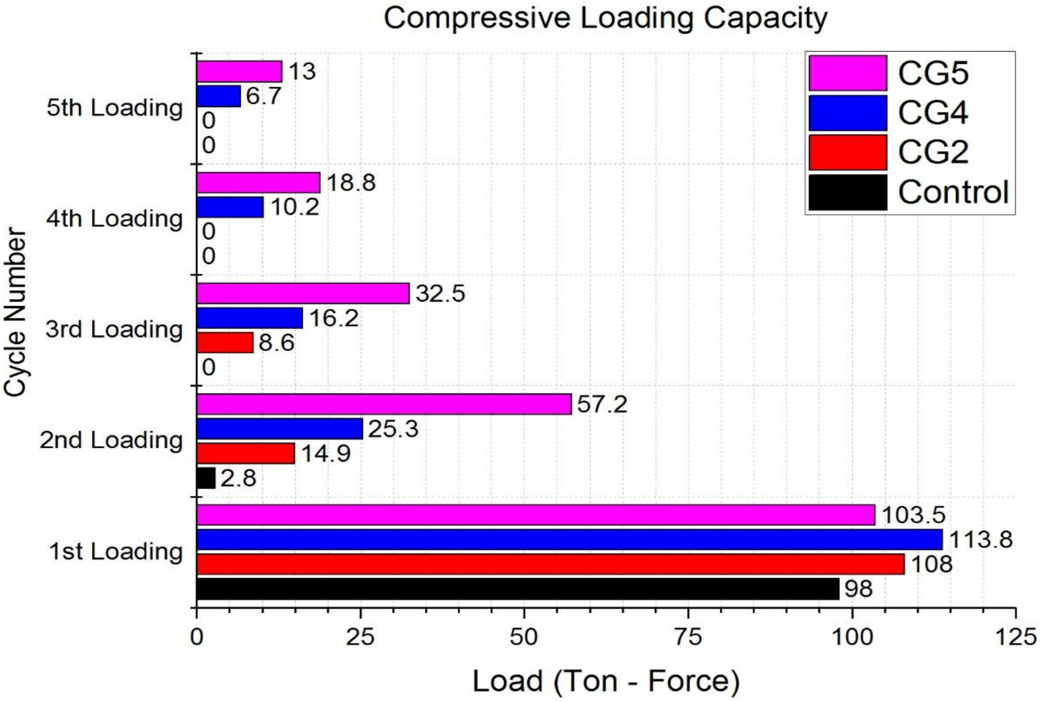


Figure 5. Compressive strength test results.

Figure 6. (a) HWM were deformed and wires were yielded at final loading stage for CG4 specimen (b) Inside CG5 specimen after removing concrete cover (c) Tensile failure mode of wires in CG5 specimen.

3.5. HWM Effects on the Tensile Behavior of HSC

The control specimen totally collapsed and halved into two identical pieces after suffering one tensile loading cycle as shown in Figure 7. Since concrete is weak in tensile loading condition, its tensile strength drops rapidly after a small deflection and reaching the maximum value HWM needs larger deformations to indicate mesh opening size and wire diameter impact on mechanical behavior. Wires yield and deform in the larger deformations. In the next loading cycles, the results in Figure 8 shows that as the mesh opening size decreases, the higher confinement results in higher tensile strength. However, it is noteworthy that the numbers of cycles are determined by wires diameter. The larger wire diameter leads to a higher number of tensile loading cycles. The results show that despite the higher tensile loading capacity for TG2 specimen but due to its thinner wires, it experienced less number of cycles compared to TG4 and TG5 specimens. HWM of the TG2 specimen was yielded or ruptured in the tensile zone as depicted in Figure 9-a after suffering three tensile loading cycles. TG5 specimen was the only one which didn’t halve completely into two pieces and specimen components were held together despite high deformation and reaching the maximum loading machine displacement course. The final condition of TG5 specimen is illustrated in Figure 9-b.

Figure 7. Control specimens after suffering one tensile loading cycle.

