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Mechanical behavior of Structural Pumice Lightweight Concrete Reinforced with Glass Fiber

Abbas Ali Nassif *, **Ikram Faraoun Al-Mulla**

Department of Civil Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq

ABSTRACT

Traditional concrete has gained several uses in recent decades; yet, it poses some concerns in the building business. The weight of the product is a limitation when it is used in applications that are more specialized. As a result, the building and construction sectors were the ones to introduce the idea of lightweight concrete. In this study, five different pumice lightweight mixtures were utilized (a reference mix that did not include any fiber, a mix that contained 1% glass fiber, a mix that contained one layer of fiber glass mesh, a mix that contained three layers of fiber glass mesh, and a hybrid mix that had both glass fiber and three layers of fiber glass mesh). Every single one of the mixtures that were used underwent tests to determine their compressive strength, center point flexural strength, and splitting tensile strength. Compressive strength, splitting tensile strength, and flexural strength all increased by (20.39%, 138%, and 60.68 %), respectively, as a consequence of the inclusion of fibers into lightweight concrete, according to the findings. There was also a significant improvement in the material's overall mechanical characteristics.

Keywords: Lightweight concrete, Pumice, Glass fiber, Glass fiber mesh, Mechanical properties.

1. INTRODUCTION

Concrete technology has come a long way in a short amount of time. This has led to the creation of new kinds of concrete with special qualities, such as high-strength concrete, self-compacting concrete, fiber-reinforced concrete, and more. It has also made the material and mechanical qualities of normal-weight concrete (NWC), which is what people usually use, better. Light-weight concrete (LWC) (density between 1120 and 1920 kg/m^3) **(ACI 213R–03, 2003)** was designed to make buildings lighter and, as a consequence, reduce the amount of seismic stresses they had to bear. It achieves this while still preserving the strength of reinforced concrete buildings **(Badogiannis and Kotsovos, 2014)** and cutting construction expenses by a lot. There are, however, some issues, such as how poorly it works beyond the

*Corresponding author
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peak, both in tension and compression, how fragile it is, and how easy it is to see cracks, particularly when the material is new. Adding reinforcing fibers to lightweight aggregates has been found to make lightweight concrete stronger and more durable in both its fresh and hardened forms. This has led to the development of fiber-reinforced lightweight concrete (FRLWC), which has been employed in both real-life and experiments **(Fantilli et al., 2015; Caratelli et al., 2016).** Use of various aggregates, such as expanded clay, pumice, and all-lightweight materials, significantly influences the behavior of concrete. This study focuses on the influence of the mechanical characteristics of pumice fiber-reinforced lightweight concrete with glass fiber on its compressive strength, splitting tensile strength, and flexural behavior. Lightweight concrete has emerged as an essential construction material globally. Individuals often use lightweight materials, such as expanded perlite, due to their minimal mass. The base has substantial water storage and is lightweight. Recent investigations have shown that the composition of this concrete mix significantly influences its properties. The performance of the mixture will be contingent upon the quantities of cement, aggregate, and additives it contains. The concrete displayed decreased weight and strength as a result of using lightweight aggregate. These modifications, however, enhanced these exceptional attributes. It was also shown that it is conceivable to adjust the quantities of the components to create an ideal combination that would provide a strong and durable concrete mix **(Jssem and Fawzi, 2024).** They utilized fine carbon in different amounts and lengths. They employed fibers that were 5 mm, 20 mm, and 30 mm long and had 0.5% and 1% carbon. Some of the natural sand was replaced with lightweight aggregates in different amounts. 0.5% and 1% carbon fibers made splitting tensile strength and flexural isolation better than short-grain concrete or fiber-containing concrete without reinforcement. Concrete's mechanical qualities became better as the fiber length was increased to 20 and 30 mm. But when some of the sand was replaced with fine to moderate lightweight aggregates, the mix became lighter and more consistent than the reference mix two quantities of lightweight aggregates were used to replace some of the natural sand **(Mohammed et al., 2023).** The use of cementitious elements in lightweight concrete mix enhances its compressive strength, density, and thermal insulation. This method transforms broken bricks into coarse aggregates, enhancing their heat-retaining properties. The best concrete has the highest compressive strength (31.240 MPa) and lowest density (1810 kg/m^3), achieved by adding the correct amount of carbon powder. Super-Plasticizer, when combined with carbon powder, improves the concrete's density and compressive strength. After 28 days, it is denser and stronger than regular lightweight concrete **(AlKarawi and Al Azzawy, 2024).** Examined the efficacy of fiber-reinforced lightweight concrete using pumice stone as a partial substitute for coarse aggregate at 20% and 40% ratios. Polypropylene and glass fibers were included at different concentrations of 0.5%, 1%, and 1.5%. The mechanical parameters, including compressive strength, splitting tensile strength, and flexural strength, were assessed at 7 and 28 days. The investigation indicated that the incorporation of fibers markedly improved tensile and flexural strength; however, an excessive amount of pumice or fiber resulted in diminished compressive strength. These results underscore the possibility of integrating pumice lightweight aggregate with fiber reinforcement to enhance the overall performance of lightweight concrete **(Karthik et al., 2015).** Lightweight aggregate (LWA) can be produced using Iraqi bentonite clay and sodium silicate from the glass industry. The mixture is heated at 750-800°C for two hours, resulting in a product with good physical properties like a Specific gravity of 1.5, a bulk density of 543 kg/m3, and a 20% water absorption rate. This material was used to create structural lightweight aggregate concrete (SLWAC), which has a compression strength of 23 N/mm^2, an oven-dry density of 1720 kg/m^3, an 8.5% water absorption rate, and a non-thermal conductivity of 0.723 W/m. SLWAC can be used in various structural applications and contributes to the reduction of pollution and eco-friendly building materials **(Khalil et al., 2015)**. The study investigated the impact of natural coarse aggregate and fibers on the strength and quality of low-grade geopolymer concrete (LWGPC). The results showed that adding 25% pumice aggregate and 1% to 2% fiber increased compressive strengths to 27 MPa and 14 MPa. The best compressive strength was found at 12MPa, and the highest flexural strength at 13MPa. The study also found that mixing volcanic aggregate and fiberglass with alkali can enhance the strength of lightweight geopolymer concrete, achieving compressive strengths exceeding 25 MPa, and reducing environmental impact **(Al-Naji et al., 2024).** Experimental work compared the structural properties of M40 grade light-weight concrete using pumice stone as a partial replacement for natural coarse aggregate and mineral admixtures. The modified concrete is 23.8% less dense and has a higher density. Pumice stone reduces compressive, splitting, and flexural strengths. Adding more admixtures increases strength and average design strength **(Singh, 2017).**

