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Mechanical Properties of Aerated-Polystyrene Concrete Reinforced by Polymer Fibers

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ABSTRACT

This study aims to produce high performance aerated-expanded polystyrene lightweight concrete by reinforcing it with chopped carbon fibers and polypropylene fibers that satisfy structural criteria with good thermal and sound insulation, to be used in modern concrete construction. The methodology was carried out to produce high performance lightweight concrete with low density by preparing reference lightweight concrete, as well as eight aerated-polystyrene lightweight concrete mixtures reinforced by chopped carbon fibers or polypropylene fibers with different ratios of 0.3%, 0.6%, 0.9%, 1.2% by volumes of concrete. The mechanical properties such as dry density, ultrasonic pulse velocity, thermal conductivity, acoustic impedance, and scanning electron microscopy were studied and compared with the reference concrete without fibers. The results showed the maximum compressive strength of aerated-polystyrene lightweight concrete reinforced by chopped carbon fibers and polypropylene fibers were 56 MPa and 48.5 MPa respectively with a maximum density of 1835 kg/m^3. The originality of this research was to develop aerated-polystyrene lightweight concrete with two types of polymer fibers. The first type was chopped carbon fibers as expensive fibers, while the second type was polypropylene fibers as cheap fibers.

1. INTRODUCTION

Global environmental change is driving humans to look for new materials, technologies, and solutions that are environmentally friendly and sustainable [1-4]. The process used to produce construction materials, the kinds of raw materials utilized, and the energy consumed in that process all have an impact on the environment [5]. Therefore, the focus has been on producing a new kind of concrete and reducing the dead load of construction [6]. Environmentally friendly buildings embrace healthier and sustainable options through their efficient utilization of energy, water, and materials [5]. The primary objective of adopting sustainable practices in building design and construction is to improve the overall quality of life [7]. The trend toward sustainability and environmentally friendly building materials has led to an increase in the use of Lightweight Concrete (LWC) in various engineering applications [8]. Reducing the density of concrete provides great benefits, such as low self-weight which constitutes an important part of the design loads in concrete buildings. As known normal concrete has a density ranging between 2240-2400 kg/m^3, while LWC must not exceed 1920 kg/m^3 with compressive strength exceeding 17 MPa to use for structural purposes [9]. The LWC has received increased attention in the civil engineering and construction industry recently due to its low density and multiple benefits [10]. The low density of LWC makes it appropriate for applications that need lightweight loads, such as high-rise buildings, bridges, and floating floors [11]. In addition, LWC exhibits excellent sound and thermal insulation properties, as well as improving energy efficiency and sound comfort in buildings [12]. LWC has several challenges including high brittleness, low compressive strength, low flexural strength, low impact strength, poor fracture toughness, and poor crack propagation resistance. There are three methods for producing LWC, the first method is to use low apparent specific gravity porous lightweight aggregates, which is known as Lightweight Aggregate Concrete (LWAC). The second method involves creating huge voids inside the mortar or concrete, different names for this kind of concrete include cellular, foamed, aerated, and gas concrete. Finally, by leaving a lot of interstitial spaces in the mix after the fine aggregates have been removed, usually, coarse aggregates of normal weight are used, it is known as no-fines concrete [13, 14]. In general, there are three important types of LWC related to their superior ability in thermal and sound insulation: Aerated concrete, polystyrene concrete, and Aerated-polystyrene beads concrete, aerated concrete is used in different applications [15, 16], which created by the chemical reaction of aluminum powder with calcium hydroxide, which results from the hydration of cement in the presence of water, to produce hydrogen gas, that aerates the mixture, generating small air voids that give the material its cellular property [14, 17]. While, polystyrene concrete is an intriguing type for reducing energy losses within concrete structures [18]. which is produced by adding Expanded Polystyrene (EPS) beads to the concrete mixture, it combines the advantages of inorganic polymer technology with those of lightweight materials such as low density and thermal insulation. EPS is most typically used as a packing material and becomes a waste after the packaging purposes are completed, which has caused major environmental concerns due to its non-decomposing nature [19]. Aerated-Expanded Polystyrene Concrete (A-EPSC) can be created by mixing aerated concrete and expanded polystyrene concrete, producing a homogenous network of air voids that improves thermal and sound abilities with decreasing mechanical properties when compared to conventional concrete [20]. As a result, a method must be found to compensate for the reduction of mechanical properties to apply these mixes for structural elements that need high strength with low density [21].

