Journal of Engineering and Sustainable Development
Vol. 29, No. 06, November 2025
https://jeasd.uomustansiriyah.edu.iq/index.php/jeasd
ISSN 2520-0917
Research Article
https://doi.org/10.31272/jeasd.2969

Characteristics of Novel Lightweight Concrete Strengthened by Waste Copper Fiber and Steel Fiber

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Article Info

Received	**28/08/2024**
Revised	**02/09/2025**
Accepted	**02/09/2025**

Abstract

Due to concerns about global warming, the construction sector seeks an alternative to traditional concrete. This work aims to develop a sustainable, high-performance aerated polystyrene lightweight concrete strengthened with micro-steel fiber and waste copper fiber, designed to meet sustainability standards for sound and thermal insulation, while achieving the high compressive strength required for structural lightweight concrete. The methodology was carried out through the formulation of baseline lightweight concrete, in addition to eight lightweight concrete mixtures strengthened by micro-steel fiber and waste copper fiber with proportions of (0.3, 0.6, 0.9, and 1.2) % by concrete volume for each kind. The mechanical characteristics, dry density, and thermal conductivity were determined for aerated polystyrene lightweight concrete with and without fibers. Destructive and nondestructive tests, such as ultrasonic pulse velocity, scanning electron microscopy, and acoustic impedance, were used to obtain the required properties of concrete. The final results displayed that the maximum compressive strength, flexural strength, and splitting tensile strength of aerated-polystyrene concrete strengthened by micro-steel fiber and waste copper fiber stayed (56.9 and 55.9) MPa, (9.02 and 8.41) MPa, and (8.85 and 8.53) MPa, correspondingly, with an ultimate dry density of 1917 Kg/m^3.

Keywords: High-performance Lightweight Concrete, Mechanical Properties, Micro-steel Fibers, Waste Copper Fibers

1. Introduction

Environmental variation forces humans everywhere to seek novel materials, technologies, and solutions that are more sustainable and environmentally friendly [1]-[3]. Therefore, the focus has been on the production of concrete and decreasing the total weight of concrete structures [4]. Sustainability criteria aim to protect natural resources by reducing their use and energy consumption, thereby providing a peaceful life for future generations [5]. The environment is affected by the methods of producing building materials, the types of raw materials used, and associated energy consumption, and to mitigate the expected adverse effects, it is necessary to move towards sustainable and locally sourced building materials [6].

Lightweight Concrete (LWC) is considered an important material in the construction of modern concrete structures because of its economic and practical advantages, on the other hand, it's a versatile construction material that offers a wide range of technological, economic, and environmental advantages, and it is expected to be an important building material in the coming century [6]. The low density due to air voids is the main advantage of LWC [7]. In the construction of concrete buildings, self-weight accounts for a significant portion of the design loads; therefore, reducing concrete density offers an important advantage [8]. The density of structural LWC must range from 1400 to 1920 kg/m^3, compared to ordinary concrete, which ranges from 2240 to 2400 kg/m^3, and should possess a compressive strength exceeding 17 MPa. [9]-[11]. LWC provides better thermal insulation than ordinary concrete [12]. Due to the requirements of modern technology in producing a green and sustainable concrete system by reducing the cost of energy consumption in heating and cooling operations and obtaining concrete with high-performance properties to meet the structural requirements, it is necessary to produce and develop LWC, in addition to Lightweight concrete faces numerous challenges, such as brittleness, low compressive and flexural strength, poor fracture toughness, and weak resistance to crack propagation [13]. In addition to their excellent characteristics in terms of noise and thermal insulation, Expanded Polystyrene Concrete.

(EPSC), Aerated Concrete (AC) and Aerated-Expanded Polystyrene Concrete (A-EPSC) have been considered significant kinds of LWC [14]-[16].AC is a type of LWC usually used as structural and non-structural elements [17]-[18]. It is formed by a reaction between aluminum powder and calcium hydroxide, which is produced during cement hydration when water is present. This reaction generates a gas of hydrogen, which airs the mix by forming minor air pores, changing the material into typical cellular building [15],[19]. Whereas, EPSC is a type of LWC created by incorporating Expanded Polystyrene (EPS) into the mix. It combines the benefits of inorganic polymer materials with the characteristics of various lightweight materials, such as low density and low thermal conductivity.

Additionally, EPSC can reduce energy loss in buildings [20]. EPS is widely used as a filling material; however, once its packaging function is fulfilled, it becomes waste. Due to its non-biodegradability, this raised significant environmental concerns [21]. A-EPSC can be produced by mixing AC with EPSC to provide a uniform distribution of air pockets, thereby enhancing thermal properties and reducing mechanical properties compared with regular concrete [22]. Therefore, it is necessary to find solutions to offset the decrease in mechanical properties and thus use this kind of concrete with different tenacities [23].

Various types of fiber are incorporated to enhance the overall properties of concrete, particularly LWC, through strong interactions between the fibers and the concrete matrix. This interaction significantly affects the mechanical and physical characteristics of aerated expanded polystyrene concrete (A-EPSC) [24]. The fibers modify tensile and flexural strength, toughness, and impact resistance. Additionally, they help prevent the formation and propagation of cracks, thereby increasing both strength and ductility. LWC reinforced with fibers reduces the total dead weight of structures compared with standard concrete [25]. It. It is also typically used to reduce carbon emissions and to enable fast construction [26]. Steel Fibers (SF) are among the most widely used reinforcement materials for concrete due to their special properties [27]-[28]. SF is available in the market in different lengths and diameters, with tensile strengths ranging from 345 to 3000 MPa and modulus of elasticity ranging from 200 to 210 GPa [29]-[30]. Copper firanging are an artificial metal fiber used to reinforce concrete [31]. Copper fibers are distinguished by their flexibility, high tensile strength, resistance to corrosion, and resistance to chemical degradation, with an elastic modulus of 147 GPa [32]. CF can be easily incorporated into the mixture, as it significantly develops the characteristics. In addition, these fibers enhance impact resistance, making concrete a suitable option for various applications [33]-[34]. There are difficulties in improving the strength of A-EPSC by employing steel fiber and waste-copper fiber to achieve high strength, minimum dry density, and good heat and noise properties, for use in structural applications.

Some researchers conducted studies on LWC reinforced with steel fibers or waste fibers. Yang et al. [35] studied the effect of straight and hooked steel fibers on the characteristics of Lightweight Aggregate Concrete (LWAC). Different kinds of steel fibers were used to produce thirteen LWAC combinations, with volumetric ratios of (0, 0.5, 1, 1.5) %. The analysis demonstrated that the use of hooked-steel fiber significantly enhanced mechanical properties but reduced LWAC workability. In contrast, straight steel fibers had a negligible effect on workability but provided significant improvements in mechanical properties.

Furthermore, Lee and Yang [36] evaluated the impact of micro-steel fibers on the compressive strength and flexural strength of LWAC composed of expanded glass as fine aggregate and expanded clay as coarse aggregate. Twenty-one mixtures were prepared with different fiber contents. The results showed that adding only 0.25% of micro-steel fibers significantly improved the compressive and flexural strengths; moreover, the fibers showed an apparent effect in preventing the growth and spread of cracks.

