Enhancement of Perlite Concrete Properties containing Sustainable Materials by Incorporation of Hybrid Fibers

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ABSTRACT

Utilizing waste resources in concrete manufacturing, while employing alternative components and minimizing the Ordinary Portland Cement (OPC) production, is a matter of great importance owing to several environmental and stability considerations. OPC is the fundamental component implemented in the conventional concrete production process. However, the OPC industry has raised environmental concerns since it produces mass amounts of carbon dioxide (CO_2). A more sustainable substance, utilizing metakaolin as pozzolanic material and local ash as a filler can serve as an OPC substitute, thereby reducing the CO_2 release into the environment. This work examines the impact of incorporating sustainable recycled copper fibers as well as alkali resistance glass fibers on the properties of perlite structural lightweight aggregate concrete containing local, sustainable materials. The research includes slump, density, and thermal conductivity tests along with tests conducted during the 7, 28, and 60 days of curing for compressive, flexural, and split tensile strength. The concrete was reinforced with 1% hybrid fibers by volume. The results reveal that adding fibers to lightweight concrete reduces the slump and increases density and thermal conductivity, while it also increases the compressive, flexural, and split tensile strengths.

Keywords-lightweight concrete; perlite; hybrid fibers; glass fibers; copper fibers; metakaolin; sustainable materials

I. INTRODUCTION

Concrete has been an essential material in civil engineering projects for a considerable time due to its flexible nature and ability to be shaped or formed into the desired cross-sectional shape and size. Additionally, it requires less maintenance and is easy to put in place. The strength-to-weight ratio of concrete may be unsatisfactory. Numerous investigations have been carried out to create Lightweight Concrete (LWC) with an improved strength-to-weight ratio to lower the concrete's overall weight. LWC has the advantage of reducing the weight of large projects while also possessing superior insulation advantages and at the same time being environmentally friendly [1]. However, LWC has certain drawbacks, such as poor tensile strength, brittleness, and relatively high cement content. Continuous enhancements are made to address these weaknesses, including fiber reinforcement and the partial substitution of more cost-effective cement binder materials [2]. The structural lightweight-aggregate concrete has a minimum 28-day compressive strength of (17 MPa) and is entirely made of lightweight aggregate or a combination of lightweight and normal aggregate. It has an equilibrium density of 1120–1920 kg/m^3 [3]. Lightweight perlite aggregate is often used in LWAC, mainly in its expanded form. Rapid heating of perlite to a temperature over its softening point 850–1200 °C makes it expand. Since it has a low density, adequate fire resistance, and high thermal insulation, expanded perlite may be used in concrete as a substitute for a portion of the cement or aggregates. [4]. Building construction has seen an increase in Fiber-Reinforced Concrete (FRC) usage due to its enhanced tensile strength, impact strength, flexural strength, and failure mode. Moreover, the concrete's elasticity modulus and its compressive strength are a little bit affected by the inclusion of fibers [5].

A composite may be called a hybrid if two or more different kinds of fibers are carefully blended to create one that benefits from each fiber type and responds synergistically. The addition of short, discontinuous fibers significantly aids the enhancement of the mechanical properties of concrete. The former affects fracture initiation and propagation by raising the elastic modulus, lowering brittleness, and decreasing crack brittleness [6]. Glass fibers are added to concrete to enhance its tensile strength and decrease the need for steel reinforcement. This minimizes the corrosion of steel reinforcement in hydraulic structures and maritime environment. Glass fibers increase flexure strength fatigue resistance and disrupt the fracture pattern by narrowing the crack width [7]. In particular, electronic waste fibers—like copper fiber, which is more hazardous than other waste—can reinforce concrete and ameliorate its mechanical properties, helping in producing strong, cheap concrete and resolve the solid waste issue [8, 9]. Metakaolin (MK) is a supplementary cementitious material obtained by submitting pure kaolin clay to a controlled heat treatment called calcination. The primary rationale for integrating MK into cement-based systems is its pozzolanic reactivity. This refers to the ability of silicates-aluminates found in supplementary cementitious materials like MK to chemically react with the calcium-hydroxide generated during cement hydration. As a result, secondary calcium-silicate hydrate is formed [10]. Most research on the construction field in Iraq has examined whether locally sourced raw materials can be viable substitutes for the imported substances required for specific real-world uses, such as sound and thermal insulation [11].