Fibers are used to improve the properties of concrete in general and the properties of LWC in particular, it is considered an important technique to reduce the weakness in the mechanical properties of LWC [22, 23]. Polymer fibers such as chopped carbon fibers and polypropylene fibers are considered a suitable choice for strengthening LWC due to their flexibility and tensile strength [24]. Chopped carbon fibers are a composite material that usually measures (5-10) µm in diameter and exhibit an important combination of properties such as low density, low thermal expansion, and high elastic modulus that provide superior mechanical behaviour of reinforced concrete despite relatively high production costs [25, 26]. The mechanical properties improve significantly with the increase in the amount or length of carbon fibers [27], while, the failure of concrete reinforced by fibers is mostly caused by forces that exceed the binding force between surfaces [28]. Polypropylene fibers are a thermoplastic polymer with a wide range of uses, that have a low modulus and are commonly used as a reinforcing material to enhance various properties of LWC [29]. polypropylene fibers improved the shrinkage resistance, tensile strength, compressive strength, and flexural properties of LWC as well as played an important role in reducing crack propagation [30-32].

There is a big challenge in improving the strength of aerated-expanded polystyrene concrete by chopped carbon fibers and polypropylene fibers to reach the limit of high strength with maintaining the low density, thermal insulation, and sound insulation of this type of concrete to obtain concrete that could be adopted in structural applications. Some researchers have studied the possibility of developing LWC with chopped carbon fibers and polypropylene fibers. Cunha et al. [26] studied the effect of adding chopped carbon fibers with proportions of 0.2%, 0.4%, and 0.6% by volume of concrete to LWAC. The tests were conducted on the mechanical properties such as flexural strength, modulus of elasticity, tensile stress, and compressive strength. The results presented that adding chopped carbon fibers played an important role in improving all properties of LWC and the density range from 1600 kg/m^3 to 1790 kg/m^3 for all mixtures, the highest compressive strength reached 32 MPa, therefore this type of LWC reinforced by chopped carbon fibers can be adopted and used in structural elements. Furthermore, Sun et al. [23] used chopped carbon fibers with different ratios of 0.5%, 1%, and 1.5% by volume of the concrete to improve the properties of environmentally friendly EPS beads concrete. The tests for LWC involved dry density, splitting tensile strength, compressive strength, and scanning electron microscopy (SEM). The results showed that adding fibers reduced the workability of concrete. The dry density, tensile strength, and compressive strength were optimally increased by 14,172, and 13%, respectively. As a result of adding these fibers, the negative effect resulting from the presence of EPS on the mechanical properties of concrete could be reduced.

Demir et al. [33] studied the effect of chopped carbon fiber lengths on the compressive strength, flexural strength, density, thermal conductivity, and shrinkage of AC. Different lengths of fibers were used 4, 6, and 12 mm, The results revealed that the 12 mm fiber reinforcement in Aerated Concrete (AC) performed the best in comparison with the other lengths, improving compressive strength by 10.36%, flexural strength by 31.48%, and thermal conductivity by 4.23% whereas decreasing shrinkage ratio by 51.47%. Moreover, Mohammed et al. [34] used different lengths 5, 20, and 30 mm of chopped carbon fiber to study the mechanical properties of pumice LWC. Four groups were prepared and tested with ratios of 0.5 and 1% by volume of concrete. The experimental results showed that adding chopped carbon fibers with a length of 20 or 30 mm was more efficient in improving flexural strength and splitting tensile strength. Furthermore, Ahmed et al. [35] studied the effect of adding chopped carbon fibers with ratios of 0.5%, 1%, and 1.5% by volume of concrete on the mechanical properties of LWAC. The results showed that adding chopped carbon fibers improves the mechanical properties of control LWAC, which had a compressive strength of 19.31 MPa, flexural strength of 3.5 MPa, and splitting tensile strength of 1.7 MPa. The best properties were found when adding 1% of the fibers, which had a compressive strength of 30 MPa, a flexural strength was 4.88 MPa, and a splitting tensile strength was 3.14 MPa, with increasing percentages of 30%, 35%, and 58% respectively, compared to specimens without fibers, while using 1.5% of chopped carbon fibers dropped the mechanical properties of LWC. Babavalian et al. [30] investigated the effect of adding polypropylene fibers with ratios of 0.1%, 0.3%, and 0.5% on compressive strength and splitting tensile strength of EPS concrete by tested cylindrical specimens. The results showed that 0.5% of added fibers improved the compressive strength by 35.5% to cover the decline that occurred in compressive strength as a result of the presence of EPS. While, the improvements in compressive strength and splitting tensile strength were 12.1% and 10% respectively for 0.1% of polypropylene fibers. Moreover, Bonakdar et al. [36] studied the effect of adding polypropylene fibers with ratios of 0.2, 0.3, and 0.4% on the mechanical properties of AC. The experimental results showed that the highest content of fibers indicated a compressive strength of 3 MPa, a ductile strength of 0.56 MPa, a flexural stiffness of more than 25 Nm, and a thermal conductivity of 0.15 W/km^2. The authors recommended to use this type of LWC for non-structural purposes. In addition, Chaudhary et al. [37] investigated the influence of adding polypropylene fibers on the flexural behaviour and failure shape of lightweight foam concrete with ratios of 0.6%, 0.8%, 1.2%, 1.4%, and 1.6%. It was observed that the effect of the presence of fibers on the failure mode in the pre-peak stage was higher than in the post-peak stage, and the flexural strength and peak ductility increased with increasing content of fibers. It was noticed that the LWC specimens without fibers appeared brittle and had a clean fracture shape, in contrast to the fixed and serrated shape that appeared in LWC specimens reinforced by polypropylene fibers. with the improvements in the results for reinforced specimens, these fibers absorb a large portion of the internal stresses in the LWC specimens during the tests.