Selvakumar et al. [37] developed and optimized the properties of AC, which contains fly ash and bottom ash, by using steel fibers. Data demonstrated that fiber enhanced the characteristics of LWC, and reached a density of 1265 kg/m^3, pressure strength, and bending strength of (19.93 and 3.86) MPa. Moreover, Skariah and Mathew [38] used different percentages of steel fibers (0%, 0.25%, 0.5%, 0.75%, and 1%) by volume from the mixture and studied the characteristics of reinforced aerated concrete. The findings for compressive strength and density with various steel fiber ratios ranged from 12 to 17.8 MPa and 1785 to 1900 Kg/m^3, respectively. Compressive strength increased with increasing the percentage of steel fibers up to 0.5 %, after which it decreased. This study recommended that the maximum steel fiber content for developing the mechanical characteristics of AC is 0.5 %. Aldikheeli and Shubber [39] used 1.5 % hooked steel fibers with aspect ratios of 64 and 67 to investigate the physical and mechanical behavior of aerated concrete. Evidence suggested that the LWC reinforced by hooked steel fibers with aspect ratios of 67 had compressive strength of 36 MPa, flexural strength of 6.9 MPa, modulus of elasticity of 16 GPa, and density of 1901kg/m^3. However, the maximum pressure strength and the bending strength were (30.01 and 4.4) MPa, and the modulus of elasticity was 14.1 GPa, and the dry density was 1901kg/m^3 when using fibers with an aspect ratio of 64. This study recommended that increasing the aspect ratio significantly improves the properties of lightweight concrete. In addition, Zheng et al. [40] studied the impact of steel fiber with volumetric proportions of (0, 0.5, 1.5, 2) %. The findings on the mechanical characteristics suggested that adding 2 % of steel fiber with an aspect ratio of 40 to LWAC enhanced the compressive strength by 12 % and the flexural strength by 78 % compared to concrete without fibers. Abdulhussein and Alfeehan [41] examined the influence of waste twisted iron fiber with a volumetric percentage range of 0-2% at 0.5 increments on the AC efficiency. The finding presented that the compressive strength, splitting strength, flexural bending strength, and static modulus increased by (12, 67.5, 134, and 27) %. Moreover, they used nondestructive tests to determine the dynamic modulus. Adding iron fibers increased it by 26%. This study recommended the possibility of using iron waste fibers to improve the mechanical properties of AC, while also considering the risk of iron fiber corrosion. While Hornakova et al. [42] studied the mechanical properties of LWAC when adding waste copper fibers with ratios of (0.5, 1.0, and 1.5) %. The density ranged from 1366.7 to 1484.9 kg/m^3, and the compressive strength ranged from 14.7 to 17.1 MPa. While the values of the dynamic modulus of elasticity ranged from 12.9 to 13.5 GPa, the static modulus of elasticity test ranged from 8.2 to 9.6 GPa, and the splitting tensile strength test ranged from 1.7 to 2.2 MPa. Finally, Horňáková and Lehner [33] conducted a complementary study on the mechanical properties of LWAC reinforced by waste copper fibers with ratios of (0.5, 1.0, and 1.5) %. The authors focused on conducting nondestructive tests and compared the results with those from destructive tests. In addition, they established specific equations to determine the mechanical properties of this type of concrete and recommended using nondestructive methods rather than destructive ones, with additional investigation required.

As an inclusion, there are no previous studies specialized in A-EPSC strengthened with micro-steel fiber and waste copper fiber to produce high-performance A-EPSC. Moreover, the relation between destructive and nondestructive testing is unclear for A-EPSC. As a result, additional research is required to develop A-EPSC for structural applications.

This study will provide new information on A-EPSC that may be employed in structural elements by improving A-EPSC, which failed to meet a high-performance threshold for lightweight concrete used for structural purposes with high acoustic impedance and low thermal conductivity. Steel fiber and waste fiber were used in volumetric ratios of 0.3 %, 0.6 %, 0.9 %, and 1.2 % for the two types of fiber to achieve high-strength A-EPSC strengthened by synthetic or sustainable waste.

2. Research Materials and Method

The types and quantities of raw materials used in this investigation are described in this section, along with the destructive and nondestructive tests.

2.1. Primary Materials

The A-EPSC is created from a combination of regular cement type I based on IQS NO.5 (2019) [43], fine aggregate particles measuring 0.6 mm based on ASTM C-33, (2016) [44], and cementitious material named silica fume, which is a powder with a maximum size of 0.06 mm based on ASTM C-1240, (2015) [45], limestone powder, also known as Al-Gubra, has a size of about 300 µm based on EFDSC (2002) [46], tap water utilized as per IQS-1703[47], a Sika superplasticiser based on ASTM C-494[48] and EPS beads add, EPS were round, tiny, and hollow with diameters of 3-5 mm. Aluminum powder, generated from scrap aluminum and produced locally, is used for experimental work. It is ground into a powder and sieved through a 150 µm. Fig. 1 shows micro-steel fibers, and Fig. 2 shows waste copper fibers that were taken out of damaged electrical device coils. The product datasheet characteristics of micro-steel fiber and waste copper fiber obtained through hands-on testing are shown in Table 1.

Table 1. Characteristics of used fibers

Kind of fibers	Micro-steel Fibers*	Waste Copper fibers
Diameter (mm)	0.2-0.25	0.2-0.25
Length (mm)	12-14	12-14
Aspect Ratio	56-60	56-60
Density (Kg/m^3)	7860	8960
Tensile strength (N/mm^2)	2850	500

* Obtained from the product datasheet.

Figure 1. Micro-steel fibers.

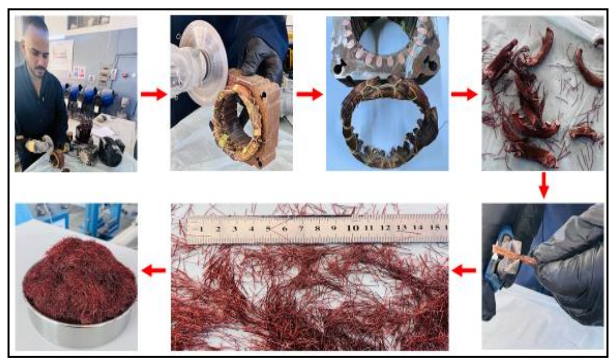

Figure 2. Preparation of waste copper fibers.

2.2. Mixtures Proportions

Table 2 shows the proportions of raw materials for each mixture in this work, obtained by the trial mix method, to achieve a strength design of more than 36 MPa.

Table 2. Lightweight concrete proportion for one cubic meter.

Material	Quantity Kg/m^3
Cement	800
Sand	800
Silica fume	80
Lime stone	240
Aluminum waste powder	1.6
Expanded Polystyrene beads	0.8
Superplasticizer	26.4
Tap water	216

Nine mixes were prepared, focusing on the required parameters of micro-steel fiber and waste copper fiber, each incorporated at volumetric ratios ranging from 0 % to 1.2 % with steps of 0.3 %. It should be noted that all mixes have satisfactory workability despite the fixed w/c. The percentage of fibers in each mixture is shown beside its code in Table 3. Fig. 3 illustrates the procedure of adding micro-steel fiber in section (a) as well as waste copper fibers in section (b) for fresh A-EPSC inside the rotating concrete-mixer.

Table 3. A-EPSC code and proportion of fibers.

