

Research Article

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Sustainable high-strength lightweight concrete with pumice stone and sugar molasses

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Abstract: The building sector benefits from high-strength lightweight concrete (HSLWC) in various aspects, particularly in reducing the structure's dead load. Incorporating waste materials into HSLWC encourages sustainable practices, reduces their environmental effect, and decreases product's costs. This research focuses on producing sustainable HSLWC using a pumice stone and additive materials such as sugar molasses, silica fume, and high-range water reduction. The physical and mechanical properties and structural efficiency were investigated. The results demonstrate that the inclusion of additive material is the primary factor controlling the properties of the concrete. Also, using pumice stone instead of gravel in high-strength concrete significantly reduced weight and increased thermal insulation by 19.31 and 43.55%, respectively. Furthermore, the addition of steel fibers in HSLWC improved the compressive strength, tensile strength, ductility, and structural efficiency.

Keywords: high strength–lightweight concrete, pumice stone, sugar molasses, ultrasonic pulse velocity, brittleness ratio

1 Introduction

Construction materials with enhanced mechanical and operational capabilities are required to construct unique buildings and structures. Conventional concrete (CC) has several flaws, one of which is a low strength-to-weight ratio [1], and to address these flaws, unique concrete varieties such as high-strength (HS) concrete of the normal

weight, structural lightweight concrete (SLWC), and most recently, high-strength lightweight aggregate (LWA) concrete have been developed [2]. HS concrete that has been predicated on utilizing very effective silica fume (SF) and high-range water-reducer combinations has improved structural engineering features such as higher compressive and tensile strengths, durability, and stiffness. Also, it allows engineers to use smaller structural parts [3]. The past studies [4–6] produced SLWC by utilizing a variety of LWAs and investigated their characteristics. They found that it has more advantageous than CC because of the reduced self-weight and construction costs, so the building industry has recently seen an increase in its use. Pumice stone is the most commonly used aggregate type in lightweight concrete production because of its porous structure [7]. Recent studies focused on the high-strength lightweight concrete (HSLWC) to investigate its characteristics and advantages of using higher strength and lower unit weight in the same type of concrete [8]. Concrete has a high degree of brittleness, which leads to poor tensile strength, crack propagation resistance, fracture toughness, and impact strength. Concrete usage in industries requiring high impact and fracture strengths has been constrained by its inherent brittleness. However, fibers can improve strength and ductility by modifying tensile and flexural strengths, toughness, fracture energy, impact resistance, and the development and proliferation of cracks [9]. Conserving energy, expanding concrete service life, enhancing structural efficiency (SE), minimizing transportation requirements, using wastes or by-product materials, lowering carbon footprint, and internal curing structural LWA contribute to the sustainable development of concrete [10]. Maintaining a sustainable ecosystem and manufacturing durable materials are critical to protecting the world. Al-Mamoori and Al-Mamoori [11] tested HS concrete of normal weight with the sugar molasses (SM) inclusion as a by-product material and studied its effect on the properties of concrete. They found that using SM that played as a retarder material also improved the strength of concrete and increased its workability. The research methodology consists of many steps: preparing the raw material, executing their tests, conducting the trial

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mixes to select the proper mix proportion for each concrete type, casting and curing of specimens, and finally testing the specimens and discussing their results. This methodology was implemented to achieve the aim of this research, *i.e.*, to investigate the possibility of replacing gravel in HS concrete with a pumice stone to produce HSLWC by incorporating SM and reinforcing it with steel fibers to reduce ductility deficiency, and also to compare its physical and mechanical properties with normal-strength (NS) concrete in terms of sustainability aspects.

2 Experimental work

2.1 Materials properties

2.1.1 Cement

Iraqi manufacture limestone Portland cement (CEM II/A-L 42.5R), from LAFARGE company, was used in this research that meets the limitations of (IQS No. 5/2019) [12].

2.1.2 Silica fume

In this research, SF was used for the preparation of HS concrete and HS fiber concrete, known commercially as Mega Add MS (D) from the company (CONMIX), and meets the requirement of (ASTM C1240-15) [13].