Authors in [1] studied the benefits of using natural perlite aggregate to make structural lightweight aggregate concrete, which would reduce the dead weight of a building. After substituting all the coarse aggregates with perlite and adjusting the water-to-cement ratio, the strength of perlite concrete was compared to that of the conventional concrete. The structure's dead load may be effectively reduced by examining the test results and using perlite concrete for in-fill and non-load-bearing walls. Authors in [12] investigated how the mechanical characteristics of high-strength green concrete were affected by adding sustainable copper fiber with different aspect ratios (l/d). The concrete mixes include copper fibers in four distinct aspect ratios: 20%, 40%, 60%, and 120%. Testing the samples' mechanical characteristics, such as their resistance to compression, flexural strength, and splitting strength, revealed that employing fibers with a higher aspect ratio significantly improved the mechanical properties of concrete and to a greater extent than implementing fibers with a lower aspect ratio.

Authors in [13] investigated the use of glass fibers and perlite in LWC. The aggregate was substituted with 30% perlite, whereas glass fibers were included in the cement mixture at rates of 0.4%, 0.6%, and 0.8% to enhance the strength of concrete and decrease its overall weight. Specimens were produced with water to cement ration (W/C) of 0.45 by reducing the amount of perlite by 30% and using glass fibers to enhance strength characteristics. The results' analysis displayed that a fraction of the coarse aggregate volume was successfully substituted by 30% perlite, attaining the targeted weight of 1792 kg/m^3. It has been shown that using glass fibers increases tensile and flexural strength. Authors in [14] examined how employing hybrid fibers affected the LWC's mechanical characteristics. Glass Fibers GF) and Polypropylene Fibers (PPF) were engaged in varying weight percentages (0.2% to 1%), depending on the binder concentration. Tests were performed to find the compressive, splitting, and flexural strengths of the produced concrete. The findings demonstrated that adding 0.7% GF significantly improved the LWC mixes' compressive, splitting tensile, and flexural strengths. Authors in [15] studied MK's impact on the properties of lightweight porcelain aggregate concrete. Different amounts of MK, between 5% and 20%, as a substitute for cement, were used to create the concrete mixes. The results indicate that a 15% MK replacement was the optimum choice.

The current research aims to produce structural lightweight aggregate concrete with good mechanical properties and low thermal conductivity employing perlite aggregate, sustainable materials, and hybrid fibers. The former also attempts to determine the optimal fiber percentage for maximum strength, with regard to sustainability by reducing the OPC production and deploying waste resources to produce concrete with substitute ingredients.

II. EXPERIMENTAL WORK

A. *Materials*

1) *Cement (C)*

OPC type CEM I 42.5 R complies with Iraqi standard specifications IQS No. 5 [16]. This cement's physical and chemical properties are portrayed in Tables I and II, respectively.

TABLE I. CEMENT PHYSICAL CHARACTERISTICS

Properties	Test results	Limits of [16]
Specific surface area (Blaine approach) (m²/ kg)	398.7	≥ 280
Initial setting time (Vicat's approach) (min)	136 min	≥ 45 min
Final setting time (Vicat's approach) (min)	6.5 hr	≤ 10 hr.
Soundness by autoclaveapproach (%)	0.19	≤ 0.80
Compressive strength (MPa)		
Compressive strength (2 days)	26	≥20
Compressive strength (28 day)	45	≥ 42.5

TABLE II. CEMENT CHEMICAL ANALYSIS

Oxide composition	Weight (%)	Limits of [16]
Lime (CaO)	62.33	Not limited
Iron oxide (Fe_2O_3)	3.89	Not limited
Alumina (Al_2O_3)	5.35	Not limited
Silica (SiO_2)	19.91	Not limited
Insoluble residue (IR)	0.55	Max (1.5)
Magnesia (MgO)	2.66	Max (5)
Loss on Ignition (LOI)	2.46	Max (4)
Sulfate (SO_3)	2.41	$SO_3 \leq 2.8$ if $C_3A > 3.5$ $SO_3 \leq 2.5$ if $C_3A \leq 3.5$

2) *Expanded Perlite Aggregate (EPA)*

The utilized EPA fulfilled ASTM C330, 2017 [17] standards by combining fine and coarse aggregate. Table III gives its chemical composition, Table IV presents the sieve analysis's results, and Figure 1 exhibits a sample of the EPA used in this study.

