The Effect of Kevlar Fibers on the Mechanical Properties of Lightweight Perlite Concrete

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ABSTRACT

Fiber-reinforced concrete contains a fibrous material that increases its structural cohesion. The use of separate short fibers distributed in a random direction improves the strength of Lightweight Concrete (LWC) without exceeding its upper-density limit, improving its high fragility and mechanical properties compared to Natural-Weight Concrete (NWC). This study investigated the effect of adding Kevlar 49 fibers with three percentages of cement weight, 0.5, 1, and 1.5%, on the workability, dry density, and tensile and compressive strength of LWC. The use of Kevlar fibers in different proportions improves mechanical properties, significantly increases durability, and reduces the workability of LWC. The increase in compressive strength when adding 0.5% fibers was 19 and 15% and when adding 1% was 10 and 6%, after 7 and 28 days, respectively. At 1.5%, after 7 and 28 days, there was a decrease in compressive strength due to fiber agglomeration. Additionally, increasing the fiber dose from the optimal value caused a sharp decrease in workability by 37-40%.

Keywords-lightweight concrete; expanded perlite aggregate; silica fume; kevlar fibers

I. INTRODUCTION

There are many types of light marble since the greater their economic benefits, the greater the interest in its application in thermal insulation or in reducing dead loads, especially when used in tall buildings. The density of lightweight marble perlite aggregate used in structural concrete industries is 160-200 kg/m^3 [1-2]. One of its advantages is that, according to BS EN 206-1, it contains an oven-dried density between 800 and 2000 kg/m^3, where the manufacturing method is to completely or partially replace dense natural particles with lightweight sets [3-4]. According to BS EN 13055, LWC has a particle density of not more than 2.0 mg/m^3 and a dry bulk density of not more than 1200 kg/m^3. The distinction between these two density descriptions is that, according to BS EN 1097-33 and 1097-64, particle density refers to the mass of the separated aggregate particles per unit volume, and the bulk density is the mass of the dry fractions contained in a specified and specific volume. The aggregate that contains the least internal voids gives the lowest possible concrete density [5-6].

High-absorption materials typically result in compressive strength losses, which are typically proportionate to the replacement ratio. Low-absorption materials exhibit little fluctuations as well, and in some cases even demonstrate gains in strength and resistance. Concretes with a density of almost 2000 kg/m^3 do not exhibit fluctuations in this characteristic. Materials such as recycled glass exhibit little variation as the substitution ratio increases [7-8]. LWC is more affordable than traditional concrete due to its reduced weight, lower shipping cost, energy savings, and lower maintenance cost. This material is not commonly used in the structural industry due to its inferior mechanical qualities compared to standard concrete. Thus, Lightweight Fiber-Reinforced Concrete (LFRC) has been used in several engineering applications because it greatly enhances concrete performance by offering greater ductility than LWC, with polypropylene and steel fibers used in varied aspect ratios. Adding fibers to LWC can increase its flexural strength, tensile strength, and fracture toughness [9-11]. Fiber-Reinforced Composites (FRC) have received the most attention and have been used extensively due to their exceptional performance, high durability, affordable manufacturing cost, and superior mechanical properties, such as light weight and significant stiffness. The most important factors affecting the performance and strength of FRCs are the volume fraction, orientation, and materials of the fibers [12-14]. When a virtual crack erodes at the interface, strong and flexible kevlar fibers can extend along the grain structure to efficiently bond the local fracture, both superficial and subsurface. Using kevlar fibers in the interface can transform the bonding link by structural strengthening using carbon fibers (epoxy composite or epoxy gap repair) to a composite adhesive joint. This can be verified by examining two different surface repair tapes, epoxy alone and containing 6 mm short kevlar fibers in gray granite samples under 3-point peak bending loads and fracture energy [15]. As LWC is considered to have low strength, the use of fibers can improve its weak strength properties while maintaining its low density. In [16], reinforced concrete with steel fibers was significantly improved using 22% polypropylene fibers, showing that concrete made of coconut fiber reinforced with sisal fiber exhibited significantly improved compressive and tensile strength after 28 days, while fiber addition of 3.0% produced a maximum increase of 14% in tensile strength. According to [17], all minimum standards were met for concrete containing 1, 2, 3, and 4% sisal fibers by cement weight [18].