The aim of this study is to explore the impact of glass fibers and meshes on the mechanical properties of pumice lightweight concrete. Unlike previous studies, it uses five lightweight mixes, including single fibers, one-layer and three-layer meshes, and a hybrid mix. The study evaluates compressive, splitting tensile, and flexural strength, providing a reliable database for modern construction applications.

2. EXPERIMENTAL PROGRAM

2.1 Materials Properties

2.1.1 Cement

Ordinary Portland cement (CEM I, 42.5R) was utilized, which follows Iraqi **(IQS No.5, 2019)**. **Tables 1 and 2**. Illustrate the physical and chemical characteristics of the cement.

Table 1. Cement chemical composition and main component.

Oxide Compositions	**Test results**	**Limits of (IQS No. 5, 2019)**
Lime (CaO)(%)	60.35	-----
Iron oxide (Fe_2O_3)(%)	4.16	-----
Alumina(Al_2O_3)(%)	5.08	-----
Silica (SiO_2)	20.64	-----
Insoluble residue (IR)(%)	0.86	≤ (1.5)
Magnesia (MgO)(%)	3.86	≤ (5)
Loss on Ignition (LOI)(%)	3.21	≤ (4)
Sulfate (SO_3)(%)	2.67	SO_3≤ 2.8 if C3A > 3. 5 SO_3≤ 2.5 if C3A ≤ 3.5
Main Compounds of Cement		
Tri-Calcium Silicate (C3S)(%)	41.07	----
Dicalcium Silicate (C2S)(%)	28.27	----
Tricalcium Aluminate (C3A)(%)	6.43	----
Tetra-calcium Aluminate –Ferrite (C4AF)(%)	12.64	----

Table 2. Physical requirements of the cement

Physical properties	Value	Limits of (IQS No. 5/2019)
Specific surface area (Blaine's approach) (m^2/ kg)	349.8	≥ 280
Setting time Initial setting (min)	90	≥ 45 min
Setting time Final setting time	4.42 hr	≤ 10 hr
Soundness by Autoclave Approach (%)	0.19	≤ 0.80
Compressive Strength (MPa)		
Compressive Strength (MPa)at age (2) day	21.75	≥ 20
Compressive Strength (MPa)at age (28) day	46.63	≥ 42.5

2.1.2 Sand (Fine aggregate)

The sand sieve grading and the main characteristics were confirmed with the Iraqi Standards **(IQS No.45, 1984)** and lie in Zone Two. **Table 3** shows the physical and chemical properties, and **Table 4** shows the sieve analysis of the sand used.

