Enhancing the Mechanical Characteristics of Lightweight Concrete with Nano-Silica Additives

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ABSTRACT

The use of Lightweight Concrete (LWC) in both structural and non-structural applications has gained significant attention due to its advantageous properties. The latter encompass diminished structural element overloading and reduced production and shipping expenses. However, the decreased density of LWC often results in compromised strength and durability. Nanotechnology has emerged as a promising approach in concrete technology, offering potential solutions to the challenges associated with reduced density in LWC. In this study, a concrete mix with a 1:3 ratio of cement to Lightweight Expanded Clay Aggregate (LECA) was used. The reference mix (LR) consisted entirely of LECA as aggregate. In the modified mix (LP), 10% of the coarse LECA aggregate was volumetrically replaced with recycled Unplasticized Polyvinyl Chloride (UPVC) plastic. To investigate the impact of Nano-Silica (NS), additional mixes were prepared by incorporating NS at dosages of 1%, 1.5%, and 2% by weight of cement into the (LP) mix, resulting in mixes LPN1, LPN2, and LPN3, respectively. This study investigates the effect of NS on the mechanical properties of the aforementioned concrete mixes, with a focus on the compressive and flexural strength.

Keywords-nano-silica; lightweight concrete; LECA

I. INTRODUCTION

LWC offers improved mechanical properties, reduced weight, and enhanced thermal and acoustic insulation, rendering it a popular choice in construction, while it also reduces the environmental impact [1]. ASTM C330, the standard specification for lightweight aggregates, is gaining attention due to its exceptional performance and functional benefits. These aggregates, whether natural or artificial, have a density below 0.88 g/cm^3 [2]. Expanded Clay Aggregate (ECA), a manufactured aggregate, is produced by expanding materials, such as clay, shale, or slate, at temperatures ranging from 900 to 1,250 °C. Its unique lightweight characteristics come from its porous, spongy composition, making it an optimal choice for various applications, including construction. [3-5]. Nanoparticles can be used to enhance the mechanical characteristics of numerous substances, like polymers and concrete [6]. They are also widely applied in engineering, the food industry, and medicine. This has motivated researchers to further investigate the effects of NS on concrete. [7, 8] NS is known to be a highly reactive additive [9, 10]. It promotes the cement hydration by serving as a nucleation site for the formation of the calcium silicate hydrate (C-S-H) gel. The NS pozzolanic effect enhances the overall production of the C-S-H gel inside its matrix. Furthermore, NS addresses deficiencies, reduces water absorption, and improves the longevity of the cementitious matrix [11, 12]. Among all these nanoparticles, incorporating NS in concrete yielded the most significant enhancement in the compressive strength [13, 14]. Authors in [15] investigated nanosized materials, including NS, nano-TiO2, carbon nanotubes, ferric oxides, polycarboxylates, and nanocellulose, and demonstrated their ability to improve the thermal characteristics of concrete, potentially decreasing the energy consumption and overall costs in the construction industry.

Nanotechnology has led to the development of concrete with unique properties, as nanoparticles have been incorporated to enhance its performance and achieve superior characteristics. Authors in [16] demonstrated that the performance of LWC can be enhanced by incorporating nanomaterials, leading to improvements in its mechanical properties, workability, and durability [16]. Adding NS to LWC improves its resistance to the water and chloride ion penetration. However, it results in only a slight increase in strength. It also leads to a reduced water penetration depth, moisture absorptivity, and chloride migration [17].

Significant advancements have been observed in the nanomaterials in LWC, resulting in numerous benefits and improved performance. Using NS significantly improves the compressive strength of LWC and its microstructure, particularly in cement paste. A 77% enhance in compressive strength was noted after 90 days of incorporation at 5% [18]. zPlastic waste, a cost-effective and abundant alternative to traditional raw materials, is used in concrete production for environmental friendly applications, especially for reducing the water pollution and promoting sustainable practices [19]. Authors in [19] also explored the safety and efficacy of partially substituting Nanoplastic Waste (NPW) with Nano-Titania (NT) in white cement compositions. Blends were prepared using varying NPW ratios and a fixed 1.0 wt.% of NT.

II. EXPERIMENTAL PROGRAM

A. Materials

1) Cement

Ordinary Portland Cement (CEM I–42.5R) was used in the compositions in accordance with IQS No. 5 (2019) [20]. Its physical and chemical properties are listed in Tables I and II.