3) *Water (W)*

Water that complied with IQS No. 1703 [18] was utilized for mixing and curing.

TABLE III. CHEMICAL COMPOSITION OF THE EPA (DATASHEET)

Oxide composition	Weight (%)
Silicon (SiO_2)	0.24
Aluminium (AL_2O_3)	0.54
Iron (Fe_2O_3)	7.5
Silica (SiO_2)	69.6
IR	---
Magnesia (MgO)	0.03
LOI	5.8
Sulfate (SO_3)	0.02

TABLE IV. EPA GRADATION

Sieve size (mm)	Cumulative passing wt. %	Limits of [17]
12.5	100	100
9.5	100	90-100
4.75	88	65-90
2.36	44.8	35-65
0.3	12	10-25
0.15	5.6	5-15
0.075	0	0-10

Fig. 1. Sample of the utilized EPA.

4) *Metakaolin (MK)*

MK was obtained from Al-Anbar City after a 2 h calcination process that included temperatures as high as 700 °C for the kaolinitic clay. The MK had a strength activity index of 89.67% at 7 days, and the percentage retained on sieve No. 325 (20.31%) fulfilled ASTM C618 [19]. Table V depicts MK's chemical requirements.

TABLE V. MK'S CHEMICAL COMPOSITION

Oxide	Test results	[19] requirement
SiO_2	52.2	(SiO_2) plus (Al_2O_3) plus (Fe_2O_3) =97.261 Min. (70%)
AL_2O_3	44.8	
Fe_2O_3	0.261	
MgO	0.15	------
SO_3	1.34	Max. (4 %)
CaO	0.192	------
LOI	4	Max (10 %)

5) *Local Ash (LA)*

LA obtained from the Al-Dora thermal electric station was deployed as a filler, replacing a percentage by weight of cement for environmental purposes. The chemical analysis of the utilized LA is presented in Table VI.

6) *Recycled Copper-Wire Fibers (CF)*

CF obtained from the coil of disabled (invalid) water pumps were implemented in this work. The utilized fibers had a diameter of 0.3 mm and a length of 12 mm, yielding an aspect ratio of 40. Figure 2 demonstrates a sample of the recycled CF that was employed.

TABLE VI. CHEMICAL COMPOSITION OF LA

Oxide	Test results (%)
Silicon (SiO_2)	12.26
Aluminium (AL_2O_3)	1.752
Iron (Fe_2O_3)	5.146
Magnesium (MgO)	2.979
Sulfate (SO_3)	4.358
Calcium (CaO)	3.611
Sodium (Na_2O)	10.26
Phosphorus (P_2O_5)	4.446
Potassium (K_2O)	28.09
Titanium (TiO_2)	0.2296

Fig. 2. Copper fibers.

7) *Alkali Resistant Glass Fibers (GF)*

The utilized alkali-resistant glass-chopped strand fiber (GF), shown in Figure 3, had the following dimensions: 12 mm length, 0.15 mm diameter, and 80 aspect ratio. Table VII presents the specifications of the utilized fibers.

TABLE VII. SUPPLIER'S CHARACTERISTICS OF THE GF

Property	Value
Appearance	Opaque
Fiber length	12 mm
Fiber diameter	0.15 mm
Specific Gravity (SG)	2.68 g/cm³
Absorption	Nil
Resistance to chemicals	Very high
Elasticity modulus	72 GPa
Tensile strength	1,700 MPa
Softening-point	860°C

8) *Superplasticizer*

BETONAC® 350 was the deployed superplasticizer. It complies with ASTM C494 [20], Type G, with a density of 1.06 ±0.02 gm/ml, according to the manufacturer.

