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The Effects of Maximum Attapulgite Aggregate Size and Steel Fibers Content on Fresh and Some Mechanical Properties of Lightweight Self Compacting Concrete

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ABSTRACT

The main objectives of this study were investigating the effects of the maximum size of coarse Attapulgite aggregate and micro steel fiber content on fresh and some mechanical properties of steel fibers reinforced lightweight self-compacting concrete (SFLWSCC). Two series of mixes were used depending on maximum aggregate size (12.5 and 19) mm, for each series three different steel fibers content were used (0.5 %, 1%, and 1.5%). To evaluate the fresh properties, tests of slump flow, T500 mm, V funnel time, and J ring were carried out. Tests of compressive strength, splitting tensile strength, flexural tensile strength, and calculated equilibrium density were done to evaluate mechanical properties. For reference mixes, the results showed that mixes with a larger maximum aggregate size of 19 mm exhibited better fresh properties, while mechanical properties negatively affected by using a larger maximum aggregate size. The results also showed that using steel fibers led to negative effects on fresh properties, especially with higher steel fibers content and larger maximum aggregate size. The marginal effect of steel fibers on compressive strength was noticed, while for both splitting and flexural tensile strength, significant increase was obtained with increasing of steel fibers content. The properties of SFLWSCC in the fresh state had a considerable effect on mechanical properties, whereas with the best fresh properties, the best mechanical properties can be obtained.

Keywords: steel fiber, lightweight concrete, self-compacting concrete, steel fiber reinforced lightweight self- compacting concrete.

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تأثير المقاس الاقصى لركام الاتبلغايت ومحتوى الالياف الفولاذية على الخواص الطرية وبعض الخواص الميكانيكية للخرسانة خفيفة الوزن ذاتية الرص

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الخلاصة

أن الاهداف الرئيسية لهذه الدراسة كانت التحري عن تأثير المقاس الاقصى لركام الاتبلكايت الخشن ومحتوى الالياف الفولاذية المايكروية على الخواص الطرية وبعض الخواص الميكانيكية للخرسانة خفيفة الوزن ذاتية الرص المسلحة بالالياف. لتحقيق اهداف هذه الدراسة تم استخدام سلسلتان من الخلطات اعتمادا على المقاس الاقصى للركام (12.5 و19) ملم, لكل سلسلة من الخلطات تم استخدام ثلاث محتويات مختلفة من الالياف الفولاذية (0.5%, 1%و 1.5%). لتقييم الخواص الطرية تم اجراء فحوصات جريان الهطول, زمن T500ملم, Jring و Lbox. فحصوصات مقاومة الانضغاط, مقاومة شد الانشطار, مقاومة شد الانثناء و الكثافة المتوازنة المحسوبة تم اجرائها لتقييم الخواص الميكانيكية. أظهرت النتائج للخلطات المرجعية ان الخلطات الحاوية على ركام ذو مقاس اقصى اكبر(19 ملم) أبدت خواص طرية أفضل, بينما الخواص الميكانيكية تأثرت سلبا بزيادة المقاس الاقصى للركام. أظهرت النتائج ايضا بأن استخدام الالياف الفولاذية أدى الى تأثيرات سلبية على الخواص الطرية وخصوصا مع محتوى الياف اعلى ومقاس ركام اقصى أكبر. لوحظ تأثير هامشي للألياف الفولاذية على مقاومة ألانضغاط بينما تم الحصول على زيادات مهمة لكل من مقاومة شد الانشطار ومقاومة شد الانثناء مع زيادة محتوى الالياف. ان الخواص الطرية للخرسانة خفيفة الوزن ذاتية الرص المسلحة بالالياف لها تأثير مهم على الخواص الميكانيكية, حيث ان مع الخواص الطرية الافضل يمكن الحصول على الخواص الميكانيكية الافضل.

الكلمات الرئيسية:الالياف الفولاذية, الخرسانة خفيفة الوزن, الخرسانة ذاتية الرص, الخرسانة خفيفة الوزن ذاتية الرص المسلحة بالالياف.