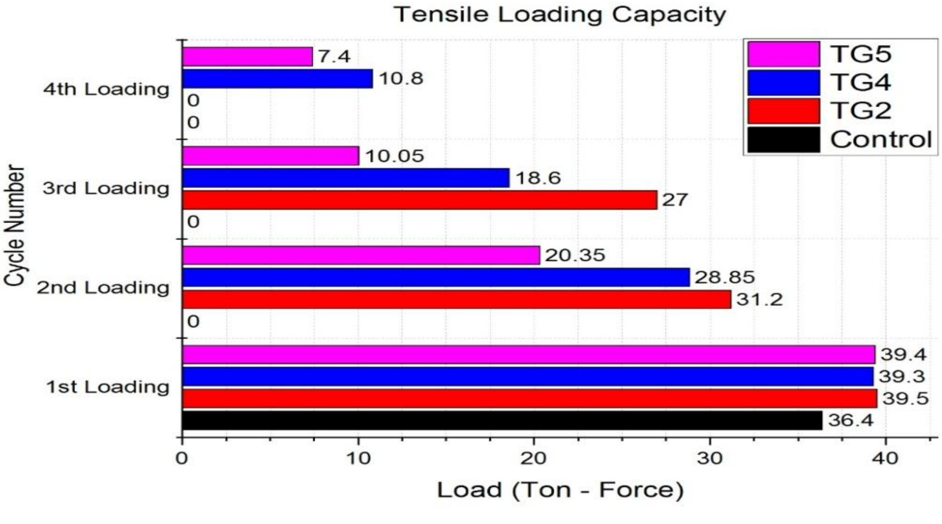


Figure 8. Tensile strength test results.

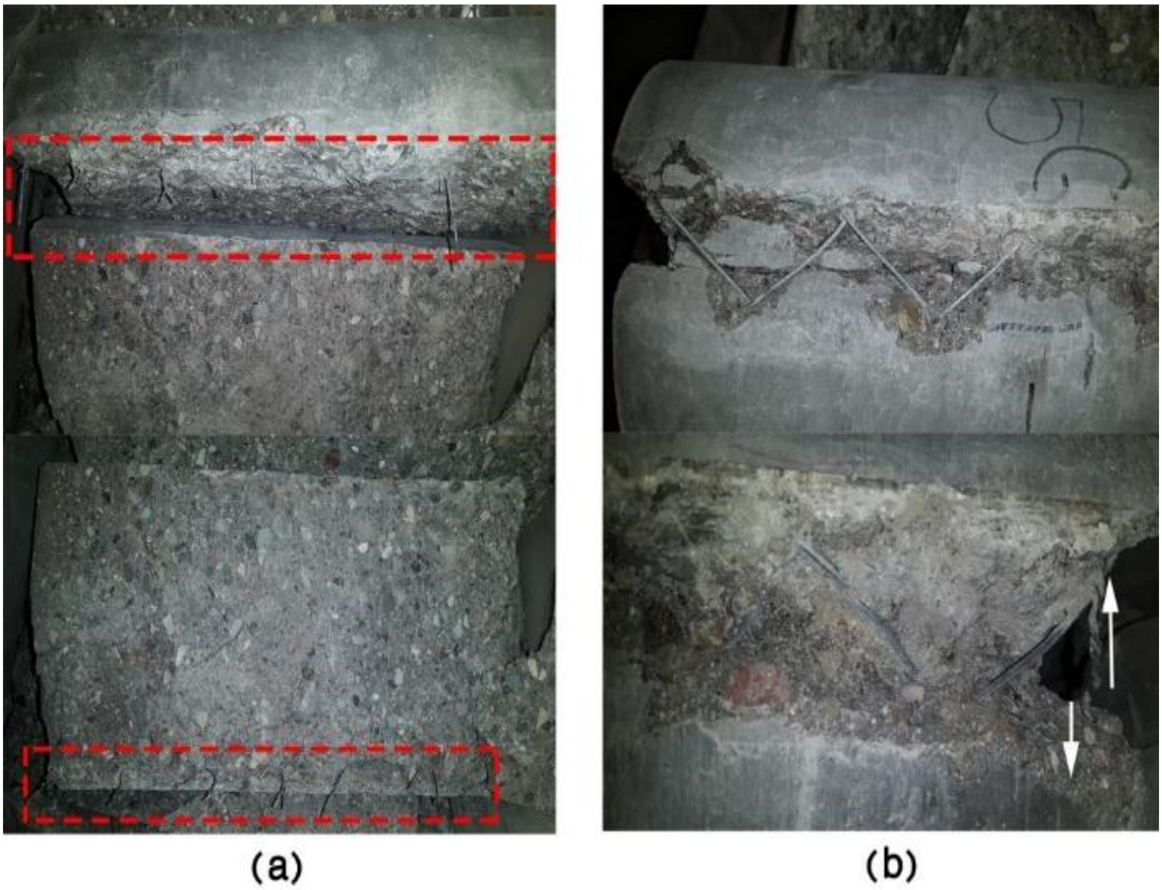


Figure 9. (a) wires failure after yielding in TG2 specimen tensile zone (b) TG5 specimen condition after the final loading stage.