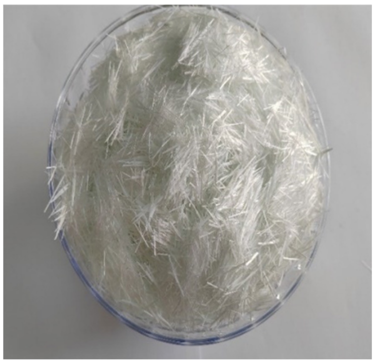

Fig. 3. Alkali resistant GF.

B. Concrete Mix Proportions

The mixtures were created and blended in compliance with ACI 2.11.2 [21] and ACI 213R [3]. Several trials were conducted to determine the optimal ratio of cement to perlite, and several ratios were used (1:6, 1:5, 1:4, 1:3, 1:2). The cement-to-perlite optimum volumetric ratio of 1:2 was utilized. For all mixes, the cement content was 350 kg/m^3, the W/C was 0.4, 15% of the cement weight was substituted with MK, and the LA filler replaced 10% of cement by weight. The manufacturer recommends using a dosage from 800 to 1500 ml of superplasticizer per 100 kg of cement and 1000 ml per 100 kg of cement. The concrete involved fibers at a volume ratio of 1% of the concrete volume. The fibers were hybrid recycled CF and GF, the mix designs are provided in Table VIII, where the (M-REF) mix consisted of LWC reinforced without fibers (reference mix).

TABLE VIII. CONCRETE MIX PROPORTIONS

Mix	C (kg/m^3)	W/C	C: EPA	MK %	Ash %	CF %	GF %	SP ml/ 100 kg C
M-RF	350	0.4	1:2	15	10	---	---	1000
M-70C30G	350	0.4	1:2	15	10	70	30	1000
M-60C40G	350	0.4	1:2	15	10	60	40	1000
M-50C50G	350	0.4	1:2	15	10	50	50	1000

C. Preparation of Concrete Specimens and Curing

The mixing method is essential for achieving the required homogeneity and workability. An electric mixer was put into service to do the mixing. To avoid mortar adhering to the surfaces, the base and sides of the molds were lightly oiled before casting. Concrete layers were then put on the molds, and any trapped air was allowed to leave by pressing them for a sufficient amount of time employing a vibrating table, according to ASTM C192 [22]. Using a hand trowel, the specimens were compacted and levelled for about a day to keep the humidity level consistent. After casting, the specimens spent a day in the lab enclosed in polyethylene bags. Subsequently, the former were taken out of the moulds and kept in water for 7, 28, and 60 days before testing.

D. Test Method

1) Slump Test

A slump test was conducted on recently mixed concrete, immediately after its preparation. Workability pertains to the effortless use of freshly produced concrete or mortar, including smooth transportation, installation, and compaction, while preventing segregation. The slump was tested deploying ASTM C143 [23].

2) Density Test

For the density (oven dry unit weight), test cylinders sized 100 mm in diameter and 200 mm in length were used according to ASTM C567 [24]. The density was calculated by:

$$Om = (D * 997)/(F - G) \quad (1)$$

where Om is the oven-dry density in kg/m^3, D is the mass of the oven-dry cylinder (kg), G is the apparent mass of the suspended-immersed cylinder (kg), and F is the mass of the saturated surface-dry cylinder (kg).

3) Compressive Strength Test

The compressive strength of the concrete 100 × 200 mm cylinder was tested according to ASTM C39 [25]. For every mix, three specimens were examined. Tests were conducted on the specimens 7, 28, and 60 days after casting. The compressive strength is calculated by:

$$Fc = P/A \quad (2)$$

where Fc is the comp. strength (MPa), A is the area (mm^2) and P is the maximum load (N).

4) Split Tensile Strength Test

The specifications of ASTM C496 [26] were used to test the cylinders' splitting tensile strength. The cylinders were examined at 7, 28, and 60 days.

$$Ft = (2 * P)/(\pi * l * d) \quad (3)$$

Ft is the tensile strength (MPa), l is the length (mm), P is the maximum. load (N), and D the diameter (mm).