1. INTRODUCTION

Self-compacting concrete (SCC) has many advantages over normal concrete. SCC does not need internal or external compaction, whereas it compacts under its weight with its high tendency to flow and fill the formwork and its corner entirely **(Okamura and Ouchi, 2003)**. The main properties of SCC in the fresh state are passing ability, filling ability, and resistance of segregation **(Grünewald and Walraven, 2009)**. For over 100 years, structural lightweight aggregate concrete (SLWAC) has been widely used as a building component. The density of structural LWAC typically ranges from 1400 to 2000 kg/m^3 **(Lotfy, 2012)**. Lightweight aggregate concrete provides many advantages such as the higher ratio of strength/weight, higher strain capacity, and excellent insulation for sound and heat due to the voids of air presence in lightweight aggregate (LWA) **(ACI 211.2, 1998)**. Using lightweight concrete could reduce the total dead loads of buildings; accordingly, the cost of construction could be saved due to a decrease in the dimensions of construction members and the amount of steel reinforcement used **(Topcu, 1997)**. Large self-weight of SCC may limit its use in building, while LWA with low density tends to segregate during concrete compaction. Therefore using LWA in SCC production is considered a good solution to overcome the problems associated with both of them **(Kim et al., 2010)**. Steel fiber reinforced concrete (SFRC) is the concrete reinforced with discontinuous steel fibers **(ACI 544.1R, 1996)**. The steel fibers are the most fiber type used in the concrete and have a wide range of types, aspect ratios, and properties. The main advantages of steel fiber using in concrete are the improvement of strength and toughness of concrete by bridging of cracks, transmitting of stress across cracks, and preventing cracks propagations **(Grünewald and Walraven, 2009)**. Using fibers can provide opportunities to substitute traditional reinforcement partially or even completely. This reduces the need for reinforcement in a concrete member such as beams and slabs, accordingly the thickness of concrete members and the structure dead loads can be decreased by reducing the minimum required concrete cover thickness **(Khayat and De Schutter, 2014)**. In the last decade, steel fiber reinforced self-compacting concrete (SFRSCC) has been used in several structural applications such as precast pre-stressed concrete members, slab on grade sheet piles, etc. Using fibers in SCC, which can be consolidated without the need for vibration, reduce the risk of fibers segregation and downward settlement during compaction and lead to the distribution of fibers uniformly within concrete members **(Ozyurt, 2007)**. **(Matar and Assaad, 2019)** studied the combined effects of polypropylene fibers with a content of 0.25% to 1.75%, and recycled aggregate with a content ranged from 25% to 100% on fresh properties of SCC such as flowability, passing ability and resistance of segregation. The researchers used different water to binder ratio ranged between 0.38 to 0.5, while superplasticizer content was adjusted to obtain a slump flow of 700 ± 25 mm. The results showed that the passing ability and flowability of SCC reduced significantly with the inclusion of polypropylene fibers, especially with using a higher proportion of recycled aggregate content in produced SCC due to increasing the resistance to flow resulting from increasing of internal friction. For segregation resistance, the results showed that increasing polypropylene fibers and recycled aggregate contents led to increasing stability of SCC mixes, and accordingly, segregation resistance had increased. **(Yardimci, et.al, 2014)** investigated the effects of fine to coarse aggregate percentage with constant paste volume, steel fiber content (20, 40, and 60 kg/m^3*)* with different aspect ratios and types [hooked-end steel fibers] on the fresh properties and fracture energy of (SFRSCC). The results showed that using both types of steel fibers led to negative effects on the fresh properties of (SFRSCC). Using of high fine to coarse aggregate percentage improve fresh properties by enhancing rheological parameters in addition to better fibers distribution and orientation, but decreased the fracture energy for both plain SCC and (SFRSCC) mixtures. **(Ghanem and Obeid, 2015)** studied the effects of steel fibers on the fresh and mechanical properties (compressive strength and flexural strength) of SCC. Five concrete mixtures were prepared with different type and aspect ratio of steel fibers. The results showed that the fibers increased the compressive strength, but it caused a negative effect on the fresh properties of the SCC, by decreasing the slump flow and increasing the flow time. At the same time, better workability was obtained by decreasing the steel fibers aspect ratio. The researcher also concluded that the geometry of the fiber had significant effects on the mechanical properties. **(Stähli, et al., 2008)** attempted to study the effects of fiber distribution and orientation on the flexural strength of SCC by using of the flow-properties of the fresh SCC. A single mixture of FRSCC containing 3% of 30 mm long straight steel fibers was used. The fiber orientation and distribution were investigated in three different parts of a U-shaped specimen, where the concrete could flow in three different directions. The results of flexural tests showed that the mechanical properties depended on the fiber orientation and distribution, which can be affected by changing of the fresh concrete viscosity. **(Ferrara, et al., 2008)** investigated correlation among the performance in the fresh state, the dispersion and orientation of fibers, and their effects on bending stress of SFSCC and vibrated SFRC. Concrete was placed as a slab then this slab was cut to obtain beams for bending test. The cut beams were either parallel or orthogonal to the main flow direction during casting. The results showed that SFRSCC exhibited uniform dispersion and high tendency to align with the direction of casting, while vibrated concrete and poorly designed SFRSCC prone to downward settlement. The researcher concluded that a strong correlation between fibers' alignment and mechanical properties.

2. OBJECTIVE OF THE RESEARCH

The main objectives of this research were to investigate the effects of maximum aggregate size and micro steel fiber content on fresh and some mechanical properties of SFLWSCC. To achieve these objectives, two series of mixes with a maximum aggregate size of (12.5 and 19.0) mm and the steel fiber content of (0.5, 1 and 1.5) % were used. For fresh properties, tests of slump flow, T500 time, V funnel, and J ring, according to **(EFNARC, 2005)** were executed. For mechanical properties, the tests of compressive strength, calculated equilibrium density, splitting, and flexural tensile strength were carried out for all mixes.

3. EXPERIMENTAL WORK

3.1. Materials

3.1.1. Cement

Tables 1. and 2. show the results of the chemical analysis and physical properties for ordinary Portland cement used in this research. Results declared that the used cement is compatible with the Iraqi Specification **(IQS No.5, 1984)**.

Table 1. Chemical composition and Main Compounds of cement.

Oxide composition	% by weight	Limits of **(IQS No.5, 1984)**.
SiO_2	19.6	------------------
Fe_2O_3	3.52	------------------
Al_2O_3	4.65	------------------
CaO	61.56	------------------
MgO	2.77	5.0(max)
SO_3	2.71	2.8(max)
Loss on ignition	1.65	4.0(max)
Insoluble residue	0.8	1.5(max)
Lime saturation factor	0.95	0.66-1.02
Main compounds(Bogue’s equation)% by weight of cement		
C_3S	57.65	-------------------
C_2S	12.7	-------------------
C_3A	6.37	-------------------
C_4AF	10.71	--------------------

Table 2. Physical Properties of Cement.