Table 6. Constants and variables parameters affecting the cost of each specimen.

Specimen Code	Normalized variable costs	Normalized constant costs	Normalized Total Specimen Cost
	Total cost of used HWM	Total cost of concrete	
Control	0	0.84	0.84
CG2 and TG2	0.10	0.84	0.94
CG4 and TG4	0.11	0.84	0.95
CG5 and TG5	0.16	0.84	1.00

4. Economic Analysis

In order to get better conclusions about the use of HWM to enhance the brittle behavior of HSC to a desirable status, an economic analysis was conducted. The economic analysis investigates the possibility of using HWM as a cost-effective technique to improve the self-compacting high strength concrete performance. For this purpose, the cost of producing each specimen shall be determined as the first step. Each specimen includes a bunch of constant and variable parameters that affect the total cost of the specimen. Since the concrete mixture is identical for all specimens, the concrete production total cost will be a constant parameter. However, the HWM is variable parameters which affect the total cost of specimen depending on HWM type and used volume as shown in Table 6. Finally, by specifying the changes in the cost of the specimen, an assessment is required to monitor changes in the behavior of the structural characteristics such as the compressive loading capacity and tensile loading capacity and compare with the changes in cost. All materials were purchased atthe local market price and overhead costs were also considered into the calculation. In order to avoid bringing the local monetary unit into presented results, finalized calculated costs are normalized by the maximum one.

An economic index is defined as follows to investigate of the possibility of using HWM as a cost-effective material to enhance the mechanical behavior.

$$P^n = \frac{\sum_{i=1}^{NC} \frac{Load_i^n}{Max(Load_i)}}{NC} \qquad (1)$$

$$\frac{c_n}{c_{control}} = C^n \qquad (2)$$

$$\frac{P^n}{C^n} - \left(\frac{P^{control}}{C^{control}}\right) = \varphi_{PC}^n \qquad (3)$$

Where (NC) is total number of cycles in the test, (i) is the number of current cycle, (Load_i^n) is maximum (compressive or tensile) loading capacity of specimen (n) in the cycle (i), ($\mathrm{Max}(\mathrm{Load}_i)$) is maximum (compressive or tensile) loading capacity between all specimens in the cycle (i). The (c_n) and ($c_{control}$) are the normalized cost of each specimen and normalized cost of control specimen respectively. (φ_{PC}^n) is the economic index of thespecimen (n).

The economic analysis results are illustrated in Figure 10 for compressive and tensile tests. As the economic index increases to higher values than zero, it means that enhancement of HSC by particular HWM type is cost-effective and saves money. While the value lower than zero means that improving the mechanical performance is along with inefficient extra cost and therefore, it is not an economic choice. Values close to zero or equal to zero means that the condition is identical to control specimen from the economic point of view and despite the change in mechanical behavior, the changes in cost are balanced to mechanical behavior as well. The economic index value is always between -1 and +1.

Figure 10-b shows that G5 HWM had the most optimal performance from the economic point of view in compressive loading condition while G2 HWM couldn’t make any noticeable change in economic efficiency. The G4 HWM stands as second cost-effective HWM in compressive loading condition after G5 by an economic index of 0.35.

In the tensile loading condition, Figure 10-a shows that G4 is the most cost-effective HWM for enhancing the HSC performance in tensile loading condition. It should be noted that despite the higher tensile loading capacity by G2 HWM, the G4 specimen could endure more cycles than G2 and with higher tensile loading capacity than G5.

In overall, the economic analysis shows that G4 is the most cost-effective HWM to improve both compressive and tensile behavior by standing as first in tensile and second in compressive loading conditions. The test results also showed that G2 HWM with smaller mesh opening size and providing more confinement is more successful in enhancing the tensile behavior while G5 HWM with larger wire diameters could enhance the compressive behavior. The G4 HWM by having smaller mesh opening size than G5 and larger wire diameter than G2 could establish a balance status and provide both compressive and tensile improvement efficiently.

