Some Properties of Hybrid Fibers High Strength Lightweight Aggregate Concrete

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ABSTRACT

This investigation aims to study some properties of high strength lightweight aggregate concrete (HSLWAC) reinforced with mono and hybrid fibers in different dimensions and types. High strength porcelinite lightweight aggregate concrete mix with compressive strength 41 MPa at 28 day age was prepared. The fibers used included macro hooked steel fiber with aspect ratio 100 (type S1), macro hooked steel fiber with aspect ratio 60 (type S2), micro polypropylene fiber (pp) and micro carbon fiber (CF). Eight HSLWAC mixes were prepared including, one plain concrete mix (without fibers), three mono (single) fiber reinforced concrete mixes (with 0.5% volume fraction of steel fiber type S1, 1% volume fraction of steel fiber type S1and 0.25% volume fraction of CF**)** and four double hybrid fiber reinforced concretes mixes [0.5% steel fiber type S1 +0.5% steel fiber S2 mix (HSF1), 0.75% steel fiber S1+ 0.25% steel fiber type S2 mix (HSF2), 0.75% steel fiber type S1+ 0.25% pp mix (HSPPF) and 0.75% steel fiber type S1+ 0.25% CF mix (HSCF)**]**. Fresh properties (workability and fresh density) and hardened properties (oven dry density, compressive strength, splitting tensile strength, flexural strength and thermal conductivity) of HSLWAC were studied.

Generally mono and hybrid fiber reinforced HSLWAC specimens show significant increase in splitting tensile strength and flexural strength in comparison with plain HSLWAC specimen. All hybrid fiber HSLWAC specimens show significant increase in splitting tensile strength and flexural strength compared to concrete specimens reinforced with 1% volume fraction of mono steel fiber type S1. The percentage of increase in splitting tensile strength for hybrid fiber reinforced specimens prepared from HSLWAC mixes HSF1, HSF2, HSPPF and HSCF is 316.6%, 361.1%, 377.7% and 433.3%, while the percentage of increase in flexural strength is 29.43%, 59.89%, 26.56% and 64.58% respectively relative to the plain specimens.

Keywords: Lightweight Concrete, Mono Fibers, Hybrid Fibers, Macro Fiber,

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بعض خواص خرسانة الركام الخفيف الوزن عالية المقاومة والمسلحة بالالياف الهجينة

الخلاصة

يهدف هذا البحث الى دراسة بعض خواص خرسانة الركام خفيف الوزن عالية المقاومة المسلحة بالالياف الاحادية والالياف الهجينة بأبعاد وأشكال مختلفة . الالياف المستخدمة هي، ألياف فولادية معقوفة النهاية بنسبة باعية 100 نوع S1، ألياف فولادية معقوفة النهاية بنسبة باعية 60 نوع S2 ، الياف دقيقة من البولي بروبلين والياف الكاربون الدقيقة. تم أعداد ثمان خلطات خرسانية متضمنة الخلطة المرجعية (بدون ألياف)، ثلاث خلطات مسلحة بنوع واحد من الالياف (0.5% نوع S1 ، 1% نوع S1 ، 0.25% ألياف كاربون) ، اربعة خلطات مسلحة بألياف هجينة مزدوجة [0.5 % نوع S1 + 0.5% نوع S2 (الخلطة HSF1) , 0.75% نوع S1 + 0.25% نوع S2 (الخلطة HSF2) ,% 0.75 نوع S1+ 0.25% الياف البولي بوبلين (الخلطة HSPPF) و 0.75% نوع S1 + 0.25% الياف الكاربون (الخلطة HSCF)]. تم دراسةالخواص الطرية للخرسانة (قابلية التشغيل والكثافة الطرية) وخواص الخرسانة في الحالة الصلبة (الكثافة الجافة ، مقاومة الأنضغاط ،مقاومة شد الانثناء ، مقاومة شد الأنشطار والموصلية الحرارية).

بصورة عامة اظهرت نماذج خرسانة الركام خفيف الوزن المسلحة بالالياف الاحادية والالياف الهجينة زيادة ملحوظة بمقاومة الشد الانشطاري وشد الانثناء مقارنة مع نماذج الخرسانة غي المسلحة بالالياف. اظهرت جميع نمادج خرسانة الركام خفيف الوزن عالية المقاومة الحاوية على خليط الالياف الفولاذية نوع S1 مع الالياف الفولاذية نوع S2 زيادة في مقاومة شد الأنثناء والشد الأنشطاري مقارنة مع الخلطة الخرسانية المسلحة بنسبة حجمية 1 % بالألياف الفولاذية المنفردة نوع S1 . كانت نسبة الزيادة في مقاومة الشد الأنشطاري للنماذج المسلحة بالألياف الهجينة والمهيئة من الخلطات HSF1 ، HSF2 ، HSPPF و HSCF هي 316.6٪، 361.1٪، 377.7٪ و 433.3٪ على التوالي بينما كانت نسبة الزيادة في مقاومة الأنثناء 6.88٪، 32.04٪، 4.52٪ و 35.91٪ على التوالي مقارنة مع النماذج غير المسلحة بالألياف .