This study aims to reduce the dead loads in the structural parts, which can reduce the basic cost and the vertical or lateral pressure of the casting molds, and allow investigation of the expansion effect. Perlite aggregate is considered to have compressive strength and density similar to LWC. Therefore, it is necessary to investigate the effect of chemical and mineral additives to obtain the best compression resistance with the lowest density and suitable workability, in addition to determining the result of adding kevlar fibers to the performance properties of LWC and their optimal dosage.

II. EXPERIMENTAL WORK

A. Materials

Ordinary Portland cement (CEM I, 42.5R) was used conforming to [18]. Clean water was used in the mix and curing, conforming to [19]. Expanded Perlite Aggregate (EPA) was used as a fine aggregate, conforming to [20].

1) Silica Fume (SF)

SF is a very fine, sphere-shaped dust that is used as an additive to enhance concrete performance. Gray-colored SF was used. Tables I and II show its physical and chemical properties, which conform to [21].

TABLE I. CHEMICAL REQUIREMENTS OF (SF) [22]

Oxide composition	**Test results %**	**ASTM C1240**
Silicon oxide (SiO_2)	92.84	Min(85)%
Moisture content %	0.33	Max(3)%
Loss of Ignition	1.59	Max(6)%

TABLE II. PHYSICAL REQUIREMENTS OF (SF) [22]

Physical characteristics	**Test result**	**ASTM C1240**
Flow test %	117.5	115
Accelerated pozzolanic strength activities index with the OPC at7 days, min % of control (MPa)	107.5	Min (105)

2) Superplasticizer

BETONAC R 350 was used as a superplasticizer. It is a light brown liquid, has a density of 1.06±0.02 g/ml. Table III shows its properties [23].

3) Kevlar49 Fibers

Kevlar49 fibers have high modulus and are used in cable and rope products. Para-aramid is a strong, heat-resistant artificial fiber, associated with other aramids such as Nomex and Technora, and has a tensile strength of about 3900 GPa and a density of 1.44 kg/m^3. Table IV shows the kevlar 49 fiber properties used in this study. The percentages used were 0.5, 1, and 1.5% by concrete volume.

TABLE III. PHYSICAL REQUIREMENTS OF SUPERPLASTICIZER [24]

Property	**Measurement**
Appearance	Transparent or light brown liquid
Calcium chloride	Nil
Density (gm/ml)	1.10 ± 0.02
Viscosity	450 c Ps at 20 ºC
Setting time	Initial and final setting time depends on temperature
Dosage	150 -1000 ml / 100 kg of cement

TABLE IV. PROPERTIES OF KEVLAR 49 FIBERS

Description*	**Specification**
Color	Yellow
Tensile strength (GPa)	3.9
Density (g/cm^3)	1.44
Diameter (µm)	12
Avg. length (mm)	6
Aspect ratio (L/D)	500

*Given by the manufacturer

B. LWC Design and Mixing Procedure

A group of experimental mixtures was prepared based on previous studies and research to obtain a structural LWC with the desired and suitable properties. In these mixtures, the amount of cement and water, the quality, the mineral additives, SF, and the amount of superplasticizer were changed to obtain a design strength ranging from 3.7 to 17 MPa after 7 and 28 days. Table V summarizes the design of the LWC mixtures containing 0.5, 1, and 1.5% Kevlar 49 fibers by volume of concrete, 800 ml superplasticizer for each 100 kg of cement, and 10% SF by weight of cement [22].

TABLE I. LWC MIXTURE

Mix	**Ratio by volume**	**Cement content (kg/m^3)**	**EPA content (kg/m^3)**	**W/C**	**Superplasticizer (ml/100 kg)**	**SF (%)**	**Kevlar fiber (%)**
MC1	1:4	247.5	113.8	0.3	800	10	0
MC2	1:4	247.5	113.8	0.3	800	10	0.5
MC3	1:4	247.5	113.8	0.3	800	10	1
MC4	1:4	247.5	113.8	0.3	800	10	1.5

C. Sample Test Methods

1) Fresh Concrete Test (Flow Testing)

The flow was tested using (1). The test stopped and a flow value was calculated after 25 strokes [24]:

$$D(Flow) = [(D - 100)/100] * 100 \qquad (1)$$

where *D* represents the spread rate on the base diameter of the concrete.