2.1.3 High-range water-reducing admixture (HRWRA)

HRWRA was used in this research for the preparation of HS concrete and HS fiber concrete, known commercially as (ViscoCrete 5930-L) from the company (Sika),

and meets the requirement of (ASTM C494/C494 M-19) [14].

2.1.4 Water

All mixing, pouring, and curing concrete specimens were performed with tap water.

2.1.5 Sugar molasses

Molasses was used in this research, which was a by-product liquid material of a sugar factory that was supplied by Etihad Food Industries CO. LTD, which has a pH of 5.37 and Brix of 83 [11].

2.1.6 Fine and coarse aggregate

Natural local fine aggregate (sand) from the Al-Ukhidher region was used in this research that meets the limitations of (IQS No.45/1984) [15], zone (two). Two types of crushed natural coarse aggregate were used in this research. The first type was normal-weight aggregate (NWA) gravel with a maximum size of 10 mm, dry density of 1573 kg/m³, and absorption of 0.6%. The second was volcanic LWA, pumice stone with a maximum size of 9.5 mm, dry density of 708 kg/m³, and absorption of 22%. The physical and chemical characteristics of NWA and LWA meet the limitations of (IQS No.45/1984) [15] and (ASTM C330/C330M-17a) [16], respectively. Figure 1 shows the grading curves of fine and coarse aggregate.

2.1.7 Steel fiber

Steel fiber (hooked end type) with a length of 35 mm and a diameter of 0.5 mm was utilized in this research. The

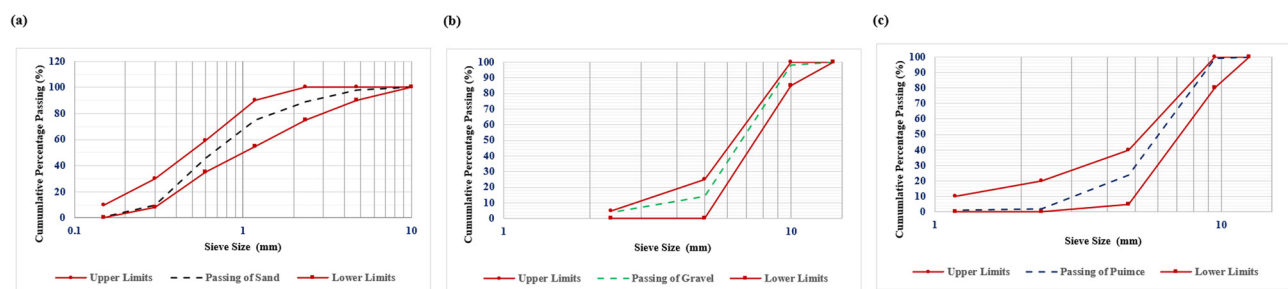


Figure 1: Grading curves of fine and coarse aggregate: (a) sand, (b) gravel, and (c) pumice stone.

hooked fiber was supplied by ARMAGES company in Turkey.

2.2 Mix proportions

Six different concrete mixtures were produced to meet the research's objectives. All details of the concrete's symbols are illustrated in Table 1.

The mix proportions for all concrete types are shown in Table 2.

Since there is no standard specification for HSLWC mix design yet, many trials mix proportions were carried out to find a proper mix that meets the limitation of HSLWC concerning compressive strength and density. The high strength-normal weight concrete (HSNWC) was produced by replacing the LWA with NWA. On the other hand, NSLWC was designed according to (ACI 211.2-98) [17], the American method of mix proportions selection. The same mix proportions were used in the production of NSNWC as in the NSLWC, except for replacing LWA with NWA at the same volumetric ratio.