Code	Steel Fibers	Waste Copper Fibers
L.AE1	0	0
L.AE1-S1	0.3	0
L.AE1-S2	0.6	0
L.AE1-S3	0.9	0
L.AE1-S4	1.2	0
L.AE1-W1	0	0.3
L.AE1-W2	0	0.6
L.AE1-W3	0	0.9
L.AE1-W4	0	1.2

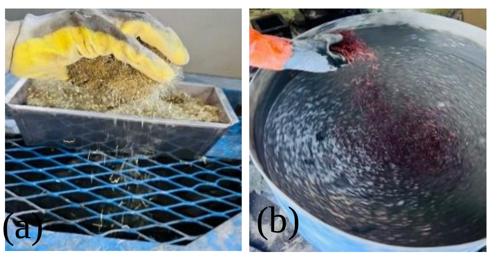

Figure 3. The method for incorporating (a) micro-steel fiber, (b) waste copper fibers.

2.3. Testing Techniques and Preparing Specimens

Destructive and nondestructive tests were used to calculate the mechanical properties, as shown in Fig. 4. The investigation was conducted on nine A-EPSC mixtures (one group for a reference mixture, four groups for mixtures reinforced by waste copper fibers, and four groups for mixtures reinforced by micro-steel fibers). Each mixture had three concrete cubes (100x100x100) mm, cylinders (100x200) mm, cylinders (150x300) mm, and prisms (100x100x400) mm, with a total of 108 specimens as shown in Fig. 5, to obtain thermal conductivity, sound impedance, ultrasonic pulse velocity, scanning electron microscopy, compressive strength, flexural strength, splitting strength, density, static elasticity modulus, and dynamic elasticity modulus. Afterward, the specimens stayed in the molds, covered with nylon to prevent water evaporation, for 24 hours. They were then removed from the molds and placed for curing (28 days at 23±2 °C). Finally, the specimens were available for testing.

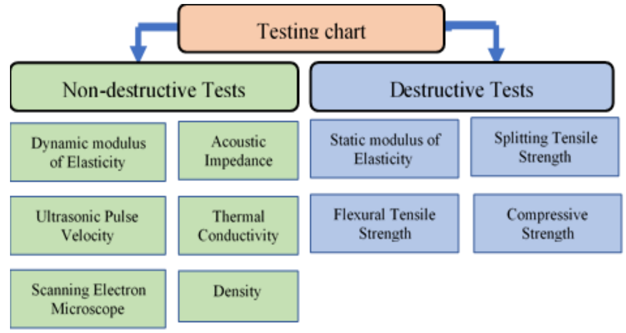

Figure 4. Diagram for destructive and nondestructive testing.

Figure 5. Prepared LWC samples for the tests.

3. Results of Experimental Program

3.1. Density

The dry density test results, conducted based on ASTM C567-05 [49] of various LWC specimens of A-EPSC strengthened with metal fiber, as well as the specimens without fiber, are displayed in Table 4 and Fig. 6. The expanded characteristics of A-EPSC are due to the presence of aluminum waste powder, which generates the pores. The density of L.AE1 was 1768 kg/m^3, and it increased further with the addition of micro-steel fiber and waste copper fiber. The results of L.AE1-S1, L.AE1-S2, L.AE1-S3, L.AE1-S4, L.AE1-W1, L.AE1-W2, L.AE1-W3, and L.AE1-W4 rise by (1.8, 3.9, 6.1, 8, 2.5, 4.1, 6.7, 8.4) %, respectively, compared with L.AE1. All the densities complied with the requirements for Structural Lightweight Concrete (SLWC), with the density of A-EPSC strengthened with micro-steel fiber varying from 1800 to 1910 kg/m^3, and those reinforced with waste copper fiber varying from 1805 to 1917 kg/m^3. Fig. 7 (a) illustrates the removal of the expanded sections of fresh concrete specimens to determine the original dimensions, while Fig. 7 (b) depicts the process of calculating density.

Table 4. Test results for A-EPSC.

Code	Density Kg/m^3	Compressive Strength MPa	Splitting Strength MPa	Flexural 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)
L.AE1	1768	38.5	4.11	3.79	24.6	24.3	2780	4.91	0.358
L.AE1-S1	1800	51.8	6.79	6.72	29.9	28.6	2915	5.24	0.425
L.AE1-S2	1838	55.4	7.71	7.84	30.8	29.4	2990	5.49	0.479
L.AE1-S3	1875	56.7	8.71	8.55	32.9	31.8	3044	5.70	0.534
L.AE1-S4	1910	56.9	8.85	9.02	33.5	32.7	3120	5.95	0.673
L.AE1-W1	1805	48.5	6.37	6.33	28.8	28.1	2856	5.15	0.457
L.AE1-W2	1840	52.7	7.74	7.56	30.4	29	2878	5.29	0.509
L.AE1-W3	1887	55.6	8.42	8.37	32	30.7	2930	5.52	0.567
L.AE1-W4	1917	55.9	8.53	8.41	32.3	31.1	3025	5.79	0.701

*ACOUSTIC IMPEDANCE = DENSITY× UPV

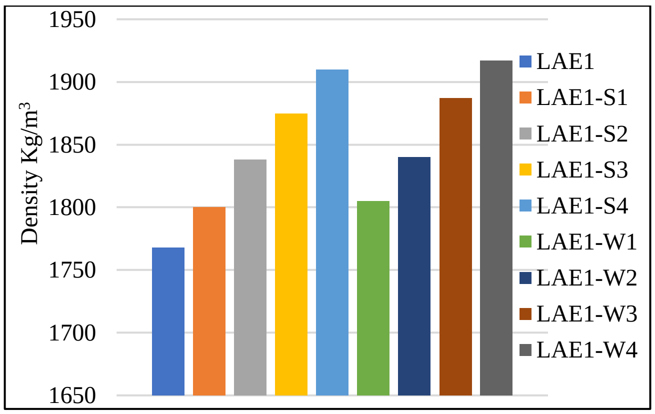

Figure 6. Density of A-EPSC specimens.

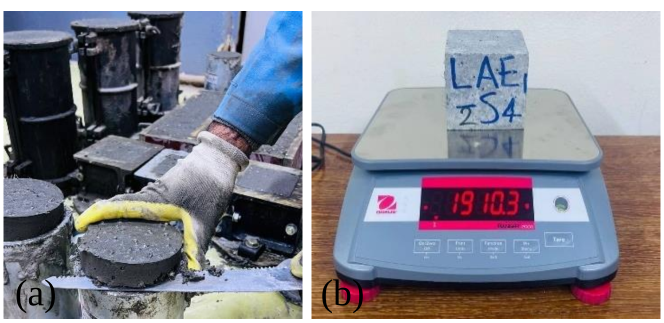

Figure 7. A-EPSC specimens: (a) cutting the extended section, (b) calculating the dry density.

3.2. Compressive Strength

Table 4 presents the A-EPSC's compressive strength at 28 days, per BS EN-12390-3 (2019) [50]. Incorporating micro-steel and waste copper fibers significantly enhanced the ultimate strength of L.AE1, which was initially measured.

38.5 MPa. The specimens of L.AE1-S1, L.AE1-S2, L.AE1-S3, and L.AE1-S4 recorded a strength of (51.8, 55.4, 56.7, and 56.9) MPa with an increment of (34.5, 43.8, 47.2, and 47.7) % respectively when compared to L.AE1. This strength improvement resulted from the arrest of crack propagation, enabled by the strong bonding between the steel fiber and the concrete matrix. Moreover, the specimens of L.AE1-W1, L.AE1-W2, L.AE1-W3, and L.AE1-W4 recorded a strength of (48.5, 52.7, 55.6, and 55.9) MPa with an improvement of (25.9, 36.8, 44.4, and 45.1) % respectively in comparison with L.AE1. This improvement is attributed to the prevention of cracks, resulting from the elasticity and uniform distribution of waste fiber within the mixture. For every specimen, the connection between density and compressive strength is displayed in Fig. 8. All A-EPSC specimens were found to meet the SLWC strength requirements, which state that the specimens must have a strength of greater than 17 MPa at 28 days [9], [11]. Finally, it was observed that A-EPSC strengthened with micro-steel fiber and waste copper fiber met the criteria for high-strength SLWC, exceeding 41 MPa [9]. Fig. 9 shows the test specimens and their failure modes.