INTRODUCTION

Lightweight concrete has many advantages in comparison with normal weight concrete such as lower density, higher strength weight ratio which leads to savings in concrete member size, reinforcement, formwork and scaffolding , foundation costs as well as the savings derived from the reduced cost of transport and erection, in addition it has lower coefficient of thermal conductivity [1, 2, 3]. Brittle nature of lightweight aggregate (LWA) reduces the tensile and flexural strength of lightweight aggregate concrete (LWAC). The brittleness of LWAC can be overcome by utilizing fibers. The recent technological development in a wide variety of fibers has been creating new opportunities in the improvement of fiber reinforced cementitious composite materials. The strategy often adopted in the design of these materials is based on the utilization of fibers of different nature in the same composite. This strategy aims to design composite with improved tensile response by taking advantage of the combined contribution of all types of fibers of different nature with distinct geometrical and material which has been reported to improve the material properties of fiber reinforced cementitious composites [4]. Many researchers studied the properties of LWAC reinforced with mono (single) fibers [5, 6, 7] but very little works have been done to investigate the properties of hybrid fiber reinforced lightweight concrete. No detailed studies are found on the properties of hybrid fiber reinforced high strength lightweight concrete containing local porcelinite as lightweight aggregate.

Chen and Lui [8] investigated the contribution of hybrid fibers to the workability, mechanical properties (compressive, splitting tensile strength, shrinkage and toughness index) of manufactured expanded clay lightweight concrete. Fiber reinforced lightweight concrete specimens divided to six groups ;three groups reinforced with single fiber (steel, carbon and polypropylene fibers) with volume fraction 1%, the other three groups were reinforced with two types of fibers (hybrid fibers) with volume fraction 0.5%for each type of fibers (0.5% steel-0.5% carbon, 0.5% polypropylene- 0.5% steel and 0.5% polypropylene-0.5% carbon). All combinations of different types of fibers resulted in an increase in strength and toughness index, among which carbon- steel fibers combination provides the best effects, i.e., a 27.6% increase in the compressive strength, 38.3% of increase in the splitting tensile strength and lowest brittleness.

Daneti and Wee [9] studied the behavior of high-strength lightweight aggregate concrete reinforced with mono and hybrid fibers. This investigation presents the segregation resistance, compressive and tensile strength, flexural toughness, stress–strain behavior, shrinkage and water absorption of LWAC with and without hybrid fibers. Two types of steel fibers (macro and micro) and micro polypropylene (pp) fiber were used. Control (without fiber), mono macro steel fiber, double hybrid

(macro steel + pp) and triple hybrid fiber (macro steel + micro steel+ pp) reinforced concrete were casted. The volume fraction of the total fiber was kept constant at 0.60% for all mixes. Lightweight aggregate concrete with hybrid fibers has shown superior performance to lightweight aggregate concrete with mono fibers in terms of flexural toughness, post-crack strength and durability.

The aim of this research is to study some properties of hybrid fiber reinforced LWAC prepared from porcilinate as locally LWA.

EXPERIMENTAL PROGRAM

Materials

Cement

The cement used in this work was ordinary Portland cement (Type I). It is produced by United Cement Company (MAS) Al-Sulaymaniyah / Iraq. Chemical composition and physical properties of cement used throughout this research indicate that the adopted cement satisfies the requirements of the Iraqi Specification No.5/1984.

Fine Aggregate

Al-Ekhaider natural sand of maximum size 4.75mm was used as fine aggregate. Its gradation lies in zone (2). The results show that sand grading; physical properties and sulfate content were within the requirements of the Iraqi Specification No.45/1984.

Coarse Aggregate

Local natural porcelinate stone was used as a coarse aggregate. The stone were crushed manually to small pieces then screened on standard sieve series (12.5mm, 9.5 mm and 4.75mm), the maximum size of aggregate was 9.5mm. The aggregate prepared with grading which conforms to ASTM C330-05 Specifications. The aggregate was washed with water in order to remove the dust associated with crushing process of porcelinite stone and then spread inside the laboratory to have saturated surface dry (SSD) condition.

Admixtures

Two types of concrete admixtures were used in this work:

a) Superplasticizer

A superplasticizer commercially known as **GLENIUM 51** was used throughout this work as a high range water reducing agent (sulphonated melamine and naphthalene formaldehyde type F). The dosage recommended by the manufacturer is 0.5-1.6 liters/100kg of cementations material. This type of admixture conforms to the ASTM C494-05 type F.

b) Silica Fume

Silica fume used in this investigation is commercially known as **MEYCO** from the Chemical Company **BASF**. The chemical composition and physical requirements show that the silica fume conforms to the chemical and physical requirements of ASTM C1240 Specifications.