Physical properties	Test results	Limits of **(IQS No.5, 1984)**
Specific surface area (Blaine method), m²/kg	240	230 (min)
Setting time (Vicate's method) Initial setting, hours: minute Final setting, hours: minute	 1:45 5:30	 00:45 (min) 10:00 (max)
Compressive strength, (MPa) 3 days 7 days	 19.6 28.6	 15.00 (min) 23.00 (min)
Soundness using Autoclave expansion, %	0.4	0.8 (max)

3.1.2 Fine Aggregate

Sand falls within zone two according to the requirement of the Iraqi Specification **(IQS 45, 1984)** was used as fine aggregate in all concrete mixes. **Table 3 and Table 4** contain the sieve analysis and chemical and physical properties of natural sand used, respectively.

3-1-3 Coarse Aggregate

Attapulgite aggregate manufactured according to the process was suggested by **(Frayyeh, et al., 2014**) by burning Attapulgite clays from the Tar of AL-Najaf region used as a structural lightweight coarse aggregate (SLWA). **Tables 5 and 6** show sieve analysis and some properties of Attapulgite lightweight aggregate, respectively.

Table 3. Sieve analysis of sand.

Sieve size (mm)	Cumulative passing %	Cumulative passing % Limits(**IQS 45, 1984)**, zone 2
4.75	99.8	90-100
2.36	84.4	75-100
1.18	65.6	55-90
0.60	41.8	35-59
0.30	11	8-30
0.15	2.2	0-10

Table 4. Chemical and physical properties of sand.

Property	Test results	Limit of (**IQS 45, 1984)**
Specific gravity.	2.6	---------------
Absorption, %	2.97	---------------
Dry loose unit weight, kg/m³	1587	---------------
Sulphate content as SO_3,%	0.07	0.5(max)
Material finer than 75µm, %	2.6	5.0(max)
Fineness modulus	2.95	---------------

Table 5. Sieve analysis of coarse lightweight aggregate.

Sieve size (mm)	% passing of 12.5 mm maximum aggregate size	Cumulative Passing (%) for (12.5 to 4.75) mm according to **(ASTMC330, 2004)**	% passing of 19 mm maximum aggregate size	Cumulative Passing (%) for (19 to 4.75) mm according to **(ASTMC330, 2004)**
25	---------		100	100
19	100	100	95	90-100
12.5	95	90-100	55	---------
9.5	55	40-80	30	10-50
4.75	10	0-20	0	0-15
2.36	0	0-10	-------	---------

3.1.4 Fly Ash (FA)

Hard coal (FA) class F, according to **(ASTM C618, 2005)** was used in this study. The chemical analysis and some physical properties of (FA) were shown in **Table 7**.

Table 6. Properties of Attapulgite aggregate.

Properties	Specifications	Max. aggregate size of 12.5 mm	Max. aggregate size of 19 mm	Limits
Absorption, %	**(ASTM C127, 2004)**	27.9	28.5	5-30
Bulk Density(dry loose),kg/m^3	**(ASTM C330, 2004)**	810	806	880(max)
Specific gravity(SSD)	**(ASTM C127, 2004)**	1.92	1.86	--------
Specific gravity(OD)	**(ASTM C127, 2004)**	1.48	1.46	2.6(max)

3.1.5 Chemical Admixture

Glinume 51 complies with **(ASTM C494, 2005)** type A, and F was used concrete superplasticizer (SP).

3.1.6 Steel fibers

Straight micro steel fibers coated with copper were used in this research. **Table 8** shows the properties of the steel fibers.

3.2 Design of Concrete Mixes

The design of self-compacting of lightweight concrete mixes in this study, was carried out to produce structural lightweight concrete confirmed with the requirements of structural LWC of (**ASTM C330, 2004)** for sand/lightweight coarse aggregate, with minimum compressive strength and splitting tensile strength of 28 MPa and 2.3 MPa at 28-day and calculated equilibrium density not exceeding 1840 kg/m^3. At the same time, the mix design of LWSCC must satisfy the criteria of **(EFNARC, 2002)**. The mix design method of **(EFNARC, 2005)** for SCC was used in this research to obtain a target slump flow of 730 ± 20 mm. The proportions of materials are modified to satisfy both self-compact-ability and requirements of structural LWC, so multi-trail mixes were carried out for this purpose. Two series of mixes were used in this research, one with a maximum aggregate size of 12.5 mm (Ref.mix1) and another with a maximum aggregate size of 19 mm (Ref.mix2). Fly ash class F was used to enhance the SCC viscosity by increasing paste volume and to improve workability due to the ball-bearing effect of spherical fly ash fine particles **(Sahmaran and Yaman, 2007)**. Fly ash addition of 110 kg/m^3 was constant for all mixes. Three micro steel fiber percentages of (0.5%, 1%, and 1.5%) by volume of concrete with an aspect ratio of 75 were added to both plain reference mixes. Eight mixes are used throughout this research. For all mixes, powder content, fine aggregate content, SP dosages, coarse aggregate content, and W/p ratio were kept constant. The details of the mixes used throughout this research are shown in **Table 9.**

Table 7. Chemical analysis and physical properties of (FA).