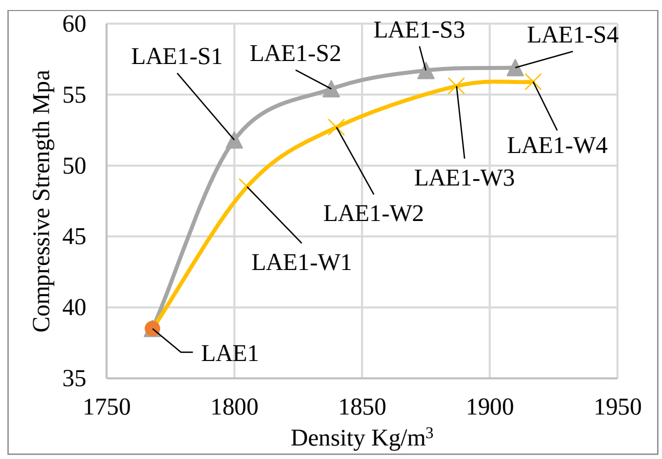

Figure 8. The relationship between compressive strength and density.

Figure 9. Compressive testing of the Cubes sample.

3.3. Flexural Bending Strength

Based on ASTM-C78/C78M (2016) [51], Table 4 and Fig. 10 display the bending strength of specimens with various proportions of micro-steel fiber and waste copper fiber at twenty-eight days. The bending strength for specimens L.AE1, L.AE1-S1, L.AE1-S2, L.AE1-S3, L.AE1-S4, L.AE1-W1, L.AE1-W2, L.AE1-W3, and L.AE1-W4 was (3.79, 6.72, 7.84, 8.55, 9.02, 6.33, 7.56, 8.37, and 8.41) MPa, respectively. The incorporation of micro-steel fiber and waste copper fiber enhanced flexural tensile strength by creating bridges that transfer interior stress, evenly restructure it throughout the concrete matrix, and limit the micro-crack, ultimately improving the flexural resistance of A-EPSC. Overall, the bending strength for L.AE1-S1, L.AE1-S2, L.AE1-S3,

L.AE1-S4, L.AE1-W1, L.AE1-W2, L.AE1-W3, and

L.AE1-W4 improved by (77.3, 106.8, 125.5, 137.9, 67, 99.4, 120.8, and 121.9) %, respectively, in comparison to the mix without fiber. Fig. 11 illustrates the mechanism and failure pattern, highlighting the uniform distribution of fibers throughout the specimen.

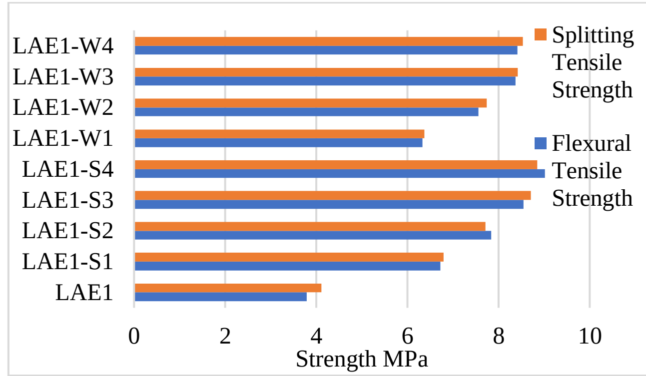

Figure 10. Bending strength and splitting strength of SLWC samples.

Figure 11. Bending strength test and failure for SLWC samples.

3.4. Splitting Tensile Strength

The splitting tensile strength results for specimens containing waste copper and micro-steel fibers, as well as those without any fibers, are presented in Table 4 and Fig. 10, based on ASTM C 496/C496M (2017) [52]. L.AE1-S1, L.AE1-S2, L.AE1-S3, L.AE1-S4, L.AE1-W1, L.AE1-W2, L.AE1-W3, and L.AE1-W4 obligated a results of (6.79, 7.71, 8.71, 8.85, 6.37, 7.74, 8.42, and 8.53) MPa with increases by (65.2, 87.5, 111.9, 115.3, 63.7, 88.3, 104.8, and 107.5) % compared with L.AE1, resulting from the attendance of fiber, which reduced the brittleness of A-EPSC, inhibited cracks, and stopped rapid failure, owning to the strong bonding between the fiber and the matrix of concrete. Splitting tensile test for A-EPSC samples is shown in Fig. 12.

Figure 12. Samples subjected to the splitting test.

3.5. Modulus of Elasticity

Table 4 displays the modules of elasticity results for A-EPSC strengthened by micro-steel fiber and waste copper fiber, as well as for the samples without fibers. Fig. 13 shows the two main tests used to determine elastic modulus.

3.5.1. Destructive test

Fig. 14 displays the test outcomes by destructive way for the static modulus, which was performed according to ASTM C469 (2014) [53], on cylinder specimens with a dimension of (150 x 300) mm, (a chord to 0.4f_{c}'). The static modules of L.AE1-S1, L.AE1-S2, L.AE1-S3, L.AE1-S4, L.AE1-W1, L.AE1-W2, L.AE1-W3, and L.AE1-W4 improved by (21.5, 25.2, 33.7, 36.1, 17, 23.5, 30, and 31.3) % in compression with a mix without fiber. The improvement in the results is attributed to the equal distribution of micro-steel fiber and waste copper fiber within the specimens following their addition, as well as to the strong bonding between these fibers and the concrete matrix.

3.5.2. Nondestructive test

The outcomes of the dynamic modules test, a nondestructive procedure executed on (150 × 300) mm cylinders, are shown in Fig. 14. This test was performed on specimens of various shapes and dimensions using the resonant frequency [54]. This standard test measures the fundamental bending frequencies and torsion frequencies based on ASTM C-215 (2014) [55]. The results of the dynamic modulus for L.AE1-S1, L.AE1-S2, L.AE1-S3, L.AE1-S4, L.AE1-W1, L.AE1-W2, L.AE1-W3, and L.AE1-W4 improved by (17.6, 20.9, 30.8, 34.5, 15.6, 19.3, 26.3, and 28.8) %, respectively, compared with L.AE1. Both types of modulus findings show a minor difference. Thus, for A-EPSC strengthened with waste copper fiber and micro-steel fiber, the findings of a nondestructive way to determine the elasticity modulus may be trusted.

Figure 13. Modulus of elasticity tests (static and dynamic).

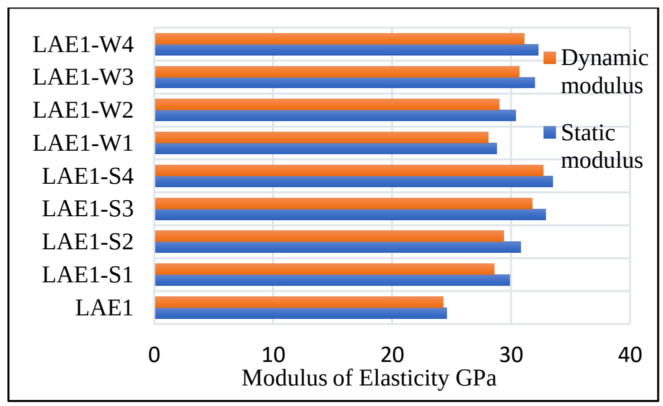

Figure 14. Modulus of elasticity of A-EPSC.