Table 3. Chemical and physical properties of fine aggregates.

Property	Test result	(IQS No.45, 1984) Limits
Specific gravity	2.6	---
Absorption, %	0.72	---
Density (kg/m^3)	1580	---
Sulfate content,% (SO_3)	0.343	0.50% (max)

Table 4. Grading of sand.

Sieve size(mm)	Passing %	Requirements of (IQS No.45,1984) zone 2
10mm	100	100
4.75mm	95	90-100
2.36mm	80	75-100
1.18mm	78	55-90
600 µm	55	35-59
300 µm	26	8-30
150 µm	5	0-10
Finance modulus (F.M)=2.61		

2.1.3 Coarse Aggregate (pumice)

The pumice complied with **(ASTM C330, 2017**) standards. The grading and properties of pumice are shown in **Table 5.**

Table 5. Grading and properties of pumice.

Physical properties		
Density (kg/m^3)		656
Hardness (MOHS)		6
Softening point (^{o}C)		900
Color		white
Absorption %		28
Grading of pumice		
Sieve size(mm)	Passing %	Requirements of **(ASTM C 330, 2017)**
19	100	100
12.5	95	85-100
9.5	40	10-60
4.75	8	0-15

2.1.4 Silica fume (SF)

The silica fume strength activity index records 121% and conforms to **(ASTM C1240, 2015)**. **Tables 6 and 7** provide the technical information for silica fume.

Table 6. Physical tests of silica fume (SF)

Physical properties	**Test results**	**(ASTM C-1240, 2015) Specification**
Percent Retained on 45-µm (No. 325) sieve (%)	7	≤10
Accelerated Pozzolanic strength Activity Index with Portland cement at 7 days (MPa)	121	≥105
Specific surface m^2/g	10	≥15

Table 7. Chemical analysis of silica fume (SF).

Oxide Composition	**Test results**	**(ASTMC1240, 2015) Specification**
Sio_2 (%)	92.84	≥85.0
Al_2O_3 (%)	0.37	--
Fe_2O_3 (%)	1.31	--
Cao (%)	1.9	--
SO_3 (%)	0.65	--
Mgo (%)	2.4	--
Na_2O(%)	0.1	--
K_2O (%)	0.09	--
Moisture Content (%)	0.33	≤3.0
Loss on Ignition (%)	1.59	≤6.0

2.1.5 Water

The water used in this study for mixing is drinking water and complies with **(IQS 1703, 2018).**

2.1.6 Glass Fibers

Glass strand fiber, Alkali-resistant, has a length of 12 mm, with a diameter of 0.15 mm, and an aspect ratio is 80. **Fig. 1 and Table 8** offer the supplier's specifications and features of the fiber applied in the experimental work.

Table 8. Characteristics of the (GF).

Properties	Details
Appearance	Opaque
Fibre Length	12 mm
Fibre diameter	0.15 mm
Specific Gravity	2.68 g/cm^3
Absorption	Nil
Resistance to Chemical	Very High
Elasticity Modulus	72 GPa
Tensile Strength	1,700 MPa
Soft-Point	860°C

*According to the manufacturer Sika Co. Ltd.

Figure 1. Glass Fibers

2.1.7 Admixture-Super-plasticizer (SP)

The used superplasticizer is a high-performance one that necessitates slump retention, good workability, enhanced flexure and compressive strengths, and reduced shrinkage and creep. It fulfils **(ASTM C494, 2013)**. Type A and G. The optional dosage by the manufacturer will typically range from 0.5 to 1.5% by weight of cementitious binder. **Table 9** shows the technical data sheet for this type of superplasticizer.

Table 9. Technical properties of superplasticizer.

Color	Whitish Liquid
Ph	3-4.5
Density	1.06+-1.08
Chloride Content	Nill

2.1.8 Fiber glass mesh (FGM)

One type of reinforcement used in this experiment is fiberglass mesh, which is available in the local market and used in construction fields. It was implemented in the mixes in one layer and three layers, as shown in the **Table 10 and Fig. 2.**

Table 10. Mechanical properties (FGM)

Dimensions	square opening size of (3 mm)
Diameter	(0.5 mm) diameter
Tensile Strength	1034 (MPa)