Oxide composition	Oxide content of (FA) %
SiO_2	65.65
Al_2O_3	17.69
Fe_2O_3	5.98
CaO	0.98
MgO	0.72
Na_2O	1.35
SO_3	0.19
K2O	2.99
L.O.I	3.1
Physical properties	
Specific Surface Area m²/kg	773
Specific Gravity	2.35
S.A.I at 7 days (%)	78
S.A.I at 28 days (%)	89

Table 8. The properties of steel fiber.

Density	Tensile strength	length	Diameter	Aspect ratio
7800 kg/m^3	2850 MPa	15 mm	0.2 mm	75

3.3 Mixing of Concrete

The Attapulgite aggregates had to be soaked for about 48 hours to prevent excessive absorption of mixing water and then dried to saturated surface dry conditions. The method of **(Doukakis, 2013)** was used in the mixing of SFLWSCC. This method includes the following steps:

1- To ensure high homogeneity, cement and FA must be mixed well before adding them to the mixer

2- The coarse aggregate with two-third of the mixing water was added to the mixer and mixed for just a few revolutions.
3-The mixer was then stopped to add sand, cement, and FA mixture, and the remaining water with SP was added, respectively.
4-The mixer was rotated for 3 minutes, rested covered for 3 minutes, and then spun covered for two more minutes.
5- Finally, steel fibers were added while the mixer was in motion to ensure proper dispersion within the mix and spun uncovered for 3 minutes.

Table 9. The details of mixes by weight (kg/m^3).

Mix designation	Max. aggregate size (mm)	% Steel fiber content by volume	Cement kg/m^3	Fly Ash kg/m^3	Sand kg/m^3	Coarse Aggregate (Attapulgite) kg/m^3	water litre/m^3 W/P=0.4	SP Litre/ m^3
Ref. mix1	12.5	0	440	110	624	630	220	5.5
Mix2	12.5	0.5	440	110	624	630	220	5.5
Mix3	12.5	1.0	440	110	624	630	220	5.5
Mix4	12.5	1.5	440	110	624	630	220	5.5
Ref mix2	19	0	440	110	624	630	220	5.5
Mix6	19	0.5	440	110	624	630	220	5.5
Mix7	19	1.0	440	110	624	630	220	5.5
Mix8	19	1.5	440	110	624	630	220	5.5

3.4 Testing of SFLWSCC Fresh Properties

The tests of (Slump flow, T500 mm slump flow, V-funnel, J-ring) were it is performed according to **(EFNARC, 2002)** for all SFLWSCC mixes.

3.5.Testing of mechanical properties of SFLWSCC

3.5.1 Compressive Strength

This test was carried out on cubes of 100 mm according to **(BS 1881, Part 116, 1989)**. The samples were tested at the ages of 28 days, and the average of three specimens testing results was dependent.

3.5.2 Splitting Tensile Strength

This test was performed on cylindrical concrete specimens of (100×200) mm, according to **(ASTM C496, 2004)**. The samples were tested at the age of 28 days,

3.5.3 Oven-Dry Density

This test was conducted according to **(ASTM C567, 2005)** on 100x200 cylinders. The average of three specimens testing results was adopted.

3.5.4 Calculated Equilibrium Density

According to **(ASTM C567, 2005)**, the calculated equilibrium density was determined by the addition of 50 kg/m^3 to oven-dry density.

3.5.5 Flexural Tensile Strength

This test was performed on prismatic concrete specimens of (100×100×400) mm, according to (**ASTM C78, 2002)**. The samples were tested at the age of 28 days; the average of three specimens testing results was adopted.

4. RESULTS AND DISCUSSION

4.1 Fresh Properties

4.1.1 Slump flow

The results of slump flow were included in **Table 10.** The results show that all results are within the acceptance criteria of **(EFNARC, 2002)** except Mix.6. For reference mixes, the results showed that Ref.mix2, which had a larger maximum aggregate size (19 mm), exhibited a higher slump flow than Ref.mix1 with maximum aggregate size (12.5 mm). This is because of the lower surface area of larger aggregate, so for constant w/c ratio and SP dosage, higher fluidity would be provided. In addition to the low surface area of larger aggregate led to excessive paste layer around it. **(Kennedy, 1940)** stated that to overcome the friction between aggregate particles enough paste layer must be provided to cover aggregate outer surface. The surface layer of paste proportioned with aggregate size and increased with reducing surface area by using a larger aggregate size.

For SFLWSCC mixes, the results showed that using steel fiber led to reducing slump flow for all mixes, and the reduction in slump flow increased with increasing of steel fiber content. The reduction in slump flow when steel fibers used can be attributed to increasing water demands and decreasing aggregate paste layer thickness required to enhance flowability by decreasing aggregate particles friction and interlocking due to high surface area of steel fibers **(Martinie, et al., 2010)**. In addition to increasing granular skeleton's porosity and reducing packing density because of the elongated needle-like shape of steel fibers **(Grünewald and Walraven, 2009)**. SCC with higher packing density possesses higher fresh properties; steel fibers reduce packing density by increasing of inter-particles voids in the granular skeleton. That means lower paste surrounding aggregate and steel fiber, which is necessary for lubricating and enveloping of fiber and coarse aggregate particles **(Ferrara, et al., 2007)**. The results also showed that the reductions in slump flow when steel fibers were used were more clearly in mixes contained larger maximum aggregate size (19 mm) at the same steel fibers content. The higher the steel fiber content and the larger the maximum aggregate size, the higher the reduction in slump flow can be obtained due to the increase in the porosity of the granular skeleton of SFLWSCC. In addition to increasing the ability of fiber to produce balling with increasing of maximum aggregate size (**ACI 544.1R, 1996).** According to **(Johston, 1996)** the numbers of stiff steel fibers that can occupy a unit volume decreases by using larger maximum aggregate size. This may cause fiber clustering and effect negatively on flow ability of SFLWSCC.