3.6. Concrete Quality

The velocity of traditional LWC is usually less than 3000 M/S [9], which indicates good qualities for SLWC, even if it ranges between 3000 and 4190 M/S [56]. Table 4 displays the Ultrasonic Pulse Velocity (UPV) for specimens, and Fig. 15 shows the correlation between UPV and dry density for A-EPSC. UPV of L.AE1-S1, L.AE1-S2, L.AE1-S3, L.AE1-S4, L.AE1-W1, L.AE1-W2, L.AE1-W3, and L.AE1-W4 improved by (4.85, 7.55, 9.49, 12.23, 2.73, 3.52, 5.39, and 8.81) % in comparison with L.AE1. At the same time, adding fibers to semi-dispersed wave transmission, as waves propagate in different directions over longer distances. Nonetheless, the UPV of the fiber-reinforced specimens was higher due to the metal fibers' properties. Fig. 16 shows the UPV test process.

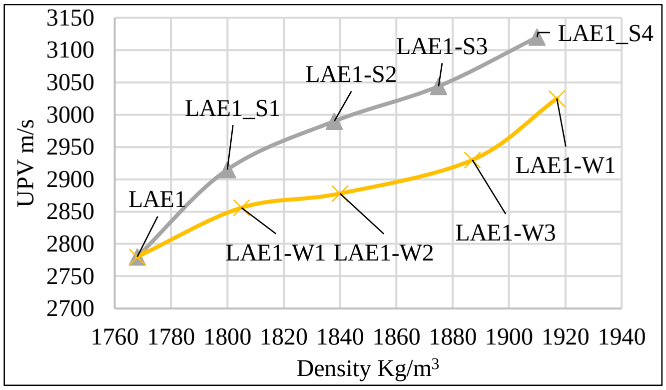

Figure 15. The density and UPV relationship.

Figure 16. UPV test for A-EPSC samples.

3.7. Thermal Ability

The thermal conductivity outcomes of A-EPSC strengthened by micro-steel fiber and waste copper fiber, along with the mix without fiber, are listed in Table 4 and Fig.17 based on

ASTM-C1113M, (2009) [57]. The thermal ability of the samples was calculated using a special technique that relies on a hot-wire, as shown in Fig. 18. The addition of micro steel fiber and waste copper fiber enhanced thermal conductivity. According to the findings, the results of L.AE1-S1, L.AE1-S2, L.AE1-S3, L.AE1-S4, L.AE1-W1, L.AE1-W2, L.AE1-W3, and

L.AE1-W4 stayed (0.425, 0.479, 0.534, 0.673, 0.457, 0.509, 0.567, and 0.701) W/ (m.k) with growths by (18.7, 33.7, 49.1, 87.9, 27.6, 42.1, 57.5, and 95.8) % respectively compared by L.AE1. The addition of metal fibers reduced thermal conductivity due to their properties. It was observed that incorporating waste copper fiber into these mixes was more active than using micro-steel fiber, due to copper’s higher thermal conductivity. Overall, the presence of polystyrene particles reduces the thermal properties of the LWC by introducing numerous closed pores. Those pores increased the resistance to heat transmission, which initially occurred through the solid phase before reaching the interior pore. A portion of the heat was conducted through the air voids, increasing the complexity of the heat transfer path and, consequently, raising energy usage. Meanwhile, another portion of the heat was conducted more rapidly through the metal fiber, with the rate and direction of transfer influenced by the fiber's orientation within the mixture. Lastly, the lasting amount of absorbed material by way of a gassy phase, therefore, impacted the thermal ability of the samples.

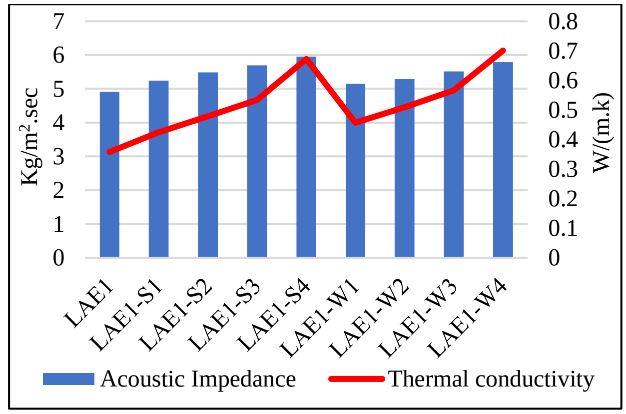

Figure 17. Acoustic impedance and thermal conductivity of A-EPSC examples.

Figure 18. Samples during thermal test.

3.8. Sound Wave Resistance

The acoustic impedance (sound properties) outcomes displayed in Table 4 and Fig. 17 were calculated by multiplying the dry density by the UPV for the sample. The results were moderately increased by differences in concrete density resulting from the addition of both fiber types. The findings of this test for L.AE1-S1, L.AE1-S2, L.AE1-S3, L.AE1-S4, L.AE1-W1, L.AE1-W2, L.AE1-W3, and

L.AE1-W4 increased by (6.7, 11.8, 16, 21.1, 4.8, 7.7, 12.4, and 17.9) % respectively compared to LAE1 due to the speed of wave transmission through metal fibers.

3.9. Microstructure of A-EPSC

The micro-structure for A-EPSC was discovered using a Scanning Electron Microscopy (SEM) test, as illustrated in Fig. 19 (a-f). All SEM images cast off in this study were captured after conducting the compressive test. L.AE1 exhibited very small, semi-uniform, round voids approximately 0.275 mm in diameter, created by the chemical reaction between waste aluminum powder and polystyrene, which were around 3.7mm in diameter. This results in a regular network of air holes, as displayed in part (a) and the microstructure of polystyrene in part (b). It might be incidental that there was an excellent bond between the A-EPSC matrix and the two types of fibers in the interfacial zone; moreover, no cracks had formed in the area of homogeneous fiber distributions. Part (c) shows that micro-steel fiber acted similarly to bridges, spreading stresses across the air holes and preventing stress concentration within the air holes, which could create a very weak zone leading to specimen failure. The diameter of the micro-steel fiber was 200.6 µm, as displayed in part (d).

Furthermore, similar behavior was observed in A-EPSC strengthened with waste copper fibers, with no chemical reaction between the fibers and the cement paste, as shown in part (e). Part (f) noted an excellent connection between the waste fibers and the cement paste, and the waste copper fiber diameter was 218.7 µm. Finally, all of the above reasons improved the behavior of A-EPSC.