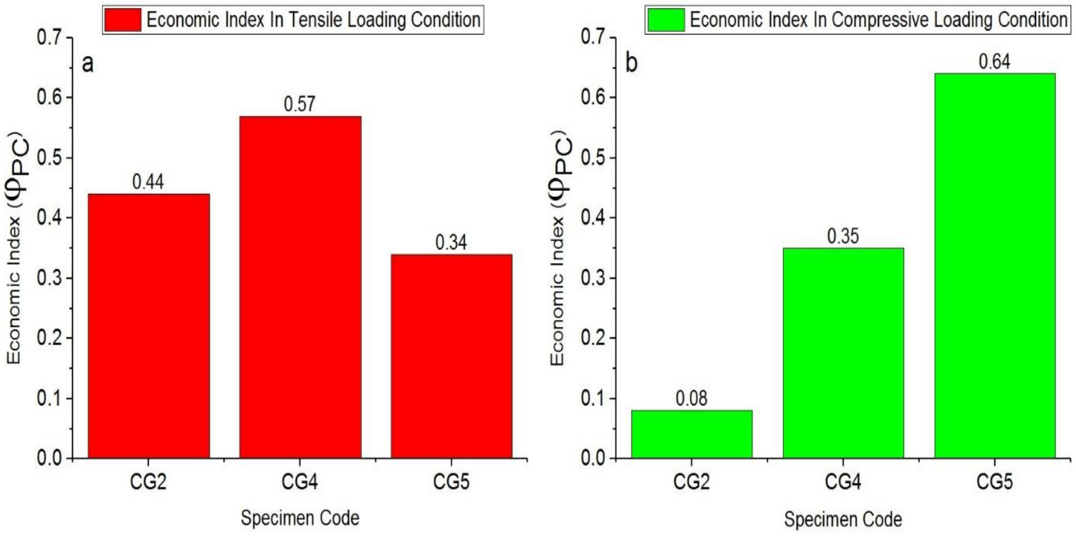


Figure 10. Economic analysis results for (a) tensile loading condition (b) compressive loading condition.

5. CONCLUSIONS

This research aims to develop a cost-effective approach for modifying the brittle behavior of high strength concrete to a desirable one by introducing a state-of-the-art reinforcing technique. The hexagonal wire mesh (HWM) is a low-cost and highly accessible material around the globe which were used for enhancing the high strength self-compacting concrete performance in the most efficient way. The following conclusions are drawn from the experiments by using three different HWM:

1. Low volume usage of silica fume increases the slump flow diameter while high volume usage of it results in decreases in slump flow diameter.
2. Silica-fume enhances the compressive strength in general. However, using silica-fume equal to or more than 20 percent is not efficient and would results in lower compressive strength than 15 percent silica-fume substitution.
3. It is possible to reach high strength in concrete without using additives such as silica-fume by reducing W/C ratio. This procedure aids the economic mass production of HSC.
4. While the control cylinder specimens were collapsed in the first compressive and tensile loading cycle, the specimens with HWM could endure a higher number of loading steps before reaching the total collapse. As wire diameter increased in both tensile and compressive tests, the number of the suffered loading cycleswere increased.
5. The thicker wire diameter of HWM in compressive tests resulted in less compressive strength reduction after each loading cycle and therefore, higher compressive strengths were achieved.
6. The smaller mesh opening size resulted in a higher tensile strength for each loading cycle.
7. HWM with 40 mm mesh opening size and 0.8 mm wire diameter, namely G4, were find out to be most optimal and economic type between the tested HWM types for enhancing either compressive and tensile performance of HSC.

6. References

[1] State-of-the-art Report on High- Strength Concrete. ACI 363R-92, American Concrete Institute Committee 363, Farmington Hills, MI. 1992.

[2] Report on High-Strength Concrete. ACI 363R-10, American Concrete Institute Committee 363, Farmington Hills, MI. 2010.

[3] S. B. Singh, P. Munjal, and N. Thammishetti, “Role of water/cement ratio on strength development of cement mortar,” J. Build. Eng., vol. 4, pp. 94–100, Dec. 2015.

[4] S. Zhutovsky and K. Kovler, “Influence of water to cement ratio on the efficiency of internal curing of high- performance concrete,” Constr. Build. Mater., vol. 144, pp. 311–316, Jul. 2017.

[5] J. C. Lim and T. Ozbakkaloglu, “Influence of silica fume on stress–strain behavior of FRP-confined HSC,” Constr. Build. Mater., vol. 63, pp. 11–24, Jul. 2014.

[6] B. H. Abdelaleem and A. A. A. Hassan, “Development of self-consolidating rubberized concrete incorporating silica fume,” Constr. Build. Mater., vol. 161, pp. 389–397, Feb. 2018.