Yang et al. [38] studied the impact of short polypropylene fibers on the compression strength of lightweight foamed concrete. The results showed that the LWC's elasticity modulus, peak strength, and ultimate linear strength increased by 208%, 42%, and 71%, respectively. At the same time, the failure mode of specimens with fibers changes from brittle to plastic. This study showed that using short synthetic fibers enhanced compressive capacity, which is considered an effective technique for achieving better mechanical strengths for LWC. Moreover, Bagherzadeh et al. [39] used polypropylene fibers with ratios of 0.15% and 0.35% by weight of cement to LWAC and studied the mechanical properties of reinforced LWC by comparing them with the specimens without fibers at the age of 28 days. As a result, the 0.35% ratio increases flexural strength by 30.1% and splitting tensile strength by 27%.

2. RESEARCH SIGNIFICANCE

This research adds new knowledge to aerated-polystyrene lightweight concrete that can be used in structural buildings by developing this concrete that was unable to obtain high strength limit for structural LWC with good sound and thermal insulation, by reinforcing it with chopped carbon fibers and polypropylene fibers, with proportions 0.3%, 0.6%, 0.9%, and 1.2% by volume of concrete for each kind of fibers, to produce high performance aerated-polystyrene lightweight concrete reinforced by synthetic polymer fibers.

3. RAW MATERIALS

Table 1. Main compounds of cement

Oxides Compositions	Weight%
Tri-Calcium Silicate (C_3S)	53.84
Di- Calcium Silicate (C_2S)	16.41
Tri-Calcium Aluminate (C_3A)	7.64
Tetra-Calcium Aluminate-Ferrite (C_4AF)	11.79

Figure 1. Chopped carbon fibers

Figure 2. Polypropylene fibers

Table 2. Properties of fibers used from the product datasheet

Type of Fibers	Chopped Carbon Fibers	Polypropylene Fibers
Diameter (μm)	10	18
Length (mm)	12	12
Density (kg/m^3)	1820	910
Tensile strength (N/mm^2)	4900	300 - 400
Modules of elasticity (N/mm^2)	230000	~ 4000

A-EPSC is produced from a mixture of ordinary Portland cement according to IQS NO.5 [40] which have main compounds as shown in Table 1, fine sand with a maximum size of 600 μm according to ASTM C33 [41], silica fume as cementitious material is a very fine powder between 1-60 μm according to ASTM C1240 [42], limestone powder locally mentioned as Al-Gubra with a maximum size of 300 μm according to the European Federation Dedicated to Specialist Construction Chemicals and Concrete Systems [43], water used according to IQS 1703 [44], a superplasticizer from Sika company according to ASTM C494 Types E [45], EPS beads were added, the beads were spherical, small, and hollow with 3-5 mm diameters, AL produced from aluminum scrap waste resulting from local industrial factories is used in this study, which is ground into a powder passing through a sieve of size 150 μm, chopped carbon fibers as shown in Figure 1, and polypropylene fibers as shown in Figure 2. Table 2 presents the properties of the fibers that were obtained from the product datasheet.

4. MIX PROPORTION

Table 3. LWC propitiation for 1 m^3 [46]

Material	Quantity kg/m^3
Cement	800
Fine sand	800
Silica fume (10% of cement)	80
Limestone (30% of cement)	240
Aluminum powder	1.6
Polystyrene beads	0.8
Superplasticizer (3% of cementitious materials)	26.4
Water (water to cement = 0.27)	216

Table 4. LWC codes and proportion of fibers

Code	Group	Chopped Carbon Fibers	Polypropylene Fibers
LAE1	Reference concrete	0	0
LAE1-C1	Group 1	0.3	0
LAE1-C2		0.6	0
LAE1-C3		0.9	0
LAE1-C4		1.2	0
LAE1-P1	Group 2	0	0.3
LAE1-P2		0	0.6
LAE1-P3		0	0.9
LAE1-P4		0	1.2

The raw materials proportions for every mixture in this study, which was created using the trial-mix method to stabilize the basic components, are displayed in Table 3 [46]. Nine mixtures were designed based on the required variables of chopped carbon fibers with ratios 0.3%, 0.6%, 0.9%, and 1.2% by volume of concrete and polypropylene fibers with ratios of 0.3%, 0.6%, 0.9%, and 1.2% by volume of concrete. Furthermore, all mixtures have an acceptable range of workability even with the constant water to cement ratio. Table 4 displays the codes of the LWC mixtures and the ratios of fibers for each mix in this study. Figure 3 shows the process of adding chopped carbon fibers and polypropylene fibers to fresh concrete in the rotary mixer.