Table 10. Results of SFLWSCC fresh Properties.

Mix designation	Slump flow (mm)	T 500 (sec)	V funnel (sec)	J Ring (mm)
Ref. mix1	730	3	8	6
Mix2	720	3.5	9.5	8
Mix3	640	4	11	9.5
Mix4	610	5	13	Blocking
Ref. mix 2	745	2.5	6	4
Mix6	655	4	10	9
Mix7	610	5	12	10.5
Mix8	585	6	17	Blocking

4.1.2 T500 mm

The results of T500 mm were included in **Table 10**. The results showed that all T500 mm values are within acceptance criteria **(EFNARC, 2002)**, except mix.8, which contained 1.5% steel fiber with maximum aggregate size of 19 mm. For references mixes, the results showed that the Ref. mix2 T500 mm exhibited lower time than Ref. mix2 due to its high flowability and lower viscosity. The viscosity of SCC paste has significant effects on the flow velocity. The higher the paste viscosity, the lower the flow velocity of SCC can be obtained **(Martinie and Rousse, 2011)**. For mixes contained steel fibers, the results showed that T500 mm time increased as steel fiber content had increased because of increasing paste viscosity, whereas high surface area of steel fibers reduces paste layer thickness surrounding both steel fibers and coarse aggregate particles. Accordingly, high friction and high flow hindrance could happen. This reduction in the paste layer led to an increase in plastic viscosity and reduce the flowability of SCC **(van Bui, et al., 2003)**. The results also showed that mixes with larger maximum aggregate were more affected with increasing steel fibers content due to an increase in the tendency of fibers to cluster with increasing maximum aggregate size.

4.1.3 V Funnel time

The results of V funnel time were included in **Table 10.** The results showed that all V Funnel time values are within acceptance criteria **(EFNARC, 2002)**, except mix.8. As in slump flow and T500 mm, the results showed that Ref. mix2 demonstrated higher V Funnel time than Ref. mix1 and the V Funnel time increased with increasing steel fiber content. At the same steel fiber content, mixes with larger maximum aggregate size (19 mm) showed higher V Funnel time than mixes with smaller maximum aggregate size (12.5 mm) for the same reasons mentioned in previous sections.

4.1.4 J Ring

The results of the J Ring test were included in **Table 10.** For reference mixes, the results showed that Ref. mix1 had higher J ring value than Ref. mix2 because the latter had higher flowability because of its lower surface area; accordingly, thicker paste layer available to lubricant aggregate particles and reducing of inter-particles friction. For mixes containing steel fibers, the results showed that not all J ring values are within acceptance criteria of **(EFNARC, 2002)**, and blocking was noticed for Mix 4 and Mix 8, despite some of these mixes exhibited good flowability. According to **(Deeb, 2013)** who stated that SCC mixes showed good flowability not necessarily show good passing ability. **(Khayat and De Schutter, 2014)** also stated that the decrease in reinforcement congestion when steel fiber used makes the dependence on L box and J ring tests to evaluate the passing ability of SCC unnecessary demanding. So, the J ring test in this study was done to compare the behavior of SCC at the different maximum aggregate size and steel fiber content. **Fig. 1 (a) and (b)** show J ring test for Ref.mix2 and Mix 8 respectively, and they show that high passing ability for Ref. mix 2, while Mix8 with steel fibers content of 1.5% suffered from blocking with poor passing ability. The results also showed that J ring values increased with increasing of steel fiber content, and the mixes with larger maximum aggregate size showed higher J ring values than mixes with lower one at the same fibers content. Because larger maximum aggregate size increased the fiber balling, especially near the j ring bars. In addition to increasing yield stress resulting from increasing viscosity makes the torque, which is necessary to align steel fibers parallel to flow direction very low **(Martinie and Rousse, 2011).** So the steel fibers would align transversely on flow direction, causing blocking when steel fibers reached J ring bars. The increasing in J ring value or blocking can also be attributed to increase the collision between particles as the distance between these particles decreases, which can cause increasing in internal stresses when concrete try to pass obstacles or narrow spaces and may cause blocking by consuming of the required energy to pass obstacles or narrow spaces **(Okamura and Ouchi, 1999)**.

(a) (b)

Figure 1. J ring test (a) for Ref. mix 2 and (b) for Mix8.