5) Flexural Strength Test

The specifications of ASTM C293 [27] were utilized for the flexural strength test on concrete prisms (50×50×250 mm). The specimens were tested 7, 28, and 60 days after casting to estimate the rupture modulus, calculated by:

$$Fr = (3 * P * L)/(2 * b * \text{ d^2}) \quad (4)$$

where Fr is the flexural strength (MPa), L is the length (mm), P is the maximum load (N), b is the width (mm), and d is the depth (mm).

6) Thermal Conductivity Test

The specifications of ASTM C1113 [28] were applied to test the thermal conductivity of a 100 mm cube after 28 days of curing. Thermal conductivity K (W/m.K) is calculated by:

$$K = (Q * d * ln(t))/(4 * \pi * d * T) \quad (5)$$

where t is the time (min), T is the test temperature (°C), Q is the average power input to the hot wire (I*V*100/L) during the test (W/m), L is the wire length (cm), V is the average voltage drop across a hot wire (V), I is the average current through the wire ($I=V_S/R_S$), (A), V_S is the average voltage drop across a standard resistor (V), and R_S is the average resistance of a standard resistor (Ω).

III. RESULTS AND DISCUSSION

A. Slump Test Results

The result of the slump test is shown in Table IX and Figure 4. When using LWC, slump is essential for getting an acceptable floor surface and should typically be kept to a maximum of 125 mm at the installation site [3]. Minimal slump is achieved utilizing the most minimal W/C and including a superplasticizer. Hence, the W/C influences the slump value and superplasticizer [29]. The workability of LWC is reduced with the incorporation of fibers. The decrease was 10.26%, 7.69%, and 6.41% for (-70C30G, M-60C40G, and M-50C50G blend, respectively. This result is in accordance with the findings in [30].

TABLE IX. SLUMP TEST RESULT

Mix	Slump (mm)
M-REF	78
M-70C30G	70
M-60C40G	72
M-50C50G	73

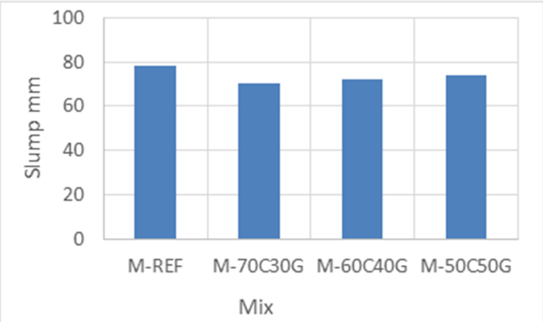

Fig. 4. Slump result.

B. Oven Dry Density Results

The mix's density value is observed in Table X and Figure 5.

TABLE X. DENSITY TEST RESULT

Mix	Density (kg/m^3)
M-REF	1614.29
M-70C30G	1704.13
M-60C40G	1701.65
M-50C50G	1691.97

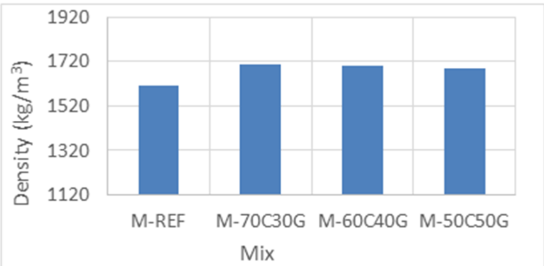

Fig. 5. Density result.

Utilizing perlite as an aggregate in concrete reduces its density [31]. Expanded perlite was added, which led to a cellular structure that raised the density of the resulting concrete. The addition of fibers enhanced the density since fibers tend to fill in gaps [32]. It can be seen that the density increased after the addition of fibers to M-70C30G, M-60C40G, and M-50C50G increased the density of concrete by 5.57%, 5.41%, and 4.81%, respectively.