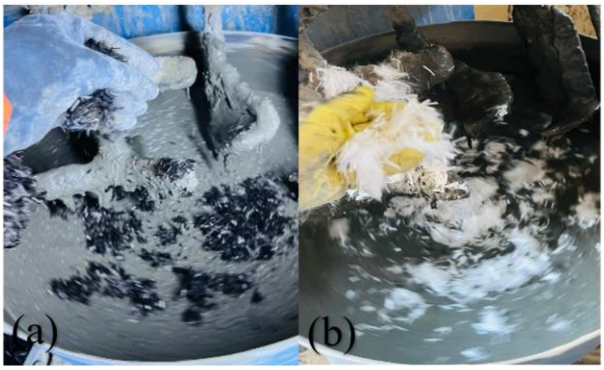

Figure 3. Process of adding fibers, (a) chopped carbon, (b) polypropylene

5. TESTING TECHNIQUES

Mechanical properties were calculated using destructive and non-destructive testing on nine LWC mixtures including varying quantities of chopped carbon fibers and polypropylene fibers, as shown in Figure 4. For each test, three specimens of cubes 100×100×100 mm, cylinders 100×200 mm, cylinders 150×300 mm, and prisms 100×100×400 mm were created for a total of 108 specimens as shown in Figure 5. They were tested to measure the density, compressive strength, flexural tensile strength, splitting tensile strength, static modulus of elasticity, dynamic modulus of elasticity, Ultrasonic Pulse Velocity (UPV), scanning electron microscope, thermal conductivity, and acoustic impedance. After casting, the specimens were left to air dry for 24 hours before being removed from the molds and put in a water tank for 28 days at 23±2℃. After that, the specimens were prepared for testing.

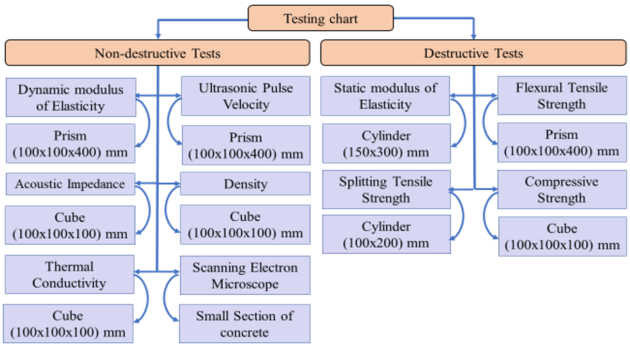

Figure 4. Destructive and non-destructive tests diagram

Figure 5. Concrete specimens before testing

6. RESULTS AND DISCUSSION

This section will explain all of the data shown in Table 5, which were taken from experimental tests.

Table 5. Test results of the concrete specimens

Code	Group No.	Density (kg/m^3)	Compressive Strength (MPa)	Flexural Strength (MPa)	Splitting Strength (MPa)	Static Modulus (GPa)	Dynamic Modulus (GPa)	Ultrasonic Pulse Velocity (m/s)	Acoustic Impedance ×10^6 (kg/m^2.sec*)	Thermal Conductivity (W/(m.k))
LAE1	Reference	1768	38.5	3.79	4.11	24.6	24.3	2780	4.91	0.358
LAE1-C1	Group1	1783	50.1	6.05	6.13	29.3	28.2	2790	4.97	0.379
LAE1-C2		1800	51.8	6.58	6.62	29.9	29	2950	5.31	0.394
LAE1-C3		1824	54.3	7.94	8.05	30.5	29.8	3024	5.51	0.418
LAE1-C4		1835	56	8.1	8.15	30.9	30.1	3075	5.64	0.44
LAE1-P1	Group 2	1776	43.2	4.67	4.51	27.3	26.3	2784	4.94	0.358
LAE1-P2		1795	45.9	5.93	6.14	28	26.9	2807	5.03	0.364
LAE1-P3		1813	48.5	6.55	6.72	28.8	27.5	2841	5.15	0.385
LAE1-P4		1819	47.2	6.07	6.24	28.1	27.1	2843	5.17	0.387

*Acoustic Impedance = Density×UPV

6.1 Density

Table 5 shows the results of the density test of different LWC specimens according to ASTM C567-05 [47] for the two groups of A-EPSC reinforced by polymer fibers as well as the reference group. A-EPSC had expansion property resulted from the chemical reaction of aluminum powder that led to producing air voids. LAE1 had a density of 1768 kg/m^3, and it slightly increased with the addition of chopped carbon fibers and polypropylene fibers due to the restricted expansion of fresh concrete. The results of LAE1-C1, LAE1-C2, LAE1-C3, LAE1-C4, LAE1-P1, LAE1-P2, LAE1-P3, and LAE1-P4 increased by 0.8%, 1.8%, 3.1%, 3.7%, 0.4%, 1.5%, 2.5%, 2.8% respectively, compared to LAE1. All results met Structural Lightweight Concrete (SLWC) requirements, as the density of A-EPSC reinforced with chopped carbon fibers ranged between 1783-1835 kg/m^3, and polypropylene fibers ranged between 1776-1819 kg/m^3. Figure 6(a) shows the expanded parts of fresh concrete, Figure 6(b) shows the process of removing the expanded parts to obtain the basic dimensions, and Figure 6(c) shows the density test.