Table 1: Description details of all concrete types

No.	Symbol	Descriptions
1	NSNWC	Normal strength-normal weight concrete
2	HSNWC	High strength-normal weight concrete
3	NSLWC	Normal strength-lightweight concrete
4	HSLWC	High strength-lightweight concrete
5	F0.25HSLWC	0.25% Steel fiber high strength-lightweight concrete
6	F0.50HSLWC	0.50% steel fiber high strength-lightweight concrete

Table 2: Mix proportions for all concrete types

Concrete type	Cement	Sand	Gravel	Pumice stone	Water	SF	HRWRA	SM	Steel fiber
NSNWC	496	700	950	—	210	—	—	—	—
HSNWC	525	590	1,100	—	142	75	7.85	1.05	—
NSLWC	496	700	—	428	210	—	—	—	—
HSLWC	525	590	—	495	142	75	7.85	1.05	—
F0.25HSLWC	525	590	—	495	142	75	7.85	1.05	19.5
F0.50HSLWC	525	590	—	495	142	75	7.85	1.05	39.0

*All proportions are represented in kg/m³.

2.3 Preparation, pouring, and curing of specimens

The concrete specimens were made by pouring the concrete into various standard molds (150 mm × 300 mm and 100 mm × 200 mm cylindrical molds) and (150 mm and 100 mm cubic molds). The molds were thoroughly cleaned and lubricated before pouring to avoid hardened concrete adhering to the mold's inside surfaces; fresh concrete was poured into the molds in layers according to the criteria for each test before being compacted with a steel rod. The top surface of each concrete specimen was leveled with a steel trowel before being covered with polyethylene sheets for 2 days (*i.e.*, 24 h) and 48 h for NS concrete and HS concrete, respectively, to prevent water evaporation. The concrete specimens were then demolded and kept in a curing tank until the age of the test (28 days).

2.4 Experimental tests

In this research, the following experimental tests were carried out, as shown in Figure 2:

- Compressive strength test: using (150 mm × 300 mm cylindrical mold) according (ASTM C39/C39M-15a) [18].
- Splitting tensile strength test: using (100 mm × 200 mm cylindrical mold) according to (ASTMC496/C496M-17) [19].
- Dry hardened density test: using (100 mm × 200 mm cylindrical mold) according to (ASTM C 642-13) [20] for normal-weight concrete and according to (ASTM C567/C567M-19) [21] for lightweight concrete.
- Ultrasonic pulse velocity test: using (150 mm cubic mold) according to (ASTM C597-16) [22].

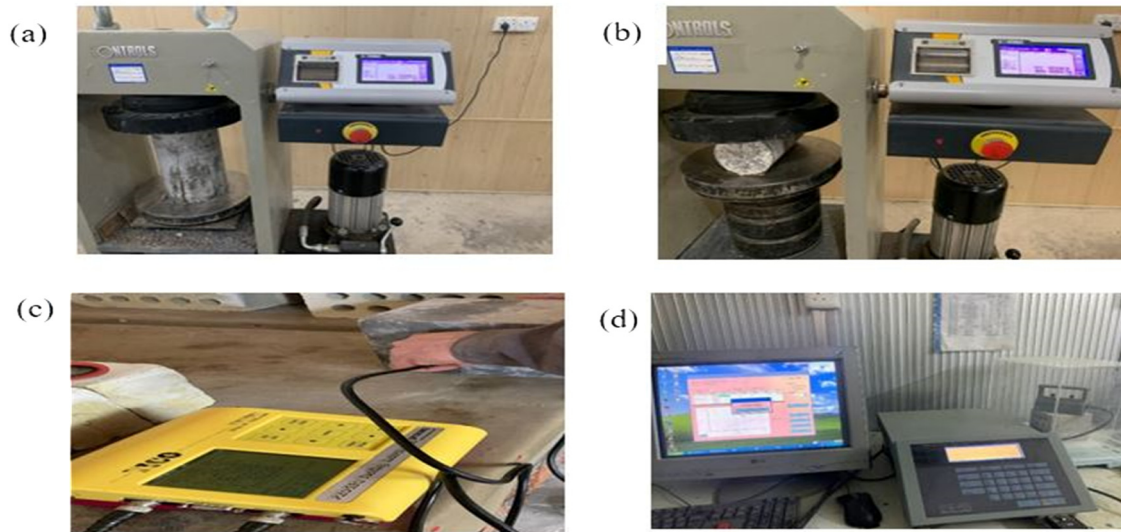


Figure 2: Experimental tests of specimens: (a) compressive strength, (b) splitting tensile strength, (c) ultrasonic pulse velocity, and (d) thermal conductivity.