[7] J. J. Chen, P. L. Ng, L. G. Li, and A. K. H. Kwan, “Production of High-performance Concrete by Addition of Fly Ash Microsphere and Condensed Silica Fume,” Procedia Eng., vol. 172, pp. 165–171, Jan. 2017.

[8] Y. Ju, K. Tian, H. Liu, H.-W. Reinhardt, and L. Wang, “Experimental investigation of the effect of silica fume on the thermal spalling of reactive powder concrete,” Constr. Build. Mater., vol. 155, pp. 571–583, Nov. 2017.

[9] M. Benaicha, X. Roguiez, O. Jalbaud, Y. Burtschell, and A. H. Alaoui, “Influence of silica fume and viscosity modifying agent on the mechanical and rheological behavior of self compacting concrete,” Constr. Build. Mater., vol. 84, pp. 103–110, Jun. 2015.

[10] EFNARC, Specifications and Guidelines for Self-Compacting Concrete, EFNARC, UK, pp. 1–32, 2002.

[11] AFGC. Recommandations pour l’emploi des bétons autoplaçants; Janvier 2008.

[12] R. Abaeian, H. P. Behbahani, and S. J. Moslem, “Effects of high temperatures on mechanical behavior of high strength concrete reinforced with high performance synthetic macro polypropylene (HPP) fibres,” Constr. Build. Mater., vol. 165, pp. 631–638, Mar. 2018.

[13] W. Abbass, M. I. Khan, and S. Mourad, “Evaluation of mechanical properties of steel fiber reinforced concrete with different strengths of concrete,” Constr. Build. Mater., vol. 168, pp. 556–569, Apr. 2018.

[14] E. Molaei Raisi, J. Vaseghi Amiri, and M. R. Davoodi, “Influence of rice husk ash on the fracture characteristics and brittleness of self-compacting concrete,” Eng. Fract. Mech., vol. 199, pp. 595–608, Aug. 2018.

[15] M. Pourbaba, E. Asefi, H. Sadaghian, and A. Mirmiran, “Effect of age on the compressive strength of ultra-high-performance fiber-reinforced concrete,” Constr. Build. Mater., vol. 175, pp. 402–410, Jun. 2018.

[16] W. Xue, L. Li, B. Cheng, and J. Li, “The reversed cyclic load tests of normal and pre-stressed concrete beams,” Eng. Struct., vol. 30, no. 4, pp. 1014–1023, Apr. 2008.

[17] H.-O. Shin, K.-H. Min, and D. Mitchell, “Confinement of ultra-high-performance fiber reinforced concrete columns,” Compos. Struct., vol. 176, pp. 124–142, Sep. 2017.

[18] B. Boulekbache, M. Hamrat, M. Chemrouk, and S. Amziane, “Flexural behaviour of steel fibre-reinforced concrete under cyclic loading,” Constr. Build. Mater., vol. 126, pp. 253–262, Nov. 2016.

[19] A. P. Lampropoulos, S. A. Paschalis, O. T. Tsioulou, and S. E. Dritsos, “Strengthening of reinforced concrete beams using ultra high performance fibre reinforced concrete (UHPFRC),” Eng. Struct., vol. 106, pp. 370–384, Jan. 2016.

[20] ASTM C39 / C39M-18, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, 2018, www.astm.org.

[21] ASTM C1611 / C1611M-14, Standard Test Method for Slump Flow of Self-Consolidating Concrete, ASTM International, West Conshohocken, PA, 2014, www.astm.org.

[22] ASTM C1621 / C1621M-17, Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring, ASTM International, West Conshohocken, PA, 2017, www.astm.org.

[23] ASTM C1610 / C1610M-17, Standard Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique, ASTM International, West Conshohocken, PA, 2017, www.astm.org.

[24] ASTM C150 / C150M-17, Standard Specification for Portland Cement, ASTM International, West Conshohocken, PA, 2017, www.astm.org.

[25] ASTM C494 / C494M-17, Standard Specification for Chemical Admixtures for Concrete, ASTM International, West Conshohocken, PA, 2017, www.astm.org.

[26] ASTM A975-11(2016), Standard Specification for Double–Twisted Hexagonal Mesh Gabions and Revet Mattresses (Metallic-Coated Steel Wire or Metallic-Coated Steel Wire With Poly(Vinyl Chloride) (PVC) Coating), ASTM International, West Conshohocken, PA, 2016.