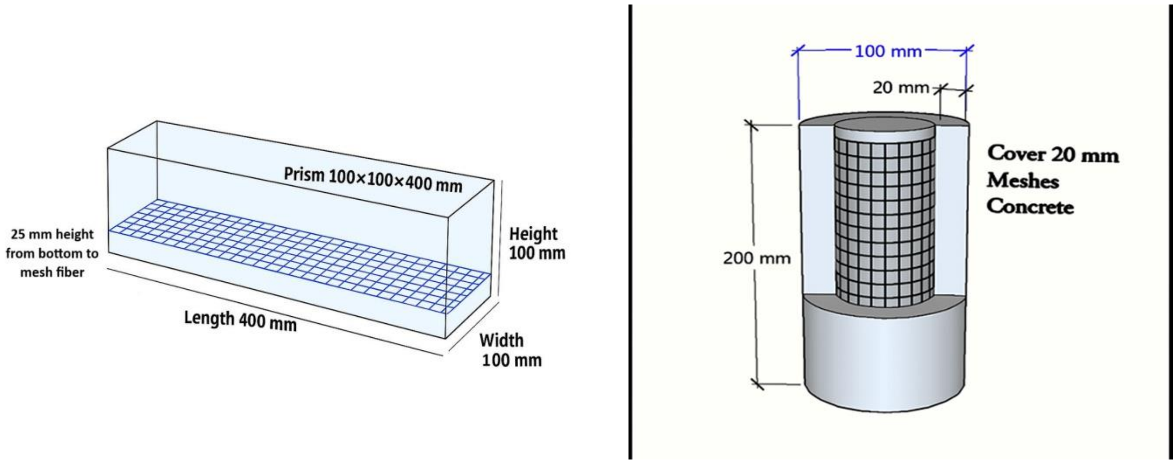

Figure 2. Position of the glass mesh in the cylindrical and prisms sample

Mixtures were designed by **(ACI-211.2-98, 2004)** and were produced after many trial mixes until the final utilized in this research the targeted compressive strength more than17MPa. Mixing, curing and sample preparations were conducted according to (**ASTM C192, 2015)**. **Table 11** contains information on the mixtures.

Table 11. Mix proportion by weight (kg/m^3)

Mix	Cement	Sand	Pumice	Silica fume	Glass fiber Vol%	Fiber Glass Mesh	SP%	W/b %
MR	450	775	490	50	----	---	1.25	0.33
M1%GF	450	775	490	50	1	---	1.25	0.33
M FGM 1 Layer	450	775	490	50	----	1 Layer	1.25	0.33
M FGM 3 Layer	450	775	490	50	----	3 Layer	1.25	0.33
M Hybrid3 Layer + 1% GF	450	775	490	50	1	3 Layer	1.25	0.33

2.2 Preparation of Concrete Specimens

The first step in preparing the samples was to oil and clean the inside of the plastic molds so that they would not stick to the concrete when it had hardened. We poured multiple layers of concrete into the molds and crushed each one in a vibrating table until it took quite some time to waste any air that might have been trapped in. Hand level of specimens was achieved by hand-trowelling of specimen and compacting hand-trowelled specimen. They were then covered with a sheet of nylon to continue regulating the quantity of humidity in the area to be approximately 24 hours. The samples out of the molds were taken and allowed to cure to the test. Each concrete mix will be analyzed in terms of dry density, compressive strength, and water absorption using the Cube (100x100x100) mm specimens. To test flexural strength, the prism we used was (100x100x400) mm, a cylinder of size (100x200) mm was used to test splitting tensile strength

2.3 Experimental Tests

2.3.1Compressive Strength Test

According to **(BS-EN-12390-3,2019)** to test the compressive strength of the concrete cube (100×100×100) mm. For each blend, three samples were examined and the average was taken. The samples were tested 28, 60, and 90 days after they were cast. The concrete samples were put through tests until they broke. Before putting the concrete cubes into the compression equipment, they were carefully cleaned on all sides. This step made guaranteed that the compressive force would be applied evenly and at a right angle to the way the concrete was poured into the molds. The Building Materials lab at the University of Baghdad tested this experiment. **Fig. 3** depicts the hydromechanical test equipment used for this test, which had a capacity of 2000 KN and a loading rate of 2.5 MPa/s. We use the following equation, Eq. (1), to get the compressive strength of each specimen:

$$fc=P/Ac \quad (1)$$

where:
fc: Compressive Strength (MPa).
P: Maximum applied -load, (N).
Ac: Cross section area (mm^2).

Figure 3. Compressive Strength Test

2.3.2 Splitting Tensile Strength Test

The tensile strength test checked how well the concrete could handle fractures in a roundabout fashion. We used the **(ASTM C496, 2017)** to check the splitting tensile strength of the cylinder is (100 x 200) mm. For this test, a concrete cylinder would be forced down on its side until it cracked from the stress. The cylinders were checked again after 28, 60, and

90 days. The test sample of split tensile is shown in **Fig. 4.** The Building Materials lab at the University of Baghdad tested this experiment. We used the calculations in Eq. (2) below to get the average of the three cylinders:

$$ft = \frac{2P}{\pi ld} \quad (2)$$

where:
ft: Tensile strength (MPa).
P: Applied load, (N).
d: Diameter of cylinder, (mm).
l: Length of cylinder, (mm).