C. Compressive Strength Results

One of the most essential qualities of hardened concrete is its compressive strength. The compressive strength test results for the cylinder are displayed in Table XI and Figure 6. The specimens reinforced with fibers exhibited a significant increase in strength compared to the M-REF specimens, due to the presence of fibers, which work as a bridge, preventing or delaying the creation of cracks [34, 35]. The compressive strength compared with the (M-REF) mix has increased by 2.19%, 3.82%, and 10.26% after 7 days, 4.8%, 7.81%, and 13.31% after 28 days, 2.81%, 6.08%, and 12.95% after 6o days for M-70C30G, M-60C40G, and M-50C50G, respectively. The compressive strength stays in the range of the structural lightweight aggregate concrete (17–28 MPa) [17].

TABLE XI. COMPRESSIVE STRENGTH RESULT

Mix	Compressive strength (MPa)		
	7 Days	28 Days	60 Days
M-REF	15.98	21.86	24.17
M-70C30G	16.33	22.91	24.85
M-60C40G	16.59	23.43	25.64
M-50C50G	17.62	24.77	27.3

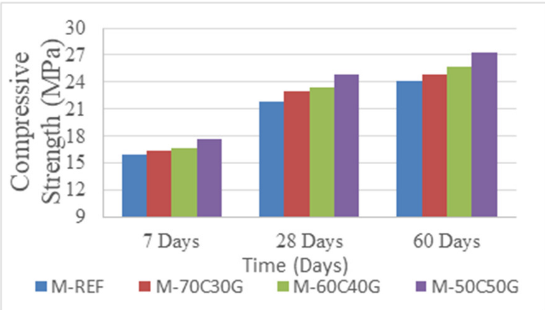

Fig. 6. Compressive strength test result.

D. Split Tensile Strength Results

Table XII and Figure 7 present the splitting tensile strength test results, which indicate how the fiber can improve tensile strength.

Using CF [12, 36] and GF [37] increases tensile strength. The fibers in the concrete composite prevent the cracks from growing and makes them stay in tension when they are transported from one end to the other, at which point they separate, pull out, or break from the matrix [38]. The results demonstrate that the tensile strength increased by 21.12%, 24.57%, and 31.03% after 7 days, by 13.82%, 18.91%, and 36.36% after 28 days, and by 14.7%, 18.15%, and 22.47% after 6o days for M-70C30G, M-60C40G, and M-50C50G, respectively.

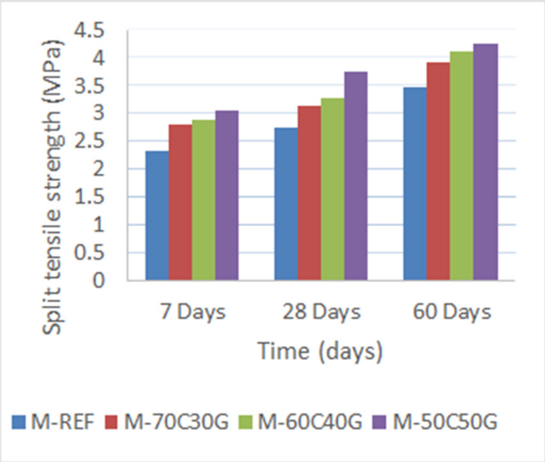

Fig. 7. Split tensile strength test result.

TABLE XII. SPLIT TENSILE STRENGTH TEST RESULT

Mix	Split tensile strength (MPa)		
	7 Days	28 Days	60 Days
M-REF	2.32	2.75	3.47
M-70C30G	2.81	3.13	3.98
M-60C40G	2.89	3.27	4.1
M-50C50G	3.04	3.75	4.25

E. *Flexural Strength Test Results*

Flexural strength was tested adopting the center-point method. The test used prisms measuring 50×50×300 mm at 7, 28, and 60 days. The test result is depicted in Table XIII and Figure 8.