4.2 Mechanical properties

4.2.1 Compressive strength

The results of compressive strength for all mixes are included in **Fig. 2.** The results showed all compressive strength values are within the requirement of **(ASTM C330, 2004)** for lightweight structural concrete. For references mixes the results showed that the Ref. mix 1 with maximum aggregate size of 12.5 mm exhibited higher compressive strength than Ref. mix2 because using of larger aggregate size without reducing water content as in this research can form a weaker intermediate transition zone (ITZ) with more microcracks **(Mehta and Monteiro, 2006)**. In addition to weaker bonding strength between aggregate and cement paste at (ITZ) due to lower surface area for coarser aggregate **(Neville, 1997)**, and increasing of aggregate size may increase the probability of the presence of the internal defects and weak points due to crushing of Attapulgite clays during the production process. For SFLWSCC mixes, the results showed that the incorporation of steel fiber led to increasing in compressive strength due to improvement of the ultimate strain and residual load-bearing capacity **(Khayat and De Schutter, 2014)**, and arresting of the cracks opening due to bridging process **(Al-Quraishi, et al., 2017)**. **Table 11** contained the percentages of strength gain relative to reference mixes and showed that contribution of steel fiber in compressive strength improvement was a marginal and ultimate gain of 11% was noticed with mix.2, which contained 0.5% steel fiber. **Table 11** also showed that the percentage gain in compressive strength reduced with increasing in steel fiber content because of the steric disturbance effect by the network of the fibers **(Khayat and De Schutter, 2014).** Increasing the porosity of granular skeleton and entrapped air is due to poor distribution of steel fibers at high content where the steel fiber may accumulate at one point in the mold and causing microcracks, these microcracks begin to propagate with increasing of applied load **(Ghasemi, et al., 2018)**. While balling of steel fibers at high content can cause inadequate bonding with concrete **(Sinha and Verma, 2017)**. For mixes with larger maximum aggregate size, **Table 11** shows that % gains in compressive strength were lower when compared with mixes with lower aggregate size at the same fiber content, because larger aggregate can cause poorer fiber distribution, also stiff steel fibers push away the aggregate particles that are relatively larger than fibers length causing increasing in porosity of granular skeleton **(Grünewald and Walraven, 2009)**. Whereas the length of fiber used in this study was 15 mm while the maximum aggregate size was 19 mm. In addition to the higher tendency of larger aggregate to produce fibers balling.

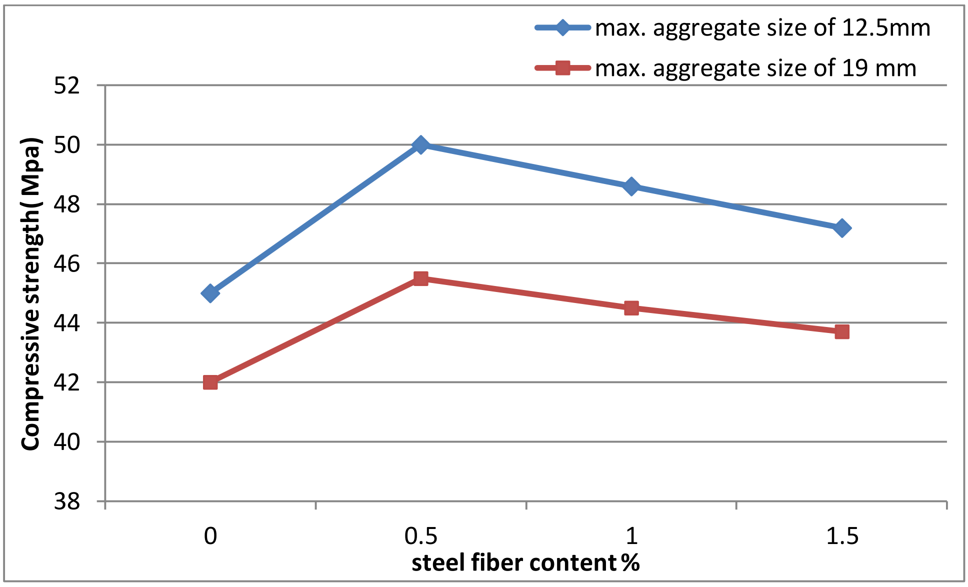

Figure 2. Compressive strength results.

4.2.2 Calculated equilibrium density

The results of the calculated equilibrium density were included in **Fig. 3**. The results showed that all densities were within the requirement of **(ASTM C 330, 2004)** for SLWC. For reference mixes, the results showed that Ref. mix2 with a maximum aggregate size of 19 mm illustrated lower densities than Ref. mix1, because of lower specific gravity for larger aggregate due to increasing of the probability of voids presence with increasing of aggregate size. According to **(ACI 213, 2003),** the relative density of LWA depends on its size, and it is higher for finer aggregate particles. For SFLWSCC mixes, the results showed that the densities increased with increasing steel fiber content due to the high density of steel fiber when compared with other concrete materials. **Table 11** shows that the percentages of increase in densities were higher for mixes with smaller coarse aggregate sizes because of the better fresh properties for mixes with smaller aggregate sizes accordingly the better steel fiber distribution with lower entrapped air and porosity in the granular skeleton.

Table 11. % gain in mechanical properties relative to reference mixes.