Figure 6. A-EPSC specimens: (a) expanded fresh concrete, (b) removing the expanded parts, (c) density test

6.2 Compressive strength

The results of compressive strength of A-EPSC at age 28 days according to BS EN 12390-3 [48] are shown in Table 5. The compressive strength for reference concrete LAE1 was 38.5 MPa, and it increased with the addition of chopped carbon fibers and polypropylene fibers. The specimens of LAE1-C1, LAE1-C2, LAE1-C3, and LAE1-C4 had a compressive strength of 51.8, 55.4, 56.7, and 56.9 MPa with increases of 34.5%, 43.8%, 47.2%, and 47.7% respectively compared to LAE1, this increase caused by arresting the growth of cracks due to the bonds between the chopped carbon fibers and concrete matrix. Furthermore, the specimens of LAE1-P1, LAE1-P2, LAE1-P3, and LAE1-P4 had a compressive strength of 48.5, 52.7, 55.6, and 49.3 MPa with increases of 25.9%, 36.8%, 44.4%, and 28% respectively compared to LAE1, this increase resulted by preventing and arresting the growth of cracks due to the flexibility and homogenous distribution of polypropylene fibers in the mixture. The relationship between compressive strength and density for all specimens is shown in Figure 7. It was noticed that all A-EPSC specimens satisfied the criteria of SLWC strength, which is required to be higher than 17 MPa at the age of 28 days [9, 49]. Furthermore, it became clear that A-EPSC reinforced by chopped carbon fibers and polypropylene fibers reached the limit of high-performance LWC, which exceeded 41 MPa [9, 50]. The compressive strength test for A-EPSC specimens is displayed in Figure 8.

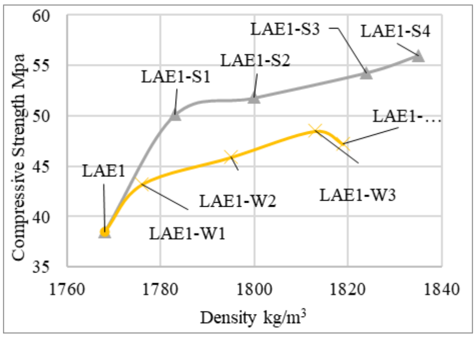

Figure 7. The relationship between compressive strength and density

Figure 8. Compressive strength test for A-EPSC specimens

6.3 Flexural strength

The results of the flexural strength of A-EPSC reinforced by different ratios of chopped carbon fibers and polypropylene fibers at 28 days according to ASTM C78/C78M [51] are shown in Table 5 and Figure 9. LAE1, LAE1-C1, LAE1-C2, LAE1-C3, LAE1-C4, LAE1-P1, LAE1-P2, LAE1-P3, and LAE1-P4 had flexural strength of 3.79, 6.05, 6.58, 7.94, 8.1, 4.67, 5.93, 6.55, and 6.07 MPa. Adding chopped carbon and polypropylene fibers improved flexural strength by forming bridges that transmitted internal stresses, redistributing them regularly in the concrete matrix, and reducing the width of cracks. In general, the flexural strength for LAE1-C1, LAE1-C2, LAE1-C3, LAE1-C4, LAE1-P1, LAE1-P2, LAE1-P3, and LAE1-P4 increased by 59.6%, 73.6%, 109.4%, 113.7%, 23.2%, 56.4%, 72.8%, and 60.1% respectively compared to LAE1. Figure 10 shows the flexural strength test in addition to the failure shape.