2) Hardened Concrete Test

The oven-dried unit weight was calculated for the structural LWC using [25]:

$$Om(FloDensity) = (D * 997)/(F - G) \qquad (2)$$

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

a) Compressive Strength

This study used [26] to determine the compressive strength of LWC samples, using a compression device in the Construction Materials Laboratory at the University of Baghdad. The total number of cylinders used was 45 for each mixture with dimensions of 100×200 mm and a density of 800 kg/m^3. This test was performed for concrete cylinders of 7 and 28 days of age. The compressive strength was determined using the mean of three samples for each age. Each cylinder's compressive strength was estimated by:

$$F = P/A \tag{3}$$

where *F* is the compressive strength in MPa, *A* is the loaded surface area in mm^2, and *P* is the total maximum load in N.

b) Splitting Tensile Strength

Cylinder specimens with dimensions of 100×200 mm were used to determine the splitting tensile strength [10]. This test was carried out in the Construction Materials Laboratory at the University of Baghdad. The total number of cylindrical samples was 24, and the cylinders were tested after 7 and 28 days, while the mean of two cylinders was calculated by [19]:

$$T = (2 * P)/(\pi * l * d) \tag{4}$$

where *T* is the splitting tensile strength in MPa, *l* is the length of a sample in mm, *P* is the maximum applied load in N, and *D* represents the diameter in mm.

III. RESULTS AND DISCUSSION

A. Fresh Properties

1) Flow Test

A flow test was carried out to evaluate the workability of LWC mixes according to [25]. Table VI shows the results of the flow test, indicating that increasing the kevlar fiber ratio reduces the workability of the mix, requiring the addition of a superplasticizer to keep the acceptable flow range 110 ± 5 at the same w/c ratio of 0.30. LWC containing 1 and 1.5% kevlar fibers required more superplasticizer than those containing 0 and 0.5% to achieve the specification flow. Kevlar fibers tend to consume the water in the mix, requiring increased amount of water to keep the flow within the specified range [20].

TABLE II. LWC FLOW PROPERTIES OF LWC

LWC mix	KF %	Flow (%)
MC1	0	117.75
MC2	0.5	111
MC3	1	110.7
MC4	1.5	108.25

B. Hardened Properties

1) Dry Density

Table III and Figure 1 show the oven-dried density of LWC according to [26]. The oven-dried density of MC1 indicates that it is LWC. The density increases with kevlar fiber content because fibers tend to fill the gaps and the cellular structure from the expanded perlite addition, causing an increase in the density of LWC [27].

TABLE III. LWC DENSITY

LWC mix	KF %	Density (kg/m^3)
MC1	0	1266
MC2	0.5	1390
MC3	1	1454
MC4	1.5	1477

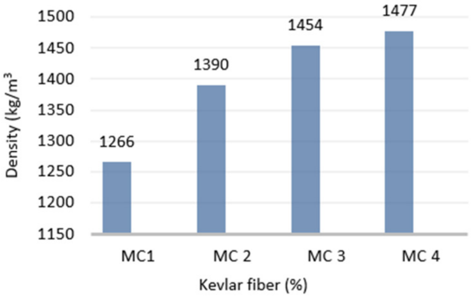

Fig. 1. Dry density of LWC.

2) Compressive Strength

Figure 2 and Table IV show the average values of the three cylinders recorded at 7 and 28 days of curing. For all samples, the compressive strength increased with curing age. When kevlar fibers were added, the compressive strength increased for MC2 and MC3, as the fibers work as a reinforcement for LWC, coinciding with the findings of [28-29]. For the MC4 samples, the compressive strength decreased below the value of MC1, demonstrating that excessive addition of fibers (more than 1.5%) reduces the mechanical properties of LWC, which could be attributed to slippage of the interlayers in the microstructure of LWC and Kevlar fibers.