Fibers

Four types of fiber were used in this work

a) Macro hooked steel fiber with 50 mm in length and 0.5 mm in diameter (aspect ratio, l/d = 100), type S1, with ultimate tensile strength for individual fibers of 1180 MPa and density 7800kg/m^3.

b) Macro hooked steel fibers with 30 mm in length and 0.5 mm in diameter (aspect ratio, l/d = 60), type S2 with ultimate tensile strength for individual fibers of 1180 MPa and density 7800kg/m^3

c) Micro polypropylene fiber (PP) with 12mm in length, 18 micron in diameter (aspect ratio l/d= 677) and minimum tensile strength 350 MPa.

d) Micro carbon fiber (CF) (5mm in length and 7µm in diameter) with tensile strength 4300 N/mm^2.

MIXING OF CONCRETE

The mixing process was performed in a pan type mixer of 0.1m^3 capacity. The interior surface of the mixer was cleaned and moistened before placing the materials. Initially, the silica fume and cement were mixed in dry state for about three minutes to disperse the silica fume particles throughout the cement particles, and then the sand and aggregates were added and mixed for two minutes. Seventy percent of the required amount of water was added to the mixer and mixed for about one minute, while thirty percent of the mixing water was added to the HRWRA. The solution was well stirred before used and then added gradually; the whole constituents were mixed for further two minutes. The mixer was stopped and mixing was continued manually especially for the portions not reached by the blades of the mixer. The mixer then operated for three minutes to attain reasonable fluidity. Fibers were uniformly distributed into the mix in three minutes, and then the mixing process continued for additional two minutes. In total, the mixing of one batch requires approximately 15 minutes ensuring uniform distribution of fibers.

CONCRETE MIXES

Eight HSLWAC mixes were prepared in this investigation; these mixes were classified to three groups as follows**:**

1. **Group1**: Plain concrete mix without fiber (0F).

2. Group2: Three HSLWAC with different mono fiber including, Concrete mix reinforced with macro hooked steel fiber with aspect ratio 100 and volume fraction 0.5 % mix (0.5SF1), Concrete mix reinforced with macro hooked steel fiber with aspect ratio 100 and volume fraction 0.5 % mix (0.5SF1), Concrete mix reinforced with macro hooked steel fiber with aspect ratio 100 and volume fraction 1 % mix (1SF1) and Concrete mix reinforced with micro CF with volume fraction 0.25% mix (0.25CF).

3. Group3: Four HSLWAC with hybrid fiber including:

- Concrete mix reinforced with a combination of macro steel fiber with aspect ratio of 100 and 0.5% volume fraction + macro steel fiber with aspect ratio of 60 and 0.5 % volume fraction (mix HSF1).
- Concrete mix reinforced with a combination of macro steel fiber with aspect ratio of 100 and 0.75% volume fraction + macro steel fiber with aspect ratio of 60 and 0.25% volume fraction (mix HSF2).
- Concrete mix containing a combination of macro steel fiber with aspect ratio of 100 and 0.75% volume fraction + micro PP with 0.25% volume fraction (mix HSPPF).
- Concrete mix containing a combination of macro steel fiber with aspect ratio of 100 and 0.75% +micro CF 0.25 % volume fraction (mix HSCF).

CASTING AND CURING OF SPECIMENS

Before casting, all molds were well cleaned and their internal surfaces were lightly oiled. All molds were filled with the concrete mix in layers and compacted by an external table vibrator according to the specification for each specimen type. The top surface of the moulds was leveled and the specimens were covered with nylon sheets to prevent the loss of moisture. After 24 hours, the specimens were demolded, marked and then cured by being completely immersed in water until the time of testing, at age of 28 days.

EXPERMINTAL TESTS

A number of experimental tests were carried out to study some properties of fiber reinforced HSLWAC. These tests are as following:

- Slump test according to ASTM C-143.
- Fresh density test according to ASTM C 138M-01.
- Oven dry density test according to ASTM C 567-05a (using cylinders of 150× 300 mm).
- Compressive strength test according to ASTM C 39 (using cylinders of 100×200 mm).
- Compressive strength test according to B.S. 1881 (using cubes of 100 mm).
- Splitting tensile strength test according to ASTM C496–04 (using cylinders of 100×200 mm).
- Flexural tensile strength test according to ASTM C 1609M–12 (using 100×100×400 mm prisms).

- Thermal conductivity using Quick Thermal Conductivity Meter (QTM-500) shown in Fig.(1) (using 100 × 50 × 20 mm prisms). This apparatus can measure the thermal conductivity by hot wire method. Two specimens were prepared, dried in oven at temperature of 110±5 ^{0}C for 24 hours. For each specimen the test was repeated three times and three values of thermal conductivity were recorded with standard deviation not more than 3% and the average value was calculated. The average value of thermal conductivity was then recorded for the two specimens.