Steel fiber content %	% gain in compressive strength relative to :		% gain in density relative to:		% gain in splitting strength relative to:		% gain in flexural strength relative to:	
	Ref. mix1	Ref. mix2	Ref. mix1	Ref. mix2	Ref. mix1	Ref. mix2	Ref. mix1	Ref. mix2
0.5	11	8.5	2.2	1.7	18	14	25	21
1	8	6	3.1	2.4	38	27	60	51
1.5	5.5	4	4	3.2	55	46	84	77

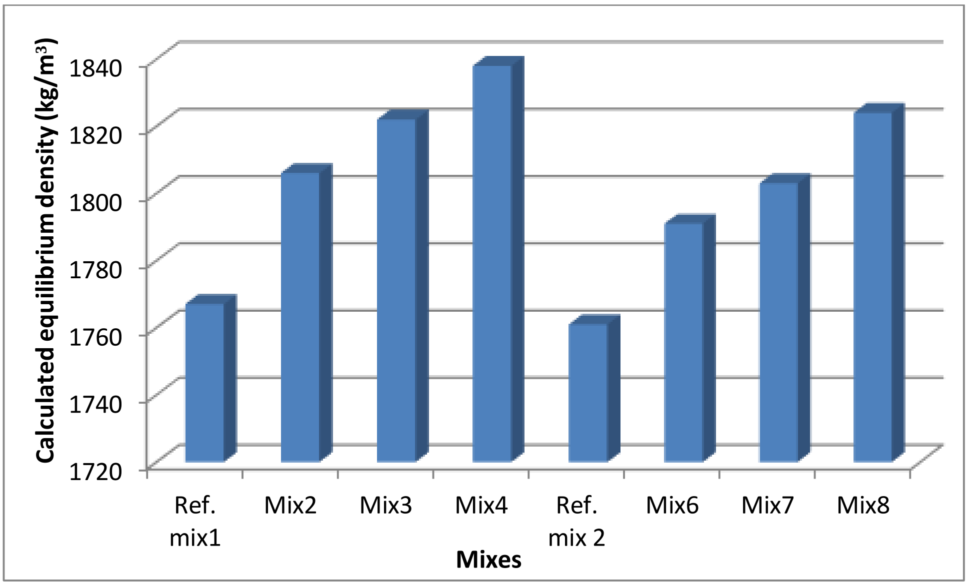

Figure 3. Calculated equilibrium density results.

4.2.3 Splitting tensile strength

The results of splitting tensile strength for all mixes were included in **Fig. 4**. The results showed that all splitting tensile strength values complied with the requirement of **(ASTM C 330, 2004)**.

For reference mixes, the results showed that the splitting tensile strength for Ref.mix1 was higher than that for Ref.mix2, for the same reasons mentioned in section 4.2.1 about the effect of the maximum aggregate size on compressive strength of reference mixes. For SFLWSCC mixes the results showed clearly that the splitting tensile strength increased with increasing of steel fiber content, due to the resistance of steel fiber against the propagation and conversion of microcracks to macrocracks in cement matrix by bridging across them **(Niş, 2018)**. The splitting loading in the cylinder can cause biaxial stress, vertical compressive, and lateral tensile stresses, and this biaxial stress had a significant effect on the behavior of post cracking **(Kadhum, 2015)**. **Table 11** showed that the mixes with smaller maximum aggregate size (12.5 mm) exhibited higher % gain in splitting tensile strength than mixes with a larger one, due to the better flowability accordingly, the better distribution and orientation of steel fibers. **Fig. 5 (a)** and **(b)** show failure plane for Ref. mix 1 and Mix 4, respectively. **Fig. 5 (a)** shows that the failure plane passes through the central line of the test specimen and divides it into two equal parts. While for Mix. 4, **Fig. 5 (b)** show that the failure plane does not pass through the central line of the test specimen because steel fibers bridge both sides of it and make failure plane indirect.

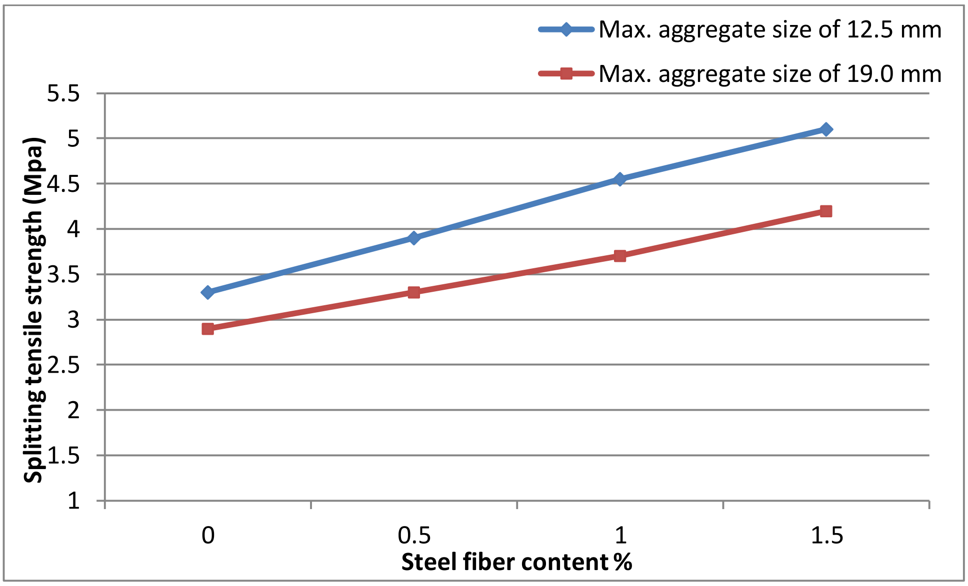

Figure 4. Splitting tensile strength results.