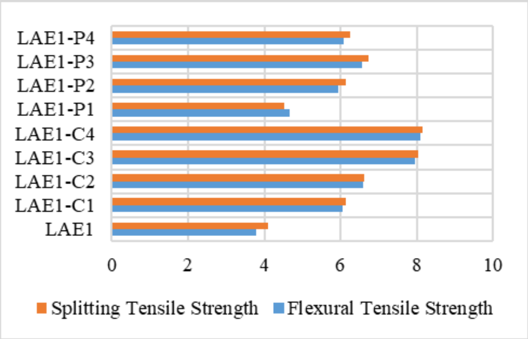

Figure 9. Flexural strength and splitting tensile strength of A-EPSC specimens

Figure 10. Flexural strength test and failure for A-EPSC specimens

6.4 Splitting tensile strength

Table 5 and Figure 9 show the results of splitting tensile strength according to ASTM C 496/C496M [52] for specimens reinforced by chopped carbon fibers and polypropylene fibers in addition to the specimens without fibers. LAE1-C1, LAE1-C2, LAE1-C3, LAE1-C4, LAE1-P1, LAE1-P2, LAE1-P3, and LAE1-P4 had a splitting strength of 6.13, 6.62, 8.05, 8.15, 4.51, 6.14, 6.72, and 6.24 MPa with increases by 49.1%, 61%, 95.8%, 95.2%, 9.7%, 49.3%, 63.5%, and 51.5% respectively compared to LAE1, as a result of the presence of fibers that decreased the brittleness of A-EPSC, arrested growth of cracks, and prevented sudden collapse, due to the significant connection between the fibers and the concrete matrix. Figure 11 shows the splitting tensile strength test for A-EPSC specimens.

Figure 11. Splitting tensile strength test for A-EPSC specimens

6.5 Modulus of elasticity

Table 5 shows the results of modules of elasticity for A-EPSC reinforced by chopped carbon fibers and polypropylene fibers in addition to the reference specimens. Figure 12 shows the static and dynamic modulus of elasticity tests.

Figure 12. Static and dynamic modulus of elasticity tests

6.5.1 Static modulus of elasticity

Figure 13 shows the results of the static modulus of elasticity test that was carried out on a cylinder of 150×300 mm, (chord to 0.4f) according to ASTM C469 [53]. The results of LAE1-C1, LAE1-C2, LAE1-C3, LAE1-C4, LAE1-P1, LAE1-P2, LAE1-P3, and LAE1-P4 increased by 19.1%, 21.5%, 23.9%, 25.6%, 10.9%, 13.8%, 17%, and 14.2% respectively, compared with LAE1. The increase in the modules of elasticity of A-EPSC was due to the uniform distribution of stresses in the specimens after adding chopped carbon fibers and polypropylene fibers, in addition to the good bonds of these fibers with the concrete matrix.

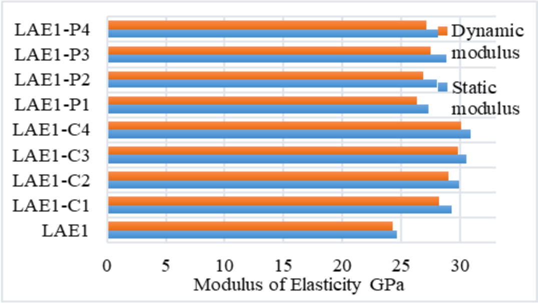

Figure 13. Static and dynamic modulus of elasticity of A-EPSC specimens

6.5.2 Dynamic modulus of elasticity

The results of the dynamic modulus of elasticity test which is a kind of non-destructive test that was carried out on cylinders of 150×300 mm are shown in Figure 13, which was done by using the fundamental resonant frequency for specimens of different dimensions and shapes [54]. This standard test based on measuring the basic bending, lengthening, and torsion frequencies of cylindrical and prismatic specimens according to ASTM C215 [54]. The dynamic modulus of elasticity of LAE1-C1, LAE1-C2, LAE1-C3, LAE1-C4, LAE1-P1, LAE1-P2, LAE1-P3, and LAE1-P4 increased by 16%, 19.3%, 22.3%, 23.8%, 8.2%, 10.6%, 13.1%, and 11.5% respectively, compared with LAE1. It can be observed that there was a slight difference between the results of the dynamic and static modulus of elasticity. Thus, it is possible to trust the results of a non-destructive test to estimate the modulus of elasticity for A-EPSC reinforced by chopped carbon fibers and polypropylene fibers.

6.6 Ultrasonic pulse velocity

Conventional LWC usually has a velocity of less than 3000 m/s and it maintains good properties even if reaches the limit of 4190 m/s [55]. Table 5 and Figure 14 show UPV results and the relationship between UPV and density for A-EPSC specimens. The velocity of LAE1-C1, LAE1-C2, LAE1-C3, LAE1-C4, LAE1-P1, LAE1-P2, LAE1-P3, and LAE1-P4 slightly increased by 0.35%, 6.11%, 8.77%, 10.61%, 0.14%, 0.97%, 2.19%, and 2.26% respectively, compared with LAE1. Polymer fibers didn't significantly affect the wave velocity due to their limited transfer abilities. This slight increase in UPV is usually due to the increase in concrete density, which affects the velocity of wave transfer. Figure 15 shows the process of the UPV test.