RESULTS AND DISCUSSIONS

Selection of Mix Proportions for High Strength LWAC

Reference concrete mix was designed in accordance with ACI 211.2 to obtain a minimum compressive strength of 20MPa at 28 days without any admixtures. The mix proportions were 1: 1.35: 0.87(cement: sand: aggregate) by weight with w/c ratio of 0.44 to obtain a slump of 90±5 mm with cement content 520 kg/m^3. Several trial mixes were carried out in order to select the optimum dosage of superplasticizer and silica fume. The superplasticizer has been used to reduce the w/c ratio and maintain the same workability of the reference mix (90±5 mm slump) which causes increase in the strength of LWAC. This is attributed to the mode of action of the superplasticizer that is when a surfactant with great number of an ionic polar group in hydrocarbon chain is added to cement–water system, these surfactants impart strong negative charge with high repulsing effect, which helps to lower the surface tension of the surrounding water and makes the cement particles hydrophilic (water attracting) for greatly enhancing the fluidity of the system [10]. The results indicate that the optimum dosage of HRWRA is 1 liter per 100 kg. Three dosages of silica fume (5%, 8%, and10%) as partial replacement of cement weight were used. The inclusion of silica fume in HALWAC mix as a partial replacement by weight of cement improves the compressive strength. This can be explained by the mechanism of silica fume in concrete including, pore-size refinement and matrix densification, reaction with free-lime, and cement paste–aggregate interfacial refinement [11]. The optimum dosage of silica fume is 5% as partial replacement by weight of cement. The percentage increase in compressive strength is 13% relative to the reference mix (without silica fume). This is because when the silica fume percentage in the concrete is increased gradually, it reaches a point called an optimum point, where the silica fume content is exactly required for reacting with the present calcium hydroxide, therefore, the excess silica fume added beyond this limit remains as it is and does not act as a binder; hence it will cause a reduction in strength [12]. The selected HSLWAC has mix proportion of 1:1.35:0.87 (cement: sand: aggregate.) by weight with w/c ratio of 0.29, HRWRA 1 liter per 100 kg and 5% SF as replacement by weight of cement. The compressive strength and oven dry density of the selected mix are 41.2N/mm^2 and 1930kg/m^3 respectively at 28 day age.

FRESH PROPERTIES

Workability

The workability of fresh LWAC before the addition of fibers was elevated by slump test (90 ± 5). High strength lightweight aggregate concrete with and without hybrid fibers was produced easily without any visible fiber balling. All HSLWAC with fibers had lower workability than plain HSLWAC (mix 0F) by 12-30 mm as shown in Table (1). This is because fibers can form a network structure in concrete, which can effectively restrain the segregation of lightweight aggregates. Due to larger surface area than that of aggregates, fibers need to adsorb a lot of cement paste to wrap around, which increases the viscosity of the mixture [8]. It can be observed that for mono fibers, as the steel fiber content increases from 0.5% to 1%, the workability of HSLWAC decreases. Carbon fibers with volume fraction of 0.25% caused higher reduction in workability of HSLWAC. Hybrid fiber concrete mixes show slightly better slump in comparison with HSLWAC mix containing 1% volume fraction of mono steel fiber type S1 fiber.

Fresh Density

The fresh densities of HSLWAC are listed in Table (1). The results show that the PP and CF fibers have less effect on the density of concrete specimens when these fibers are used in hybrid fibers HSLWAC mixes, (HSPPF mix and HSCF mix) relative to HSLWAC mix which contains 1% macro steel fiber type S1 (mix 1SF). This is because non-metallic fibers are much lighter than steel fiber. The density of carbon and polypropylene fiber is approximately 80% and 88% less than that of steel fiber respectively [8]. The concrete density is mainly affected by incorporation of steel fibers compared to mix without fibers. This is clearly due to the high specific gravity of steel fibers. The highest increase in fresh density was recorded for hybrid fiber HSLWAC mixes HSF1 and HSF2 by about 10.1% and 10.3% respectively relative to reference mix (without fibers).

HARDENED PROPERTIS

Oven Dry Density

Oven dry density of HSLWAC mixes prepared in this investigation is shown in Table (1) and Fig. (2).The results show that adding steel fibers to LWAC increases its density. This is because this fiber has high specific gravity. The results show that usually a higher dosage of steel fibers causes heavier LWAC. In order to reduce the density of steel fiber LWAC, low fiber content (1% by volume or less), with or without other types of fibers that do not significantly affect the density (e.g. polypropylene etc.) should be used in LWAC [13].