4.2.4 Flexural tensile strength

The results of flexural tensile strength are included in **Fig. 6**, and it shows that flexural tensile strength for Ref. mix1 as in compressive and splitting tensile strength is higher than that for Ref. mix2. For SFLWSCC mixes, the results show that a significant improvement in flexural tensile strength when steel fibers were used. **Table11** shows that the percentage gains in flexural tensile strength increased with increasing steel fiber content because the inclusion of steel fibers in concrete with random distribution can act as a small reinforcement with a high ability to reduce cracks width (**ACI 544.1R, 1996)**. In addition to the resistance of steel fiber to pull out from the cement matrix, which is resulting from the bonding strength between fibers and cement matrix. As a result, to pull out of the fibers gradually from the cement matrix when the concrete is under loading, fibers provide post crack ductility to the cement matrix, which is brittle in failure and behavior **(Gray and Johnston, 1987)**. Accordingly, using steel fibers in LWSCC can cause a big improvement in flexural tensile strength due to the more brittle nature of lightweight aggregate **(Balendran, et al., 2002)**. **Table 11** also shows that the percentage gains in flexural tensile strength were more significant than those of compressive and splitting strength because the ductile behavior of SFLWSCC on the tension zone of test specimen modifies the elastic distribution of strain and stress over the depth of test specimen. The modification of stress distribution, which is elastic in the compression zone and plastic in the tension zone, leads to shifting the neutral axis toward the compression zone **(Hannant, 1978)**. Mixes with a maximum aggregate of 12.5 mm exhibited higher % gain in flexural strength than mixes with a maximum aggregate of 19 mm at the same steel fiber content, due to the higher flowability and lower yield stress for the former. High flowability and lower yield stress with high induced torque caused the steel fiber to align with the flow direction **(Ferrara, et al., 2008)**. In this research SFLWSCC was poured during placing of test specimens at the middle third of molds, so the fresh SFLWSCC moved from the middle third toward both sides of the molds, this caused the alignment of fiber to be with the flowing direction accordingly with the direction of principal stress at right angle to the formed cracks, this makes the fibers more effective to bridge both sides of cracks, while the fibers become less effective when aligned parallel to the direction of cracks propagation **(Ige, 2017)**.

(a) (b)

Figure 5. Failure plane of splitting tensile test specimen (a) for Ref. mix 1 and (b) for Mix 4.

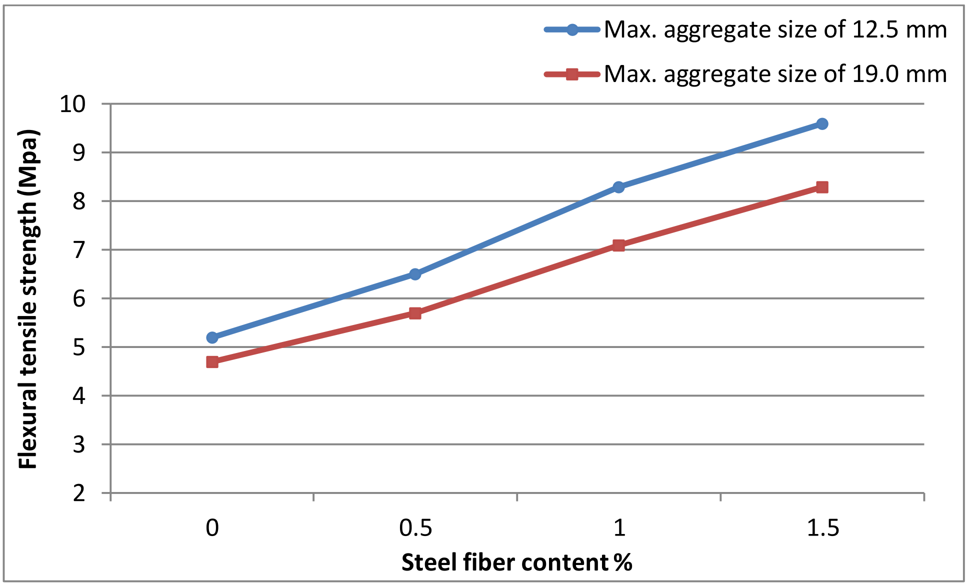

Figure 5. Flexural tensile strength results.

5. CONCLUSIONS

The following conclusion can be drawn from the results of experimental work:

1- Reference mixes with a maximum aggregate size of 19 mm exhibited better slump flow, T500, V funnel time and J ring values than mixes with a maximum aggregate size of 12.5 mm due to its high fluidity and deformability resulting from the lower surface area.

2- Using steel fiber led to detrimental effects on the fresh properties of SFLWSCC. The higher the fiber content, the higher the detrimental effects. Mixes with larger maximum aggregate exhibited a more negative effect on fresh properties than those with lower maximum aggregate size.

3- Reference mixes with lower maximum aggregate size showed better mechanical properties than mixes with the larger one, due to the higher bonding stress resulting from, the higher surface area and the lower microcracks in ITZ.

4- There is a strong correlation between fresh and mechanical properties for SFLWSCC. I.e., the higher fluidity, passing ability, and filling ability of SFLWSCC, the higher mechanical properties can be obtained due to better distribution and orientation of steel fiber within the cement matrix.

5- Steel fiber led to a marginal effect on compressive strength, and the gain in compressive strength reduced with increasing of steel fiber content due to the increasing of entrapped air and porosity of granular skeleton.

6- Using steel fiber led to significant improvements in splitting and flexural tensile strength, and this improvement was more pronounced with high steel fiber content due to the ductile behavior of SFLWSCC and preventing of microcracks propagation by bridging across them.

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