Figure 4. Splitting Tensile Strength Test

2.3.3 Flexural Strength Test

Prisms measuring (100×100×400) mm are utilized to measure Center point flexural strength according to **(ASTM C-293, 2002).** The test is administered at 28, 60, and 90 days of age. The testing apparatus is used to conduct a center-point flexural strength test, shown in **Fig. 5**. The listed reading represents the average of three specimens. The formula was used in Eq. (3) to calculate the rupture modulus.

$$f_r = \frac{3PL}{2bd^2} \quad (3)$$

where:
fr: Flexural strength (MPa).
P: Load (N).
L: Length between support (mm).
b: specimen width (mm).
d: depth of specimen (mm).

Figure 5. Flexural Strength Test

3. RESULTS AND DISCUSSION

The test results for Compressive, flexural, and splitting tensile strength for the used mixes are introduced in **Table 12 and Figs. 6 to 11**.

Table12. Results of the mixes

Mix	Compressive strength			Flexural strength			Splitting tensile strength		
	28 day	60day	90day	28 day	60 day	90 day	28 day	60 day	90 day
Mr	18.98	21.23	23.66	3.22	3.46	3.6	1.38	1.43	1.73
M1%GF	20.7	22.56	24.56	4.3	4.5	4.7	2.68	3.35	3.53
M FGM 1 layer	21.68	23.63	24.83	3.27	3.49	3.65	2.22	2.37	2.92
M FGM 3 layer	22.73	23.85	25.18	3.6	3.73	3.9	2.47	2.79	3.5
M hybrid 3 Layer	22.85	23.94	25.68	3.9	4.52	4.93	2.95	3.41	3.64