- Thermal conductivity test: using (100 mm cubic mold) according to (ASTM C1113/C1113M-09) [23].

3 Experimental results and discussion

The results of the mechanical and physical properties at 28 days of age are presented in Table 3.

3.1 Cylinder compressive strength (f'_c)

As shown in Table 3, using HSLWC instead of NSLWC increased the compressive strength by about 81.12%. The improvement in its strength was due to the effect of additive materials (SF, HRWRA, and SM). These materials significantly improve the interfacial transition zone

between the aggregate and mortar matrix. Changing the concrete type from HSNWC to HSLWC decreased its strength by 27.24%. This reduction is because pumice is weaker than gravel, so its resistance to the progression of cracks created during the compressive test with increasing load will be less, as stated in the previous study [24]. Furthermore, the dual effect of pumice stone and additive materials in HSLWC increased its compressive strength by 24.12% over NSNWC, which is considered CC (*i.e.*, without additive materials and LWA). Furthermore, the inclusion of steel fibers with two volumetric ratios (0.25 and 0.50)% in HSLWC enhanced its strength by 11.14 and 16.35%, respectively.

3.2 Splitting tensile strength (f_t)

The use of HSLWC instead of NSLWC increased f_t by about 34.78%. This increase belonged to the significant role of additive materials, as explained earlier. Replacing

Table 3: Results of all concrete types' mechanical and physical properties

Test	NSNWC	HSNWC	NSLWC	HSLWC	F0.25HSLWC	F0.50HSLWC
f'_c (MPa)	34.0	58.0	23.3	42.2	46.9	49.1
f_t (MPa)	3.4	4.7	2.3	3.1	3.8	4.0
γ_c (kg/m ³)	2,313	2,408	1,927	1,943	1,962	1,973
UPV (km/s)	4.355	5.487	3.823	4.441	4.653	5.230
λ (W/(m K))	1.158	1.435	0.707	0.810	0.795	0.890

*Average of three specimens for each mix batch.

the gravel with a pumice stone in HSLWC decreased f_t by 34.04% compared to HSNWC. This is due to the attribute to the drop in the compressive strength and influence of pumice stone. While changing the type of concrete from NSNWC to HSLWC decreased f_t by only 8.82%. The steel fiber in F0.25HSLWC and F0.5HSLWC increased f_t by 22.58 and 29.03% over HSLWC, respectively. This behavior was due to the use of hooked-end steel fibers enabling them to bridge cracks more efficiently. The results given earlier found that the improvement effect of steel fibers on tensile strength is more significant than on compressive strength. Furthermore, it can be seen in Table 4 that the relationship between the compressive strength and tensile strength (f'_c/f_t) was known by the brittleness ratio (BR) [25]. The NSNWC gave less value of BR, while HSLWC gave a higher value of BR. This finding agreed with the study by Cui *et al.* [26]. The addition of steel fibers played a better role in increasing the ductility of HSLWC and overcoming ductility reduction due to using HSLWC instead of HSNWC.

3.3 Dry hardened density (γ_c)

As shown in Table 3, dry density results for LWA concrete mixtures were below $2,000 \text{ kg/m}^3$ (i.e., comply with the definition of lightweight concrete [27]). Changing NSLWC to HSLWC showed a slightly higher γ_c by 0.83%. Using HSLWC instead of NSNWC decreased the γ_c by 16.00%. Meanwhile, changing HSNWC to HSLWC decreased the γ_c by about 19.31%. This reduction was owing to the lighter pumice aggregate replacing the considerably heavy gravel. Although the inclusion of steel fibers in F0.25HSLWC and F0.5HSLWC increased their density, it remained within the limits of lightweight concrete. The relationship between the compressive strength and density (f'_c/γ_c) was known by SE [28]; as illustrated in Table 4, HSLWC yielded higher values of SE than NSLWC and NSNWC by 79.34 and 47.62%, respectively. The improvements of 10.14 and 14.75% in SE were found for 0.25 and 0.50% steel fiber addition in HSLWC, respectively. This behavior was due to an increase in the compressive strength of HS fiber concrete.