Hybrid HSLWAC mixes containing a combination of steel- carbon (0.75% S1+ 0.25% CF) or steel – polypropylene fibers (0.75% S1+0.25% pp) show densities less than that containing mono steel fiber with volume fraction of 1%. This is attributed to the low density of carbon and polypropylene fiber. It can be concluded that in structural LWAC instead of using a high volume fraction of steel fiber, a combination of low volume fraction of steel fiber with a non-metallic fiber (hybrid fiber) can be used.

Compressive Strength

The compressive strength results of different HSLWAC studied in this investigation are shown in Table (1) and Fig. (3). The results indicate that the inclusion of mono steel fiber type S1with volume fraction of 0.5% slightly improves the cube and cylinder compressive strength by about 1.96% and 1.5% respectively as compared with plain concrete (without fibers). It was found that the dispersion of fibers in concrete mix becomes very difficult when fiber volume fraction is further increased to 1% and concrete may not be fully compacted, thus the compressive strength of concrete reduces relative to the plain concrete. Among the three concrete mixes containing mono fiber, carbon fibers show the highest compressive strength of about 7.1% and 9.7% for cube and cylinder compressive strength respectively in comparison with plain specimens. This is obvious because the short fibers reinforced the mortar phase at micro crack stages and enhanced the response during crack initiation. References found that the incorporation of a very nominal percentage of carbon fibers into a mortar mixture produces strong and durable composite that leads to the produce of smart material properties [10]. The comparison between HSLWAC mix with volume fraction of 1% macro steel fiber type S1(1SF) and mixes with hybrid fiber (HSF1, HSF2, HSPPF and HSCF) indicates that the use of low volume fraction of steel fiber type S2 (0.5% and 0.25%), micro polypropylene fibers (0.25%) and micro carbon fibers (0.25%) as partial replacement to steel fibers type S1 increases the cube compressive strength by about 2.4%, 10.4%, %, 7.2% and 19.2%, while cylinder compressive strength increases by about 9.9%,17.1%, 16% and 24% respectively . This is due to the fact that hybrid fibers with different sizes and types would offer different restraint conditions. Furthermore, this condition can be attributed to the improvement in the mechanical bond strength when the fibers both have the ability to delay the micro- crack formation and arrest their propagation afterward up to a certain extent [14, 15]. Hybrid fibers of HSLWAC specimens with 0.75% volume fraction of macro steel fiber type S1 and 0.25% volume fraction of carbon fiber show the highest improvement in compressive strength. This is because, in comparison with longer and high specific gravity fibers, shorter and low specific gravity are more efficient in delaying cracks owing to the high specific contact surface of non metallic fibers [16]. The inclusion of two types of macro steel fibers in HSLWAC with volume fraction 0.5% for each (mix HSF1), shows reduction in compressive strength in comparison with plain mix (mix 0F). This is due to the defects such as voids and honeycombs which can be form during placing of high volume fraction of steel fibers as a result of improper consolidation [17].

Splitting Tensile Strength

Generally the results in Table (2) and Fig.(4) indicate that the inclusion of fibers in HSLWAC significantly improves the splitting tensile strength for both mono and hybrid fiber concrete specimens relative to the plain specimens (without fiber). The percentage increase in splitting tensile strength for HSLWAC mixes containing mono steel fiber type S1with volume fraction 0.5%, 1% and 0.25% carbon fiber is 388.9%, 300% and 344.41% respectively relative to the plain specimens. This is attributed to the mechanism of fibers in arresting crack progression and the improvement of bond between fibers and matrix due to the extra dense calcium silicate hydrate gel obtained from silica fume addition [18].

The comparison between splitting tensile strength values of HSLWAC mix containing mono steel fiber type S1with volume fraction of 1% and the hybrid fiber mixes HSF1, HSF2, HSPPF and HSCF, shows that the percentage of increase in splitting tensile strength of hybrid fiber HSLWAC is about 4.17%, 15.27%, 19.4, 33% respectively. Similar to the case of compressive strength, steel-carbon fibers mix (HSCF) shows the highest splitting tensile strength relative to all fibrous HSLWAC mixes (with mono or hybrid fiber). This is attributed to the synergy phenomenon of hybrid fibers, short fibers can bridge microcracks more efficiently, because they are very thin and their number in concrete is much higher than that of the long thick fibers, for the same fiber volume quantity. As the microcracks grow and join into larger macrocracks, the long hooked-end fibers become more and more active in crack bridging. In this way, primarily the ductility and the tensile strength can be improved. Long fibers can therefore provide a stable post-peak response, while short fibers will be less and less active because they are being more and more pulled out, as the crack width increases [19].

Splitting failure characteristics of HSLWAC completely change with presents of fibers. Non fibrous concrete specimens suddenly failed in a brittle manner and separated into two parts; all samples of mono and hybrid fibrous HSLWAC consist of two parts still connected by fibers bridging the major crack. A reduction in crack width was observed in hybrid fibers HSLWAC which significantly contributed to the reduction in overall crack area.