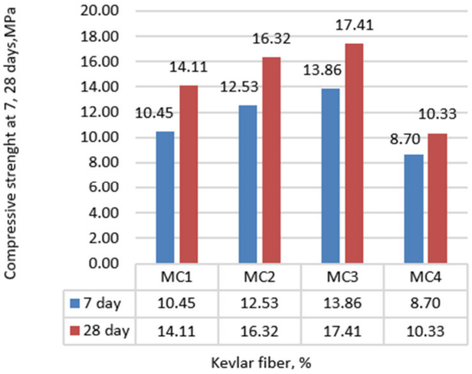

Fig. 2. Compressive strength of LWC cured for 7 and 28 days.

TABLE IV. COMPRESSIVE STRENGTH OF LWC

LWC Mix	KF %	Compressive strength		Change (%)	
		7 days (MPa)	28 days (MPa)	28 days	7 days
MC1	0	10.45	14.11	-	-
MC2	0.5	12.53	16.32	15.6	19.9
MC3	1	13.86	17.41	23.4	32.6
MC4	1.5	8.7	10.33	-26.8	-16.7

3) *Splitting Strength*

Table V and Figure 3 show the splitting strength results of LWC cured for 7 and 28 days with and without the addition of kevlar fibers. For all samples, the splitting strength increased with curing age. The addition of kevlar fibers (MC2, MC3, and MC4) provided a substantial increase in splitting-tensile strength. The results were approximately 30% higher with the addition of 1% kevlar fibers at 28 days of curing. MC3 had the best performance, which could be possibly an indication of the good bonding between the fibers and the concrete matrix and the higher bond developed at the interface of the fiber and the concrete matrix [30].

TABLE V. SPLITTING STRENGTH OF LWC

LWC Mix	**KF %**	**Splitting strength**		**Change (%)**	
		7 days (MPa)	**28 days (Mpa)**	**28 days**	**7 days**
MC1	0	1.57	1.91	-	-
MC2	0.5	1.65	2.16	13	5.1
MC3	1	1.7	2.5	30.9	8.2
MC4	1.5	1.43	1.52	-20.4	- 9

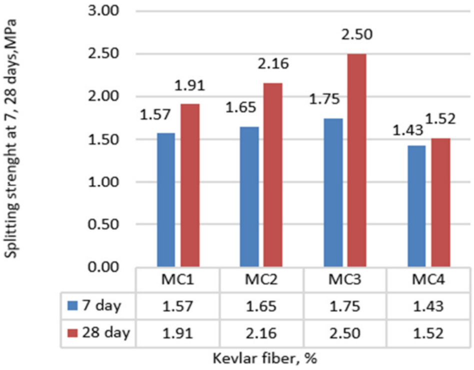

Fig. 3. Splitting strength of LWC cured for 7 and 28 days.

IV. CONCLUSIONS

This study investigated the best mixing ratio of LWC using lightweight Expanded Perlite Aggregate (EPA) reinforced with kevlar fibers due to its charming mechanical properties, including low density and high strength, compared to other conventional homogeneous materials. The following conlcusions were drawn from this study:

- As the lightweight aggregate percentage increases, the dry density of concrete decreases in all mixture designs. After adding kevlar fibers, a slight increase in dry density was observed because.
- The workability of fresh concrete gradually decreased after adding kevlar fibers, due to the fiber agglomeration and poor distribution, as well as the high water absorption of the fiber, which requires additional mixing water.
- The increase in compressive strength after adding 0.5% fibers was 19.9 and 15.6% compared to the reference mixture after 7 and 28 days, respectively. This increase was 32.6 and 23.4% after 7 and 28 days, respectively, for 1% fibers, which is the optimal value of addition, but decreased by 16.7 and 26.8%, respectively, when the dose increased to 1.5%.
- The increase in splitting strength after the introduction of 0.5% fibers was 5.1 and 13% after 7 and 28 days, respectively. The respective increase when adding 1% fibers was 8.2 and 30.9% after 7 and 28 days, respectively, which was the optimal dose. When the fiber dose increased to 1.5%, the splitting strength decreased by 9 and 20.4% after 7 and 28 days, respectively, due to the low workability and low mixing water, leading to nonhomogeneity of the mixture.

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