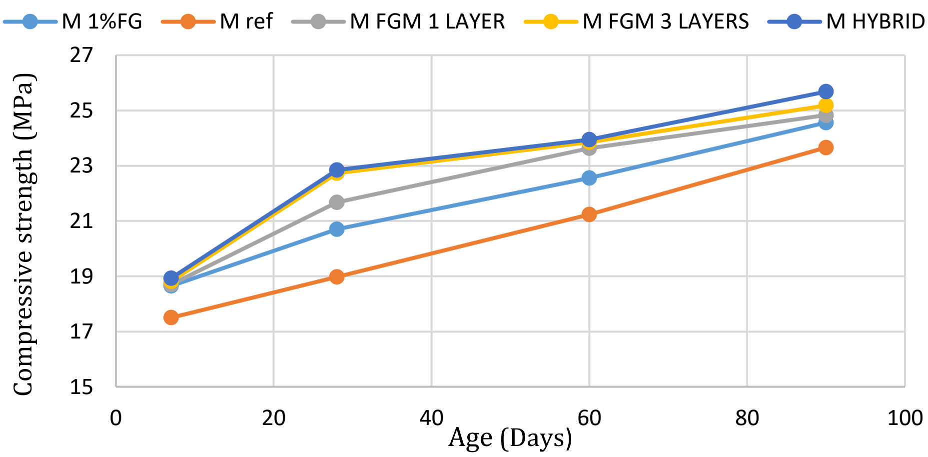

Figure 6. Compressive strength with time for all mixes

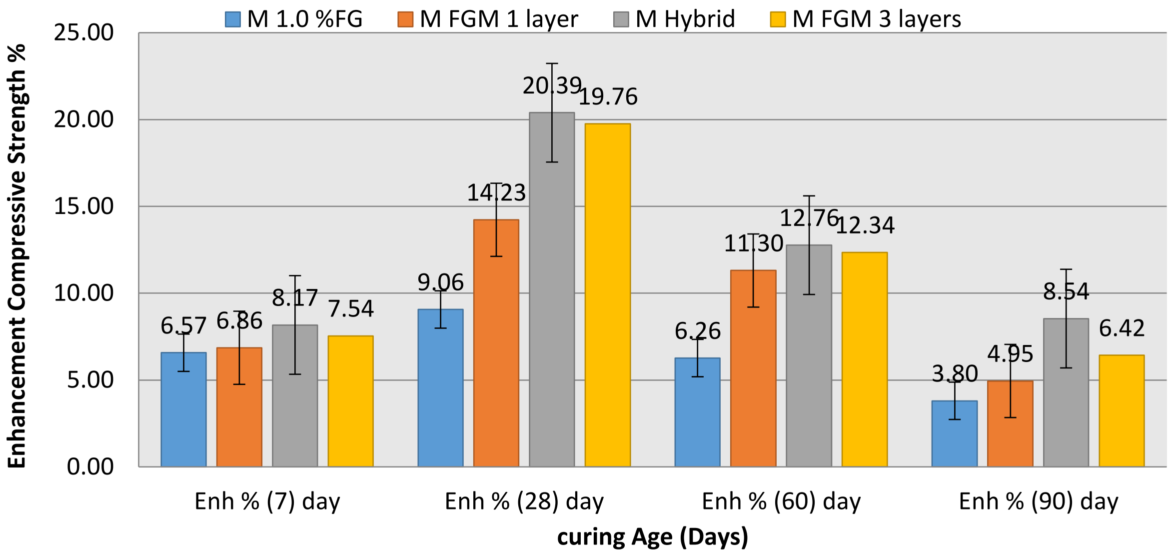

Figure 7. Error bars for compressive strength % enhancement

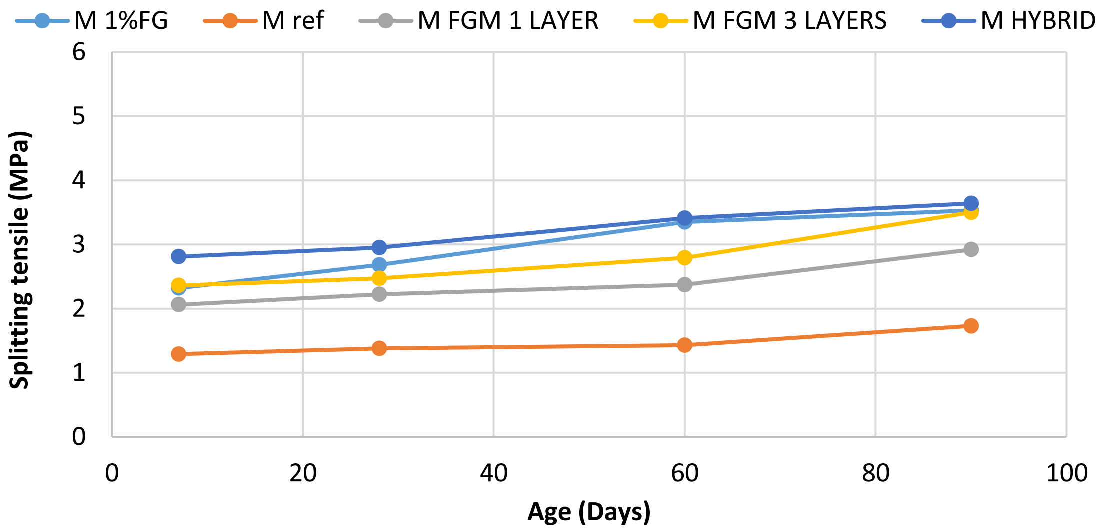

Figure 8. Splitting tensile strength with time for all mixes

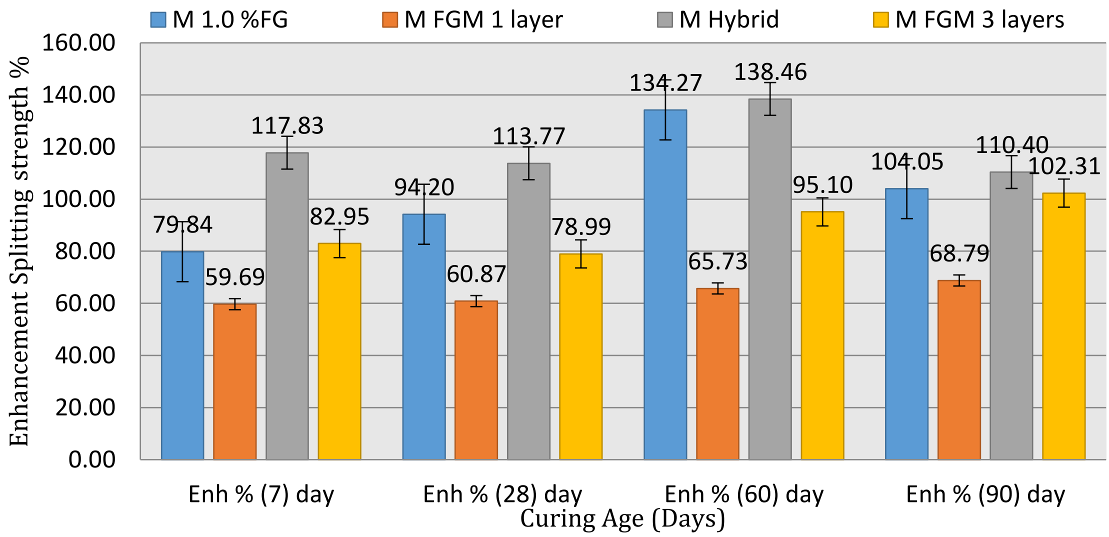

Figure 9. Error bars for splitting tensile strength % enhancement

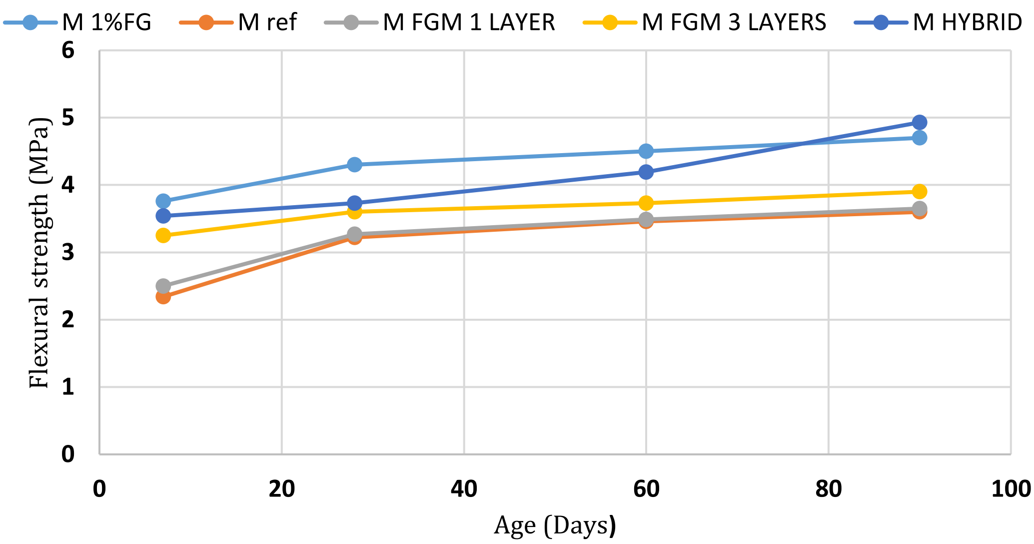

Figure 10. Flexural strength with time for all mixes

From the results, it can be observed that the compressive, splitting tensile, and flexural strengths show enhancement of about 20.39%, 138%, and 66.67%, respectively, compared to the reference mix. This may be attributed to the nature of the stresses applied to the samples, as the splitting shows an enhancement of 138% due to the pure tensile forces resisted by the fibers and meshes. The flexural shows 66.67% enhancement compared to the reference mix, since the flexural test applies compressive strength at the top of the prism and flexural stresses at the bottom of the prism.