3.4 Ultrasonic pulse velocity (UPV)

The (BS 1881: Part 203) [29] code classified the concrete quality from (excellent to very weak). This quality depends on the result of the UPV test. From the results of UPV, as shown in Table 3, it can be found that the use of HSLWC instead of NSLWC and NSNWC increased the UPV by 16.17 and 1.97%, respectively, and maintained the same good quality concrete grade. On the other hand, changing HSNWC to HSLWC decreased the value of VPV by 19.06% and changed the concrete quality from excellent to good. The addition of steel fibers in HSLWC with (0.25 and 0.5)% increased the UPV by 4.77 and 17.77%, respectively. Furthermore, this addition changed the concrete quality to an excellent grade (i.e., UPV above 4.5 km/s). The relation between the density and UPV could be used to calculate the acoustic impedance for all types of concrete by using Eq. (1) [30]:

$$AI = \gamma_c \times UPV, \quad (1)$$

where AI is the acoustic impedance (Rayl), γ_c is the concrete density (kg/m^3), and UPV is the ultrasonic pulse velocity (m/s).

The acoustic impedance for all concrete types is illustrated in Table 4. The results of the AI indicated similar behavior for UPV and AI when using LWA instead of NWA and also, when using two different ratios of steel fibers in HSLWC. However, the reduction in the void ratio, which had a detrimental impact on concrete density and acoustic impedance, increased concrete compressive strength and UPV.

3.5 Thermal conductivity (λ)

It was evident from Table 3 that the λ depends on the strength and the density of concrete. Using HSLWC in place of NSLWC increased the thermal conductivity by 14.57%. On the other hand, the λ decreased by 30.05 and 43.55% when using HSLWC instead of NSNWC and HSNWC. The outcomes revealed the positive impact of using LWA instead of NWA, which decreased the λ (i.e.,

Table 4: The relationships between some of the mechanical and physical properties

Relation-ship	NSNWC	HSNWC	NSLWC	HSLWC	F0.25HSLWC	F0.50HSLWC
f'_c/f_t	10.00	12.34	10.13	13.61	12.34	12.28
f'_c/γ_c	1.47×10^{-2}	2.41×10^{-2}	1.21×10^{-2}	2.17×10^{-2}	2.39×10^{-2}	2.49×10^{-2}
$\gamma_c \times UPV$	10.07×10^6	13.21×10^6	7.37×10^6	8.63×10^6	9.13×10^6	10.32×10^6

increased thermal insulation). The effect of HSLWC with steel fibers on the λ was unclear, which decreased by 1.85 when 0.25% of steel fiber was used and increased by 9.88 when 0.50% was used. This behavior may belong to the distribution of steel fibers in concrete mixes.

4 Conclusion

The following conclusions are drawn from the results and discussions:

1. The replacement of 100% of gravel as the volumetric ratio with pumice stone and the inclusion of SM with (0.2% of cement weight) gave HSLWC compliant with the strength limitations of ACI code 213R-14.
2. Using pumice stone instead of gravel in concrete production improved their physical properties, such as dry density, thermal conductivity, and acoustic impedance; hence, the thermal and sound insulations are improved, and the unit weight of the structure is reduced.
3. Using both pumice stone and additive materials increased the compressive strength, tensile strength, and SE by 81.12, 34.78, and 79.34%, respectively, while the ductility decreased compared with concrete without additive materials.
4. The inclusion of steel fibers with two volumetric ratios (0.25 and 0.50)% in HSLWC led to the recovery of 8.10 and 11.90% of compressive strength reduction and recovery of 14.89 and 19.15% of tensile strength, respectively.
5. Using steel fibers together with a pumice stone in HS concrete yielded promising results regarding improved safety (strength and ductility).

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