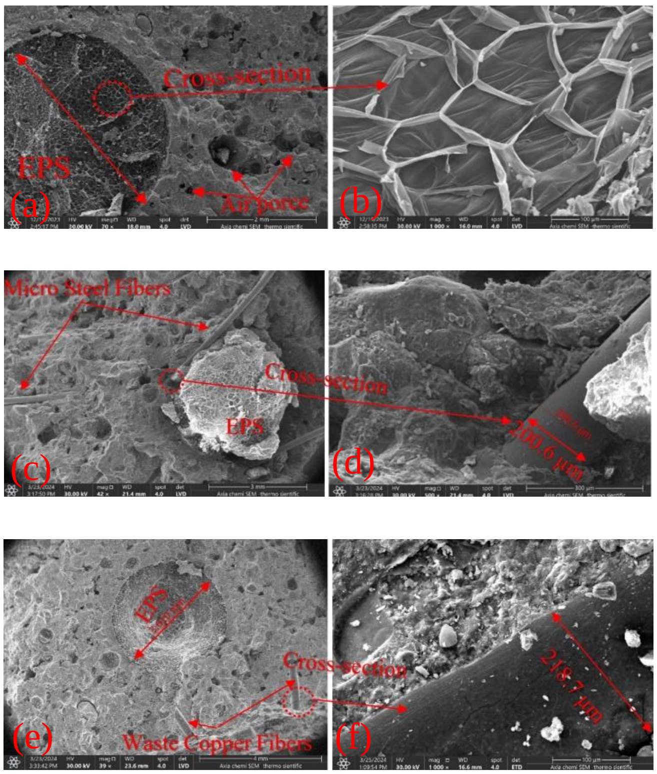

Figure 19. Micro-structure images of: (a) L.AE1, (b) EPS, (c) A-EPSC strengthened by micro-steel fiber, (d) micro-steel fiber, (e) A-EPSC reinforced by waste copper fiber, (f) waste copper fiber.

4. Conclusion and Recommendations

The significance of eco-friendly sustainability through waste reuse in improving the characteristics of A-EPSC should be carefully considered. This experimental work was carried out to study the impact of micro-steel fiber and waste copper fiber on the performance of A-EPSC and to assess the feasibility of using waste copper fibers as a sustainable, zero-cost alternative to micro-steel fibers to achieve high-strength characteristics, in contrast to earlier reports that did not meet this criterion. This work demonstrated that samples strengthened with micro-steel fiber had a dry density of about (1800 - 1910) Kg/m^3, although those with waste copper fiber had a density of about (1805 - 1917) Kg/m^3. In comparison, the specimens without fiber have a dry density of 1768 Kg/m^3. Every sample fully complied with the LWC requirement, which requires a density under 1920 Kg/m^3. The maximum compressive strength in A-EPSC strengthened by micro-steel fiber touched 56.9 MPa, with an improvement of 47.7 % in comparison with L.AE1, and rose to 55.9 MPa in L.AE1-W4 with a development of 45.1 % in comparison with the reference concrete. The findings met the criteria for high-strength SLWC, with a strength exceeding 41 MPa. Therefore, this concrete may be used as an eco-friendly material in numerous structural requests that demand high strength while also reducing the dead load of the construction. The properties like bending, splitting, as well as static and dynamic modulus showed top increases of (137.9, 115.3, 36.1, and 34.5) % at 1.2 % of micro-steel fiber content, and (121.9, 107.5, 31.3, and 28.5) % respectively at 1.2 % of waste copper fiber content. L.AE1-S4, containing 1.2 % of micro-steel fiber, improved the thermal ability and acoustic impedance by 87.9% and 21.1 % respectively, in comparison with L.AE1. Similarly, L.AE1-W4 with the parallel 1.2% waste copper fiber ratio increased thermal performance and acoustic impedance by 95.8% and 17.9%, respectively, compared with L.AE1. SEM testing presented that micro-steel fiber and waste copper fiber were successfully connected with the matrix of A-EPSC. Waste copper fiber showed behavior similar to micro-steel fiber in preventing crack growth and arresting internal cracks. The optimal distribution of waste copper fiber was observed at a 1.2% ratio, which helped evenly redistribute stress within the concrete matrix, prevent rapid failure by reducing brittleness, and enhance the material's capacity to absorb internal stresses until failure. Additionally, no noticeable impact of increasing fiber ratio was noted on the distribution or quantity of voids formed inside the matrix. Waste copper fibers extracted from damaged electrical device coils (zero-cost fibers) performed similarly to micro-steel fibers (expensive fibers) in improving the characteristics of A•EPSC. As a result, waste copper fibers can be used as crucial sustainable reinforcement fibers at an optimal volumetric ratio of 1.2% to achieve high-performance A-EPSC.

The authors suggested conducting a comprehensive investigation into the impact of using chopped carbon fiber and polypropylene fiber in A-EPSC. This would allow comparison of results for each fiber type at equal volumetric proportions, enabling selection of the ideal fiber and its ratio based on mechanical characteristics and price.

Acknowledgments

The authors would like to thank Mustansiriyah University (www.uomustansiriyah.edu.iq) and Universiti Sains Malaysia for their support of this work.

Conflict of interest

There is no conflict of interest between the authors.

Author Contribution Statement

Samer S. Abdulhussein developed the theory, delineated the key concepts, and described the results.

Izwan B. Johari, M.Z.A. Mohd Zahid, and Nada Mahdi Fawzi assisted in organizing and supervising this work.

References

[1] K. A. Mohd Sari and A. R. Mohammed Sani, "Applications of Foamed Lightweight Concrete," *MATEC Web of Conferences*, vol. 97, p. 01097,

2017, doi: https://doi.org/10.1051/matecconf/20179701097

[2] A. Humad, "Shrinkage and Related Properties of Alkali-Activated Binders Based on High MgO Blast Furnace Slag," *PhD Thesis. Luleå University of Technology*, 2019. Available: http://ltu.diva-portal.org/smash/record.jsf?pid=diva2%3A1360129&dswid=-6060. [Accessed: Jan. 23, 2025]

[3] Y. Cui, K. Gao, and P. Zhang, "Experimental and Statistical Study on Mechanical Characteristics of Geopolymer Concrete," *Materials*, vol. 13, no. 7, Apr. 2020, doi: https://doi.org/10.3390/ma13071651. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7178337/. [Accessed: May 09, 2021]

[4] J. Leslie *et al.*, "Methods, Impacts, and Opportunities in the Concrete Building Life Cycle," Research Report R11-01, Concrete and Sustainability Hub, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, No. August, P. 119, 2011. Available: https://dspace.mit.edu/bitstream/handle/1721.1/105108/MIT%20Buildings%20LCA%20Report%202011.pdf?sequence=1. [Accessed: Jan. 23, 2025]

[5] N. M. Ibrahim *et al.*, "Preservation of Natural Resources by Utilizing Combustion Ash in Concrete and Determination of Its Engineering Properties," *International Journal of Conservation Science*, vol. 14, no. 2, pp. 753–762, Jun. 2023, doi: https://doi.org/10.36868/ijcs.2023.02.25

[6] K.-C. Thienel, T. Haller, and N. Beuntner, "Lightweight Concrete-From Basics to Innovations," *Materials (Basel, Switzerland)*, vol. 13, no. 5, Mar. 2020, doi: https://doi.org/10.3390/ma13051120. Available: https://pubmed.ncbi.nlm.nih.gov/32138207/

[7] M. A. Khalaf, C. B. Cheah, M. Ramli, N. M. Ahmed, and A. Al-Shwaiter, "Effect of Nano Zinc Oxide and Silica on mechanical, Fluid Transport and Radiation Attenuation Properties of Steel Furnace Slag Heavyweight Concrete," *Construction and Building Materials*, vol. 274, p. 121785, Mar. 2021, doi: https://doi.org/10.1016/j.conbuildmat.2020.121785

[8] S Sindhuja, K. S. Raman, and P Bhuvaneshwari, "A Review on Strength Characteristics of GGBS Based fiber-reinforced Lightweight Aggregate Concrete," *IOP Conference Series Materials Science and Engineering*, vol. 872, no. 1, pp. 012135–012135, Jun. 2020, doi: https://doi.org/10.1088/1757-899x/872/1/012135

[9] American Concrete Institute, *Guide for Cellular Concretes ACI 523.3 R14*, vol. 14. ACI 523.3 R14, 2014.