Flexural Strength

The flexural strength test results for all HSLWAC mixes are presented in Table (2) and Fig. (5).The results show that the inclusion of fibers increases the flexural strength in mono and hybrid fiber mixes relative to plain mix. The percentages of increase in modulus of rupture for mono fiber HSLWAC containing volume fraction 0.5%, 1% of steel fiber type S1 and 0.25% carbon fiber are 52.37%, 29.52% and 60.64% respectively compared to the plain specimens. The reason for this improvement in modulus of rupture is that after matrix cracking, the fibers will carry the load that the concrete sustained until cracking by interfacial bond between the fibers and the matrix. Therefore, the fibers resist the propagation of cracks and do not fail suddenly, which causes an increase in load carrying capacity [20]. The flexural performance of fiber reinforced concrete can be improved by blending two or three different fibers together in a matrix, because these different fibers play a role at two different levels, material and structural, according to the type, length and diameter of fibers [21].

The comparison between flexural strength values for HSLWAC specimens containing 1% volume fraction of steel fiber type S1(mix 1SF) and hybrid fiber specimens HSF1, HSF2, HSPPF and HSCF shows that the percentage of increase in flexural strength for hybrid fiber HSLWAC specimens is 6.88%, 32.04%, 4.52% and 35.91% respectively. It can be observed that HSLWAC specimens containing a combination of steel and polypropylene fibers (mix HSPPF) shows the lowest percentage increase in modulus of rupture relative to mono steel fiber mix 1SF. This is attributed to the lower tensile strength of polypropylene fibers and also the weaker bonding between polypropylene fibers and the cement matrix [22]. The combination of steel and carbon fibers (mix HSCF) shows the highest percentage increase in modulus of rupture relative to 1SF mix. This is because carbon fibers are strong and stiff and they can blunt and arrest micro-cracks before they coalesce into macro cracks leading to fracture [23].

Plain HSLWAC exhibited brittle failure under flexural with the specimen being separated into two pieces. Fibrous high strength lightweight aggregate concrete mix with carbon fiber content 0.25% shows the same behavior. This is due to the lower elastic modulus of the carbon fiber. Other fibrous HSLWAC specimens were not separated into two parts and still connected by fibers bridging the major crack. Straight and wider cracks were observed in HSLWAC reinforced with mono fibers compared with HSLWAC reinforced with hybrid fibers.

Thermal Conductivity

Thermal conductivity of concrete is increase with the increase of the moisture content. For this reason all HSLWAC specimens were oven dried before thermal conductivity test was carried out. Deminboga et al. concluded that using silica fume as a partial replacement by weight of Portland cement is effective for decreasing the thermal conductivity of LWAC due to the relatively low conductivity of this admixture [24]. Replacing normal aggregate with pore lightweight aggregate increases the total porosity of concrete which affects the thermal conductivity. Thermal conductivity of normal weight concrete is in the range of 1.98-2.94 W/(m.K) according to different aggregate[25]. Thermal conductivity of plain HSLWAC prepared in this investigation is 1.3961 w/(m.K) which is lower than that of normal weight concrete, this means that using HSLWAC improves the thermal performance of the buildings. The low unit weight and thermal conductivity combined with the ability to cast in any desired shape enable this structural lightweight concrete to be a suitable material for casting different structural members. Table (2) and Fig.(6) show that the inclusion of fibers reduces the thermal conductivity compared to the plain HSLWAC. This may be due to the formation of air voids in the microstructure of fiber reinforced HSLWAC which reduces the thermal conductivity of concrete. It can be concluded that the inclusion of fibers in LWAC not only enhances its structural behavior but also improves its thermal performance.

CONCLUSIONS

Based on the results of this study, the following conclusions can be drawn:

1. The addition of steel fibers to LWAC increases its oven dry density. Hybrid HSLWAC mixes containing a combination of steel- carbon fibers (0.75% steel fiber type S1+ 0.25% carbon fiber) or steel – polypropylene fibers (0.75% steel fiber type S1+0.25% pp) show densities less than that containing 1% volume fraction of mono steel fiber type S1.
2. The use of low volume fraction of macro steel fiber type S2 (0.25%), micro polypropylene fibers (0.25%) and micro carbon fibers (0.25%) as partial replacement of macro steel fibers type S1 increases the cube compressive strength by about 3.51%, 4.12%, % and 10.41% , while cylinder compressive strength increases by about 3%, 5.75%, and 10.25% respectively relative to the plain specimens.
3. The inclusion of fibers in HSLWAC significantly improves the splitting tensile strength for both mono and hybrid fiber reinforced specimens relative to the plain specimens (without fiber). Hybrid fiber reinforced HSLWAC specimens show significant increase in splitting tensile strength. The percentage of increase in splitting tensile strength for HSLWAC specimens' prepared from HSF1, HSF2, HSPPF and HSCF mixes is about 316.6%, 361.11%, 377.7% and 433.3% respectively relative to the plain specimens.
4. The inclusion of fibers increases the flexural strength in mono and hybrid fiber specimens relative to the plain specimens. the percentage of increase in flexural tensile

strength for hybrid HSLWAC specimens' prepared from mixes HSF1, HSF2, HSPPF and HSCF is 29.43%, 59.43%, 26.56% and 64.58% respectively relative to the plain specimens.