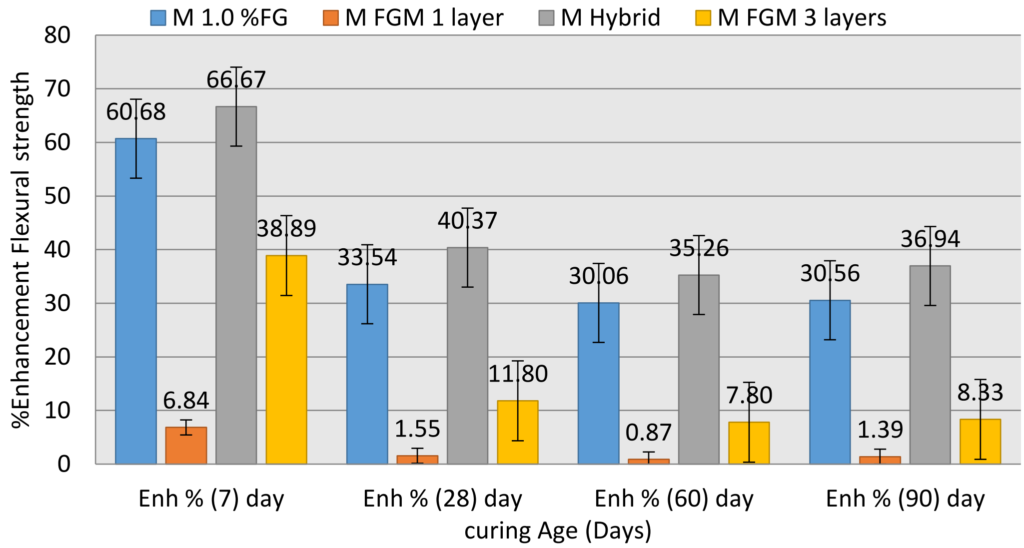

Figure 11. Error bars for flexural strength % enhancement

From the above figures, it can be noticed that the maximum compressive strength was recorded for mixes reinforced with hybrid glass fibers and mesh **(Fig. 6)**, with an improvement of about 20% **(Fig. 7).** This behavior is due to the crack-arresting technique that can be acquired when using fibers and mesh, and this attitude is in conformed with **(Badogiannis et al., 2010; Al-Mulla et al., 2024).** Whereas, the maximum splitting tensile strength **(Figs. 8 and 9)** was recorded for mixes with hybrid reinforcement, with an improvement of 138% compared to the reference mix. This behavior is due to the weak behavior of lightweight concrete in tension and the superior performance of fibers in tension due to their high elasticity; such behavior conforms with **(Al-Mulla et al., 2024; Badogiannis et al., 2006; Al-Mulla and Al-Rihimy, 2025).** For flexural strength **(Figs. 10 and 11),** the mixes with hybrid reinforcement show better behavior than other mixes due to the combined effect of the fibers and meshes in enhancing the bending behavior of the mixes **(Abd and Ahmed, 2021; Abd Al Kareem and Ahmed, 2021; Zhang et al., 2019; Gharkan, 2017).**

4. CONCLUSIONS

This research investigated pumice lightweight concrete reinforced with glass fibers to improve its mechanical properties. The findings indicated that mixtures with hybrid and glass fiber reinforcement exhibited the most significant enhancements in compressive, flexural, and splitting tensile strengths. The error analysis validated the dependability of these improvements.

1-The use of Pumice lightweight aggregate introduces promising results in producing structural lightweight concrete of compressive strength above 17 MPa.
2- Mixes with hybrid reinforcement, glass fiber meshes, and glass fibers recorded the best results for compression, flexural, and splitting.
3- The highest improvement for the used mixes was recorded in comparison with the reference mix. The results revealed 20.39%, 138%, and 66.67% for compressive, splitting tensile, and flexural strength, respectively.
4-The error bars show an overlap between the same mixes while the different mixes record no overlap.

NOMENCLATURE

Symbol	Description	Symbol	Description
GF	Glass Fibers	SP	Super-plasticizer
SF	Silica fume	FGM	Fiber glass mesh

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Credit Authorship Contribution Statement

Abbas Ali Nassif: Conceptualization, Methodology, Data curation, Writing – original draft. Ikram Faraoun Al-Mulla: Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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السلوك الميكانيكي للخرسانة الإنشائية خفيفة الوزن المقواة بالألياف الزجاجية

عباس علي نصيف *، اكرام فرعون احمد

قسم الهندسة المدنية ،كلية الهندسة، جامعة بغداد، بغداد، العراق.

الخلاصة

اكتسبت الخرسانة التقليدية تطبيقاتٍ عديدة على مدار العقود الماضية، إلا أنها تواجه بعض التحديات في مجال البناء. ومن بين قيودها وزنها عند استخدامها في تطبيقات خاصة. لذلك، برزت ابتكارات الخرسانة خفيفة الوزن في قطاع البناء والتشييد. تم تنفيذ خمسة خلطات خفيفة الوزن من الخفاف في هذا البحث (خلطة مرجعية بدون ألياف، خلطة ألياف زجاجية 1%، خلطة شبكة ألياف زجاجية أحادية الطبقة، خلطة شبكة ألياف زجاجية ثلاثية الطبقات، خلطة هجينة (من ألياف زجاجية وشبكة ألياف زجاجية ثلاثية الطبقات). تهدف هذه الدراسة إلى دراسة الخواص الميكانيكية للخرسانة خفيفة الوزن من الخفاف المقواة بألياف زجاجية وشبكات من ألياف زجاجية. تم إجراء قوة الضغط، وقوة الانحناء عند نقطة المركز، وقوة الشد الانشطاري على جميع الخلطات المستخدمة. أظهرت النتائج أن دمج الألياف في الخرسانة خفيفة الوزن أدى إلى تحسن في الخواص الميكانيكية للمادة بنسبة (20.39%، 138%، و60.68%) لقوة الضغط، وقوة الشد الانشطاري، وقوة الانحناء على التوالي. وقد ثبت ذلك من خلال حقيقة أن دمج الألياف أدى إلى زيادة كبيرة في قوة المادة.

الكلمات المفتاحية: الخرسانة خفيفة الوزن، الخفاف، الألياف الزجاجية، شبكة الألياف الزجاجية، الخصائص الميكانيكية.