[10] M. R. Ali, M. Maslehuddin, M. Shameem, and M. S. Barry, "Thermal-resistant Lightweight Concrete with Polyethylene Beads as Coarse Aggregates," *Construction and Building Materials*, vol. 164, pp. 739–749, Mar. 2018, doi: https://doi.org/10.1016/j.conbuildmat.2018.01.012

[11] F. Colangelo *et al.*, "Mechanical and Thermal Properties of Lightweight Geopolymer Composites," *Cement and Concrete Composites*, vol. 86, pp. 266–272, Feb. 2018, doi: https://doi.org/10.1016/j.cemconcomp.2017.11.016

[12] A. S. Al-Tamimi, O. S. Baghabra Al-Amoudi, M. A. Al-Osta, M. R. Ali, and A. Ahmad, "Effect of Insulation Materials and Cavity Layout on Heat Transfer of Concrete Masonry Hollow Blocks," *Construction and Building Materials*, vol. 254, p. 119300, Sep. 2020, doi: https://doi.org/10.1016/j.conbuildmat.2020.119300

[13] M. Hafiz Bin, "Properties Of Lightweight Foam Concrete With The Inclusion Of Fibres," Ph.D. Thesis. Universiti Sains Malaysia, 2015, 2015. Available: http://eprints.usm.my/30169/1/MUHAMMAD_HAFIZ_BIN_AHMAD.pdf. [Accessed: Oct. 23, 2025]

[14] M. F. Junaid *et al.*, "Lightweight Concrete from a Perspective of Sustainable Reuse of Waste Byproducts," *Construction and Building Materials*, vol. 319, p. 126061, Feb. 2022, doi: https://doi.org/10.1016/j.conbuildmat.2021.126061

[15] A. Thakur and S. Kumar, "Mechanical Properties and Development of Light Weight Concrete by Using Autoclaved Aerated Concrete (AAC) with Aluminum Powder," *Materials Today: Proceedings*, vol. 56, pp. 3734–3739, 2022, doi: https://doi.org/10.1016/j.matpr.2021.12.508

[16] R. A. Rahman, A. Fazlizan, N. Asim, and A. Thongtha, "A Review on the Utilization ofWaste Material for Autoclaved Aerated Concrete Production†," *Journal of Renewable Materials*, vol. 9, no. 1, pp. 61–72, 2021, doi: https://doi.org/10.32604/jrm.2021.013296

[17] K. Janamian and J. Aguiar, *Concrete Materials and Technology*, 1st ed. Boca Raton: Taylor and Francis Group, CRC Press, 2023. doi: https://doi.org/10.1201/9781003384243

[18] Z. Damene, M. S. Goual, J. K. Houessou, R.-M. Dheilly, A. Goullieux, and M. Queneudec, "The Use of Southern Algeria Dune Sand in Cellular Lightweight Concrete manufacturing: Effect of Lime and Aluminium Content on porosity, Compressive Strength and Thermal Conductivity of Elaborated Materials," *European Journal of Environmental and Civil Engineering*, vol. 22, no. 10, pp. 1273–1289, Nov. 2016, doi: https://doi.org/10.1080/19648189.2016.1256233

[19] C. Ridtirud, "Properties Of Lightweight Aerated Geopolymer Synthesis From High-Calcium Fly Ash And Aluminium Powder," *International Journal of GEOMATE*, vol. 16, no. 57, May 2019, doi: https://doi.org/10.21660/2019.57.4651

[20] T. R. Gyawali, "Effect of the Mixing Procedure on the Properties of Lightweight EPS Mortar," *Journal of Building Engineering*, vol. 68, p. 106012, Jun. 2023, doi: https://doi.org/10.1016/j.jobe.2023.106012. Available: https://www.sciencedirect.com/science/article/abs/pii/S2352710223001912?via%3Dihub. [Accessed: Apr. 24, 2023]

[21] B. A. Herki and J. M. Khatib, "Valorisation of Waste Expanded Polystyrene in Concrete Using a Novel Recycling Technique," *European Journal of Environmental and Civil Engineering*, vol. 21, no. 11, pp. 1384–1402, Apr. 2016, doi: https://doi.org/10.1080/19648189.2016.1170729

[22] Y. Xu *et al.*, "Effect of Foam Stabilization on the Properties of Foamed Concrete Modified by Expanded Polystyrene," *Journal of Building Engineering*, vol. 73, p. 106822, Aug. 2023, doi: https://doi.org/10.1016/j.jobe.2023.106822. Available: https://www.sciencedirect.com/science/article/pii/S235271022301001X

[23] R. Shabbar, A. A. Al-Tameemi, and A. M. J. Alhassani, "The Effect of Expanded Polystyrene Beads (EPS) on the Physical and Mechanical Properties of Aerated Concrete," *Open Engineering*, vol. 12, no. 1, pp. 424–430, Jan. 2022, doi: https://doi.org/10.1515/eng-2022-0020

[24] A. Z. A. Altera, O. Y. Bayraktar, B. Bodur, and G. Kaplan, "Investigation of the Usage Areas of Different Fiber Reinforced Concrete," *Kastamonu University Journal of Engineering and Sciences*, vol. 7, no. 1, Jun. 2021.

[25] L. Nguyen, A.-L. Beaucour, S. Ortola, and A. Noumowe, "Influence of the Volume Fraction and the Nature of Fine Lightweight Aggregates on the Thermal and Mechanical Properties of Structural Concrete," *Construction and Building Materials*, vol. 51, pp. 121–132, Jan. 2014, doi: https://doi.org/10.1016/j.conbuildmat.2013.11.019

[26] N. Haque Nayem, "The Potential of Sustainable Materials for Green Building Practices," *American Journal of Civil Engineering*, vol. 11, no. 3, Aug. 2023, doi: https://doi.org/10.11648/j.ajce.20231103.11. Available: http://article.amjce.com/pdf/10.11648.j.ajce.20231103.11.pdf

[27] S. S. Weli, I. S. Abbood, K. F. Hasan, and M. A. Jasim, "Effect of Steel Fibers on the Concrete Strength Grade: a Review," *IOP Conference Series: Materials Science and Engineering*, vol. 888, no. 1, p. 012043, Jul. 2020, doi: https://doi.org/10.1088/1757-899x/888/1/012043

[28] A. Khaloo, E. Molaei Raisi, P. Hosseini, and H. Tahsiri, "Mechanical Performance of self-compacting Concrete Reinforced with Steel Fibers," *Construction and Building Materials*, vol. 51, pp. 179–186, Jan. 2014, doi: https://doi.org/10.1016/j.conbuildmat.2013.10.054. Available: https://www.sciencedirect.com/science/article/pii/S0950061813009756. [Accessed: May 24, 2019]

[29] V. Marcos-Meson, A. Michel, A. Solgaard, G. Fischer, C. Edvardsen, and T. L. Skovhus, "Corrosion Resistance of Steel Fibre Reinforced Concrete - a Literature Review," *Cement and Concrete Research*, vol. 103, pp. 1–20, Jan. 2018, doi: https://doi.org/10.1016/j.cemconres.2017.05.016