5. Hybrid fiber HSLWAC specimens containing the combination of 0.75% volume fraction of macro steel fiber with aspect ratio 100 (type S1) and 0.25% volume fraction micro carbon fiber shows the best performance in terms of compressive strength, splitting tensile strength and flexural strength relative to the plain specimens. The percentage of increase is about 10.4%, 433.3% and 64.58% respectively relative to the plain specimens.

6. The inclusion of fibers in LWAC not only enhances its structural behavior but also improves its thermal performance.

Figure (1) Thermal Conductivity Test Set-up

Table (1): Some Properties of Fibrous HSLWAC

Mix Symbol	**Slump (mm)**	**Fresh Density (kg/m^3)**	**Oven Dry Density at 28 days (kg/m^3)**	**Cube compressive Strength*(fcu)* at 28 days (MPa)**	**Cylinder Compressive Strength *(f 'c)* at 28 days (MPa)**
0F	90	2060	**1930**	41.30	40.00
0.5SF (0.5%S1)	78	2186.70	1987	42.10	40.60
1SF (1%S1)	65	2198.50	2033	38.95	35.50
0.25CF (0.25%CF)	60	2120.00	1944	44.23	43.85
HSF1 (0.5%S1+0.5%S2)	68	2267.65	2078	39.90	38.20
HSF2 (0.75%S1+0.25%S2)	65	2270.50	2070	42.75	41.20
HSPPF (0.75%S1+0.25%PP)	62	2195.69	1998	43.00	42.30
HSCF (0.75S1+0.25CF)	66	2198.39	2009	45.60	44.10

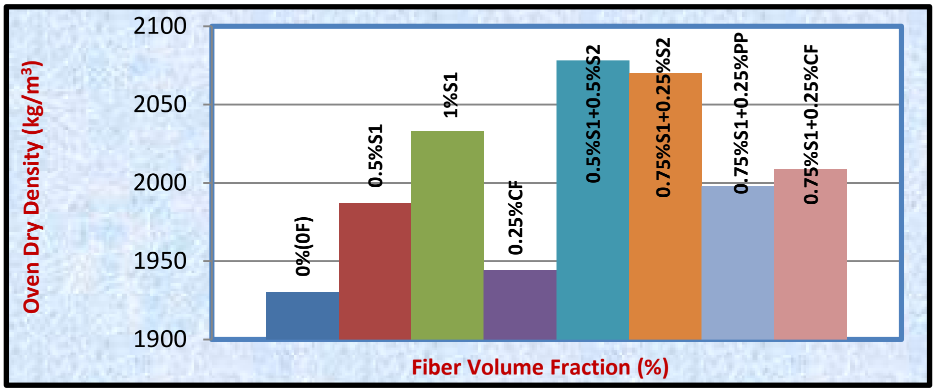


Figure (2) oven dry density of fibrous HSLWAC

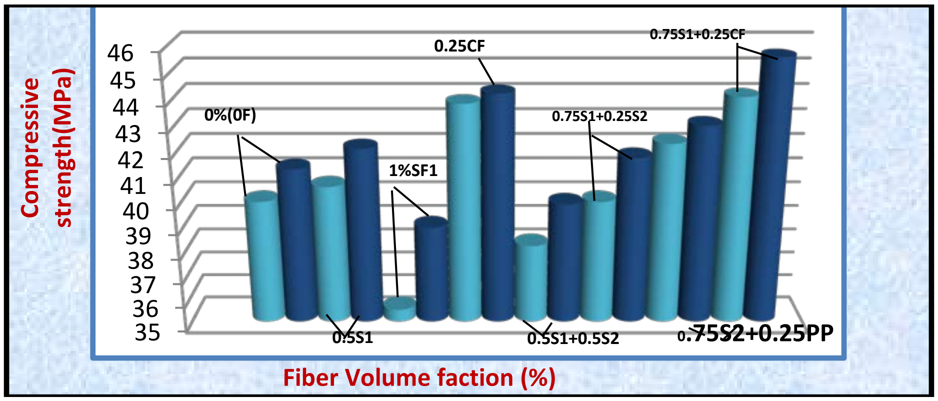
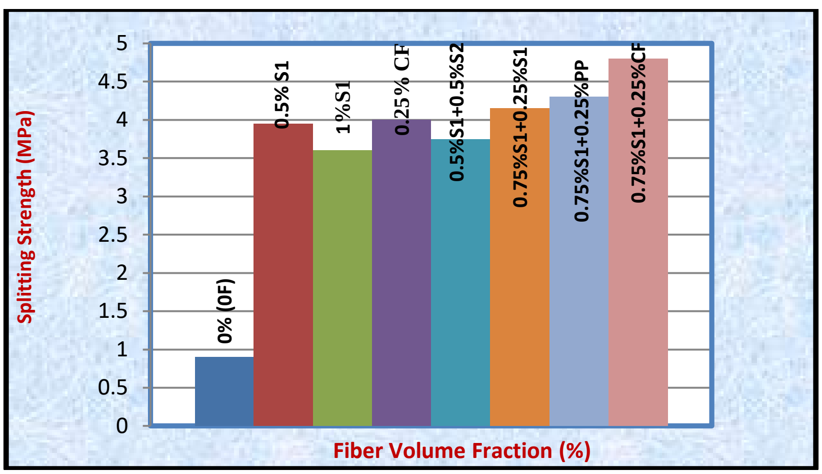