TABLE XIII. FLEXURAL STRENGTH TEST RESULTS

Mix	Flexural strength (MPa)		
	7 Days	28 Days	60 Days
M-REF	2.34	3.6	4.32
M-70C30G	4.04	5.16	5.85
M-60C40G	4.12	5.28	5.96
M-50C50G	4.41	5.53	6.24

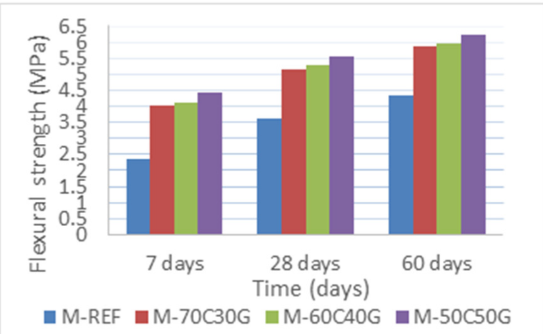

Fig. 8. Flexural strength test result.

Concrete flexural strength increased when using GF and CF [39] along with its mechanical properties [11, 44]. The flexural strength test results disclosed that incorporating fibers positively improved the flexural strength of the mixes, because the fibers resist the stresses they are exposed to and through which they are transferred to the solid parts of the matrix. The fibers act within the concrete as a bridge, preventing the spread of cracks and delaying their formation and expansion [40]. The addition of fibers to concrete increased flexural strength by 72.65%, 76.07%, and 88.46% after 7 days, 43.33%, 46.47%, and 53.61% the 28 days, and 35.42%, 37.96%, and 44.44% the 6o days for M-70C30G, M-60C40G, and M-50C50G, respectively.

F. *Thermal Conductivity Test Results*

Thermal conductivity was measured employing the hot wire technique after 28 days of curing. The thermal conductivity of perlite affects the decrease in thermal conductivity of perlite concrete. The decrease is directly proportional to content of expanded perlite [45]. The test results are displayed in Table XIV and Figure 9. Adding fibers to the perlite concrete increased the thermal conductivity by 30.18%, 20.85%, and 10.01%), compared with the mixture without fibers due to the high thermal conductivity coefficient of the fibers, especially CF, but overall the results were limited to insulating concrete (0.22-0.43 W/m.K) ASTM C332 [46].

TABLE XIV. THERMAL CONDUCTIVITY TEST RESULT

Mix	Thermal conductivity (W/m.K)
M-REF	0.3118
M-70C30G	0.4059
M-60C40G	0.3768
M-50C50G	0.3430

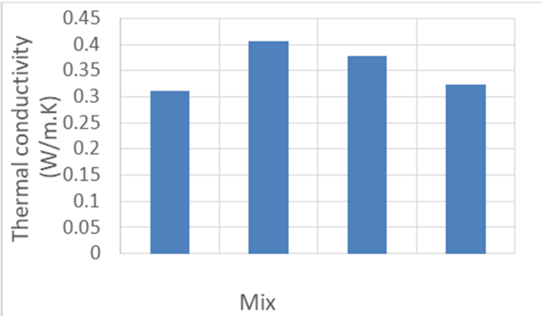

Fig. 9. Thermal conductivity test result.

IV. CONCLUSION

The main conclusions drawn from the findings obtained through this research are:

- The results of the slump test showed a decrease in slump value after adding fibers, but within the limitations of ACI 213 (maximum slump 125 mm) for structural lightweight aggregate concrete.
- Adding fibers to the concrete increased its density in general. The density was inside the limits of the structural lightweight aggregate concrete (1120–1920 kg/m^3).
- The compressive strength has slightly increased after the incorporation of fibers. In general, the former stayed in the range of the structural lightweight aggregate concrete (17-28 MPa) according to ASTM C330.

- The splitting tensile strength of the mix containing hybrid fibers has a higher value than that of the mix without fibers. The ASTM C330 requires that structural lightweight aggregate concrete possess a splitting tensile strength of at least 2.0 MPa.
- Adding hybrid fibers to perlite concrete resulted in a significant increase in flexural strength.
- Adding hybrid fibers in concrete increased thermal conductivity, but within the ASTM C332 (0.22-0.43 W/m.K) limits.
- The addition of hybrid fibers to the concrete improved its mechanical properties.
- Structural lightweight perlite concrete provides superior thermal insulation and reduced dead load and has good mechanical properties. So, it can be used in many applications when the weight of the structural component is important.

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