[30] J.-S. Choi, H.-J. Lee, T.-F. Yuan, and Y.-S. Yoon, "Mechanical and Shrinkage Performance of Steel Fiber Reinforced High Strength self-

compacting Lightweight Concrete," *Cement and Concrete Composites*, vol. 144, p. 105296, Nov. 2023, doi: https://doi.org/10.1016/j.cemconcomp.2023.105296. Available: https://www.sciencedirect.com/science/article/abs/pii/S0958946523003700. [Accessed: Oct. 12, 2023]

[31] P. P. Pal-Val *et al.*, "Unusual Young's Modulus Behavior in ultrafine-grained and Microcrystalline Copper Wires Caused by Texture Changes during Processing and Annealing," *Materials Science and Engineering: A*, vol. 618, pp. 9–15, Nov. 2014, doi: https://doi.org/10.1016/j.msea.2014.08.069. Available: https://www.sciencedirect.com/science/article/abs/pii/S0921509314010697. [Accessed: Mar. 22, 2024]

[32] M. H. Naser, F. H. Naser, and M. K. Dhahir, "Tensile Behavior of Fiber Reinforced Cement Mortar Using Wastes of Electrical Connections Wires and Galvanized Binding Wires," *Construction and Building Materials*, vol. 264, p. 120244, Dec. 2020, doi: https://doi.org/10.1016/j.conbuildmat.2020.120244

[33] M. Horňáková and P. Lehner, "Analysis of Measured Parameters in Relation to the Amount of Fibre in Lightweight Red Ceramic Waste Aggregate Concrete," *Mathematics*, vol. 10, no. 2, p. 229, Jan. 2022, doi: https://doi.org/10.3390/math10020229

[34] Md. H. R. Sobuz *et al.*, "Development of Self-Compacting Concrete Incorporating Rice Husk Ash with Waste Galvanized Copper Wire Fiber," *Buildings*, vol. 12, no. 7, p. 1024, Jul. 2022, doi: https://doi.org/10.3390/buildings12071024

[35] K. Yang, H.-Y. Kim, and H.-J. Lee, "Mechanical Properties of Lightweight Aggregate Concrete Reinforced with Various Steel Fibers," *International Journal of Concrete Structures and Materials*, vol. 16, no. 1, Sep. 2022, doi: https://doi.org/10.1186/s40069-022-00538-4

[36] H.-J. Lee and K.-H. Yang, "Compressive and Flexural Toughness Indices of Lightweight Aggregate Concrete Reinforced with micro-steel Fibers," *Construction and Building Materials*, vol. 401, pp. 132965–132965, Oct. 2023, doi: https://doi.org/10.1016/j.conbuildmat.2023.132965

[37] M. Selvakumar, S. Geetha, and S. Muthulakshmi, "Strength Properties of Aerated Cement Composite Reinforced with Steel Fibres," *Materials Today: Proceedings*, vol. 46, pp. 7061–7068, 2021, doi: https://doi.org/10.1016/j.matpr.2020.08.811

[38] B. Skariah and P. Mathew, "Characteristics of Fiber Reinforced Light Weight Concrete Wall Panel," International Research Journal of Engineering and Technology, Vol. 05, No. 04, Pp. 3549–3555, 2018.

[39] M. R. Aldikheeli and M. S. Shubber, "The Effects of Fibre on the Mechanical Properties of Aerated Concrete," *IOP Conference Series Materials Science and Engineering*, vol. 671, no. 1, pp. 012076–012076, Jan. 2020, doi: https://doi.org/10.1088/1757-899x/671/1/012076

[40] X. Zheng, T. Ji, S. M. Easa, B. Zhang, and Z. Jiang, "Tensile Basic Creep Behavior of Lightweight Aggregate Concrete Reinforced with Steel Fiber," *Construction and Building Materials*, vol. 200, pp. 356–367, Mar. 2019, doi: https://doi.org/10.1016/j.conbuildmat.2018.12.138

[41] S. S. Abdulhussein and A. A. Alfeehan, "Utilization of Iron Lathe Waste and Post-Tensioned Steel Reinforcement in Lightweight Concrete Ribbed Slabs," *2020 2nd Al-Noor International Conference for Science and Technology (NICST)*, pp. 44–50, Aug. 2020, doi: https://doi.org/10.1109/nicst50904.2020.9280310

[42] M. Hornakova, J. Katzer, J. Kobaka, and P. Konecny, "Lightweight SFRC Benefitting from a Pre-Soaking and Internal Curing Process," *Materials*, vol. 12, no. 24, p. 4152, Dec. 2019, doi: https://doi.org/10.3390/ma12244152

[43] IQS No.5, "Iraqi Specification, No. 5, 2019, Portland Cement, Ministry of Planning, Central Organization for Standardization and Quality Control," 2019. [Online]. Available: https://www.iso.org/standard/76744.html.

[44] ASTM C33, "Standard Specification for Concrete Aggregates," American Society for Testing and Materials, 2016, [Online]. Available: https://doi: 10.1520/C0033_C0033m-16.

[45] ASTM C1240, "Standard Specification for Silica Fume Used in Cementitious Mixtures," Standard Specification for Silica Fume Used in Cementitious Mixtures, 2015, [Online]. Available: https://doi: 10.1520/C1240-15.

[46] EFNARC, "Specification and Guidelines for Self-Compacting Concrete," Association House, 2002, [Online]. Available: www.efnarc. org

[47] IQS 1703, "Iraqi Standard Specification for Water Used for Curing Concrete and Mortar," Central Agency for Standardization and Quality Control, 2018. [Online]. Available: https://www.iso.org/standard/76744.html.

[48] ASTM C-494 Types E, "Standard Specification for Chemical Admixture for Concrete," American Society for Testing and Materials International, 1999. [Online]. Available: https://www.astm.org/Standards/C494.htm

[49] ASTM C567-05a, "Standard Test Method for Determining Density of Structural Lightweight Concrete 1," 2005. [Online]. Available: www.Astm. Org

[50] BS EN 12390-3, Testing Hardened Concrete. Part 3, Compressive Strength of Test Specimens.British Standard. 2019. [Online]. Available: https://www.bsigroup.com/en-GB/bs-en-12390-3-testing-hardened-concrete-part-3-compressive-strength-of-test-specimens/

[51] ASTM C78/C78m, "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading) 1," American Society for Testing and Material, 2016, https://doi: 10.1520/C0078_C0078m-16.

[52] ASTM C 496/C496m, "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens 1," American Society for Testing and Material, 2017, https://doi: 10.1520/C0496_C0496m-17.

[53] ASTM C469, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression 1," American Society for Testing and Material, 2014, https://doi: 10.1520/C0469_C0469m-14.

[54] S. Abdulhussein, I. Johari, and M. Fawzi, "Mechanical Properties of Aerated-Polystyrene Concrete Reinforced by Polymer Fibers". Annales de Chimie Science des Matériaux. Vol. 48. No. 4, 2024. https://doi.org/10.18280/acsm.480401.

[55] ASTM C215, "Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens 1," 2014, https://doi: 10.1520/C0215-14.

[56] A. H. Medher, A. I. Al-Hadithi, and N. Hilal, "The Possibility of Producing Self-Compacting Lightweight Concrete by Using Expanded Polystyrene Beads as Coarse Aggregate," Arab J Sci Eng, Vol. 46, No. 5, Pp. 4253–4270, May 2021, https://doi: 10.1007/S13369-020-04886-9.

[57] ASTM C1113/C1113m, "Standard Test Method for Thermal Conductivity of Refractories by Hot Wire (Platinum Resistance Thermometer Technique)," 2009. [Online]. Available: http://www.ansi.org.