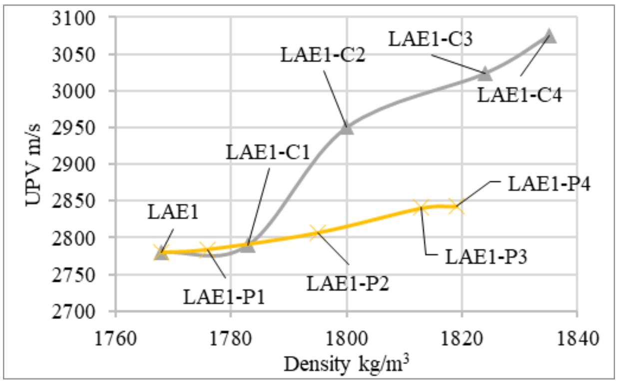

Figure 14. The relationship between UPV and density

Figure 15. The test of UPV for A-EPSC specimens

6.7 Thermal conductivity

The results of the thermal conductivity of A-EPSC reinforced by chopped carbon fibers and polypropylene fibers in addition to the reference group are shown in Table 5 and Figure 16 according to ASTM C1113/C1113M [56]. The thermal conductivity was determined using a hot wire technique (using a platinum resistance thermometer) as shown in Figure 17. The results showed that the thermal conductivity slightly increased when adding chopped carbon fibers and polypropylene fibers due to the increase in the density for each specimen. The thermal conductivity of LAE1-C1, LAE1-C2, LAE1-C3, LAE1-C4, LAE1-P1, LAE1-P2, LAE1-P3, and LAE1-P4 were 0.379, 0.394, 0.418, 0.44, 0.36, 0.364, 0.385, and 0.387 W/ (m.k) with slight increases by 5.8%, 10%, 16.7%, 22.9%, 0.5%, 1.6%, 7.5%, and 8.1% respectively compared by LAE1. It was noted that adding chopped carbon fibers to A-EPSC was more effective than adding polypropylene fibers. In general, the presence of EPS beads reduced thermal conductivity, because the incorporation of EPS presented a large number of closed pore structures into the LWC, which increased the resistance to heat transfer that transmitted to the surface of the specimens, which occurred first in the solid phase, then it contacted the internal pores. Part of the heat moved through the air pores, but this increased the path of heat transfer, which increased heat consumption, another part transmitted faster through the metal fibers in different directions depending on the direction of the fibers' spread. Finally, the remaining part passed into the material as a gaseous phase and thus affected the thermal insulation of the concrete.

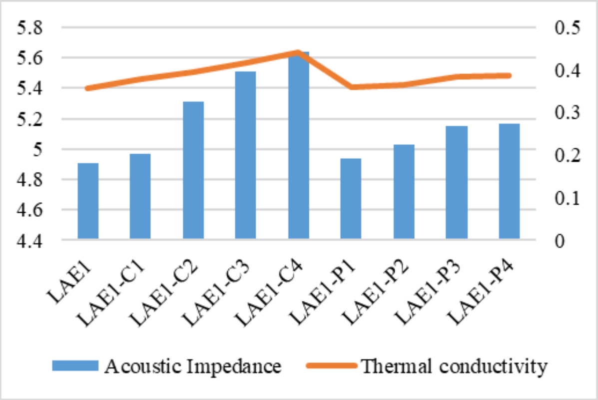

Figure 16. Thermal conductivity and acoustic impedance for A-EPSC specimens

Figure 17. Thermal conductivity test of A-EPSC specimens

6.8 Acoustic impedance

The results of the test slightly increased by changes in concrete density resulting from the increase of the content of the two types of fibers as shown in Table 5 and Figure 16, which were obtained by using UPV multiplied by the density of the A-EPSC specimens [34]. The increase in results of acoustic impedance for LAE1-C1, LAE1-C2, LAE1-C3, LAE1-C4, LAE1-P1, LAE1-P2, LAE1-P3, and LAE1-P4 were 1.2%, 8.1%, 12.2%, 14.8%, 0.6%, 2.4%, 4.8%, and 5.2% respectively compared to LAE1.

6.9 Scanning electron microscopy

SEM test was used to discover the microstructure of the A-EPSC specimens as shown in Figure 18(a-g). All SEM photos used in this study were taken after the compressive strength test. The reference group LAE1 had small semi-homogeneous spherical pores with an average diameter of 275 µm generated by chemical reaction of aluminum waste powder, and EPS beads had an average diameter of 3.7 mm, both formed a homogeneous network of air voids as shown in section (a) and the microstructure of EPS beads in section (b). It could be inferred that there was a good connection in the interfacial zone between the A-EPSC matrix and chopped carbon fibers while polyproline fibers showed weak bonding. It was noted from sections (c-d) that chopped carbon fibers were like bridges transmitting stresses across the air voids and preventing the accumulation of these stresses in the air voids from generating a weak point leading to the collapse of the specimen. The diameter of chopped carbon fiber was 10 µm as shown in section (e). Nonetheless, it was observed a weak bonding between polyproline fibers and matrix of A-EPSC as shown in section (f). Moreover, the diameter of polyproline fibers was 30 µm, and the cracks could transfer through the polyproline fibers zone as shown in section (g). Finally, all of the above reasons had a significant effect on the mechanical properties of A-EPSC.