Figure (3) Cube and Cylinder Compressive strength of Different Fibrous HSLWAC Mixes



cube compressive strength
cylinder compressive strength

Figure (4) Splitting Tensile Strength of Fiber reinforced

HSLWAC Mixes

Table (2) Tensile strength and thermal conductivity of Fiber Reinforced HSLWAC Mixes

Mix Symbol	Splitting Tensile Strength (f *sp)* at 28 days (MPa*)*	Flexural Strength (f r) At 28 days (MPa)	Thermal Conductivity (λc) W/(m.K)*
0F	0.90	3.84	1.3961
0.5SF	3.95	5.47	1.0244
1SF	3.60	4.65	1.1622
0.25CF	4.00	5.76	1.2461
HSF1	3.75	4.97	1.1297
HSF2	4.15	6.14	1.3686
HSPPF	4.30	4.86	1.1328
HSCF	4.80	6.32	1.0952

*Thermal conductivity of porcelinate stone is 1.3708 W/ (m.K)

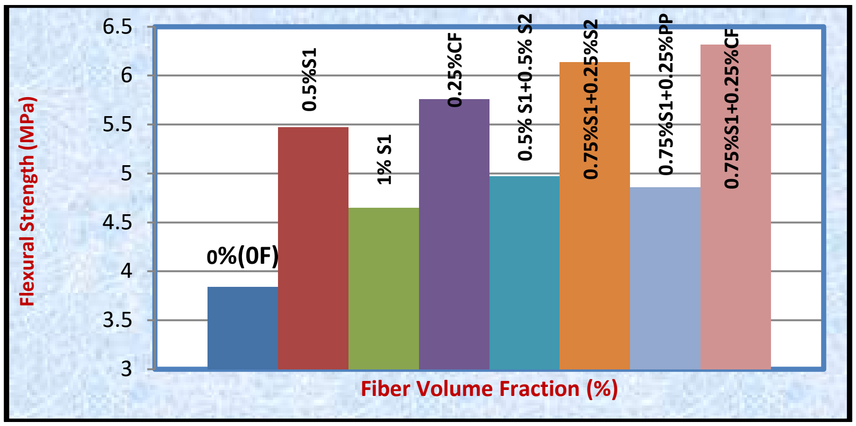


Figure (5) Flexural Strength of Fibrous HSLWAC Mixes

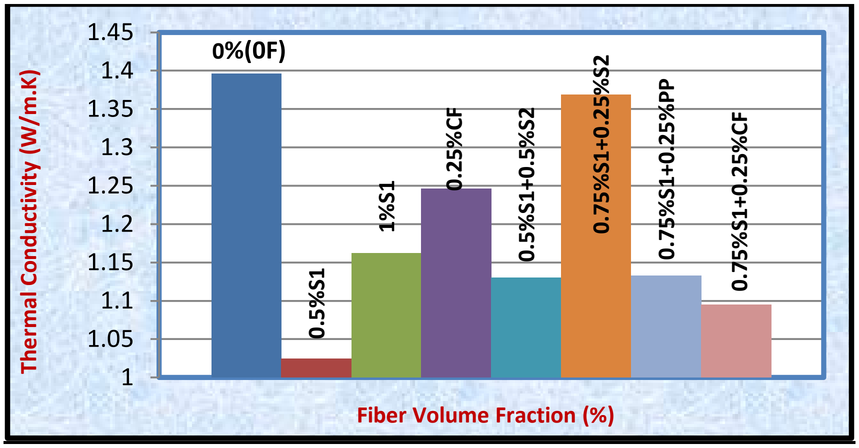


Figure (6) Thermal Conductivity of Different Fibrous HSLWAC Mixe

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