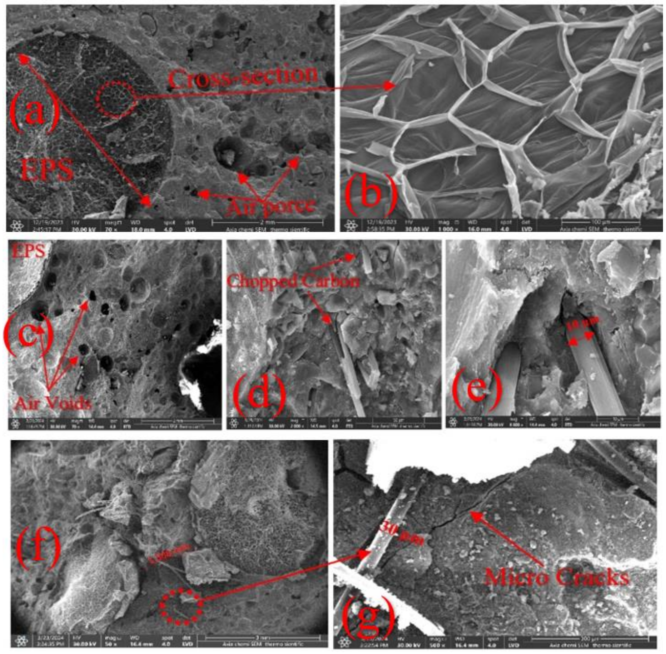

Figure 18. Microstructure of (a) LAE1, (b) EBS beads, (c) A-EPSC reinforced by chopped carbon fibers, (d) chopped carbon fibers, (e) diameter of chopped carbon fibers, (f) A-EPSC reinforced by polypropylene fibers, and (g) polypropylene fibers

7. CONCLUSIONS AND RECOMMENDED

The importance of environmental sustainability through improving the properties of A-EPSC must be considered. This experimental study was conducted to investigate the effect of chopped carbon fibers and polypropylene fibers on the mechanical properties of A-EPSC as a novel study since it hasn't been studied how these types of fibers affect A-EPSC to obtain High-performance properties, unlike previous studies that did not reach this limit. The most important conclusions for this experimental work are:

1. This study showed the specimens with chopped carbon fibers had a density ranged from 1783 to 1835 Kg/m^3 and specimens with polypropylene fiber had a density ranged from 1776 to 1819 Kg/m^3, while the reference specimen had a density of 1768 Kg/m^3. All the specimens still meet the criteria of SLWC density which should be less than 1920 Kg/m^3.
2. The highest compressive strength in A-EPSC reinforced by chopped carbon fibers reached 56 MPa with an increase of 45.4% compared with LAE1, and reached 48.5 MPa in LAE1-P3 with an increase of 25.9% compared with LAE1. All the results achieved the limit of high-performance LWC that must have compressive strength exceeding 41 MPa, thus, this concrete can be adopted as sustainable concrete in various structural applications that need high compressive strength in addition to reducing the total weight of the structure.
3. Flexural strength, splitting tensile strength, static modulus of elasticity, and dynamic modulus of elasticity reached maximum increase by 113.7%, 98.2%, 25.6%, and 23.8% at 1.2% of chopped carbon fibers, and 72.8%, 63.5%, 17%, and 11.5% at 0.9% of polypropylene fibers.
4. LAE1-C4 with a ratio of 1.2% of chopped carbon, the increase of thermal conductivity and acoustic impedance were 22.9% and 14.8% respectively compared with LAE1, similar LAE1-P4 at the same ratio of polypropylene fibers increased the thermal conductivity and acoustic impedance by 8.1% and 5.2% respectively compared with LAE1. It should be noted that all extracted results stayed within acceptable ranges of SLWC. Thus, this concrete meet customer requirements in terms of thermal and sound insulation.
5. SEM test showed that chopped carbon fibers effectively connected with the A-EPSC matrix, prevented crack growth, and arrested internal cracks, in addition to reducing crack width. The best distribution of chopped carbon fibers was observed at a ratio of 1.2% that redistributed the stress within the concrete matrix regularly, as well as prevented sudden collapse (reduced brittleness), and increased its ability to absorb stresses until failure.
6. SEM test showed that polypropylene fibers had a slight effect on the properties of A-EPSC, which took the curvature of EPS beads and formed a fibrous tissue surrounding the EPS beads, which reduced the weakness that resulted from EPS beads. It was also noticed that when the ratio of the fibers reached 1.2%, polypropylene fibers formed weak points which caused the failure of specimens. Also, it was not observed that the increase in fiber content had any effect on the spread or number of voids generated within the concrete matrix

The authors recommended conducting a comprehensive study on the effect of adding micro-steel fibers and copper waste fibers to compare the results for A-EPSC reinforced with each type of fiber for the same volumetric proportions and select the optimal type and ratio in terms of mechanical properties, thermal insulation, sound insulation, and cost.

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