TABLE I. PHYSICAL TEST OF ORDINARY PORTLAND CEMENT

Physical properties		Test results	The limits of IQS no. 5, 2019
Setting time	Initial (mins)	1;35	Min. 45 (mins)
	Final (hrs)	4;25	Max 10 (hrs.)
Compressive strength (MPa)	2 days	23.8	Min. 20
	28 days	45.5	Min. 42.5

TABLE II. CHEMICAL PROPERTIES OF ORDINARY PORTLAND CEMENT

Oxide composition		Content %	The limits of IQS no. 5, 2019
CaO		61.78	-
SiO_2		20.79	-
Al_2O_3		4.800	-
Fe_2O_3		4.400	-
MgO%		3.670	Max 5
SO3 Max	C3A <3.5	Not applicable	2.5
	C3A >3.5	2.130	2.8
LOI		2.340	Max 4
IR		0.980	Max 1.5
C3S		48.87	-
C2S		22.38	-
C3A		5.280	-
C4AF		13.38	-

2) Coarse and Fine Aggregate

The combinations used LECA, with an optimal size varying from 12.5 mm to 0, in accordance with ASTM-C332-17 [21]. The grading and the characteristics of LECA are presented in Tables III and IV.

TABLE III. PARTICLE SIZE DISTRIBUTION OF LECA

Sieve size (mm)	Passing (%)	ASTM C332-17 nominal size 12.5 mm to 0 mm
19	100	100
12.5	100	95-100
4.75	60	50-80
150	9	2-15
300	15	5-20

TABLE IV. PROPERTIES OF LECA

Property	Value	Specifications	Limit of IQS no.45/1984
Specific gravity	0.7	ASTM C127	-
Absorption	19%	ASTM C127	-
Bulk density (loose)	320 kg/m^3	ASTM C29/C29M	-
Sulphate content (SO_3)	0.05 %	Iraqi Reference Guide No.500/3	≤ 0.1

3) Plastic Waste

UPVC was utilized with a particle size range of 9.5-2.36 mm, in accordance with ASTM C332-17 [21]. Table V shows the particle size distribution of UPVC used in this study.

4) Nano-Silica

The NS used in this study was sourced from Honguw International Group, Ltd., China and incorporated into the mixture. Its physical properties are presented in Table VI.

5) Superplasticizer

The Superplasticizer (SP) employed was Hyperplast PC175. The manufacturer proposed a dosage ranging from 0.4 to 2.5 L/100 kg of the cement, in accordance with ASTM C494-19 [22]. The manufacturer's specifications for this SP are listed in Table VII.

TABLE V. PARTICLE SIZE DISTRIBUTION OF UPVC

Sieve size (mm)	Passing percentage (%)	ASTM C332-17 standard size 9.5-2.36 mm
12.5	100	100
9.50	87	80-100
4.75	10	5-40
2.36	8.0	0-20

TABLE VI. PROPERTIES OF NS

Properties	Specifications
Appearance	White
Type	Hydrophilic
Form	Powder
Purity	99.8 %
Average particle size	30 nm
Density at 20 C°	2.17-22.66 g/cm^3
Melting point	1610-1728 °C

TABLE VII. PROPERTIES OF SP

Characteristics	Description
Color	Yellowish liquid
PH	6
Specific gravity	1.08
Chloride concentration	Nill

6) Water

Tap water was used in the preparation of the concrete mixtures for this study. The water was required to be suitable for its intended use and to meet the standard criteria outlined in IQS No. 1703 (2018) [23].

B. Design Mixture

LECA was utilized as the aggregate component, combined with water, cement, and a plasticizing admixture. To modify the mix, 10% of the coarse LECA was partially replaced by volume with UPVC plastic waste. NS was then incorporated at varying dosages of 1%, 1.5%, and 2% by weight of cement. The mix LR represents the reference mixture containing 100% LECA, while LP consists of 90% LECA and 10% plastic waste (UPVC). Mixes LPN1, LPN2, and LPN3 include 90% LECA and 10% plastic waste (UPVC) with the addition of 1%, 1.5%, and 2% NS by weight of cement, respectively.

1) Mixing Procedure

The preparation of the material involved weighing Portland cement, lightweight aggregate, UPVC, nanoparticles, water, and a SP. The mixture was uniformly mixed, and the nanoparticles were dissolved in water. The concrete was compacted and the samples' mechanical properties were tested for various testing periods [24].

TABLE VIII. MIX DESIGN DETAILS

Mix type	**Cement**	**LECA**	**UPVC**	**Nano particles**	**SP**	**Water**
LR	375	470	-	-	1.3	154
LP	375	438	71	-	1.3	154
LPN1	375	438	71	4.9	1.3	154
LPN2	375	438	71	7.4	1.3	154
LPN3	375	438	71	9.8	1.3	154

III. RESULT AND DISCUSSION

A. Compressive Strength Test

The compressive strength of the concrete mixtures was evaluated using 100 × 100 × 100 mm cubes in accordance with BS EN 12390-3:2019 [25], as shown in Figure 1.

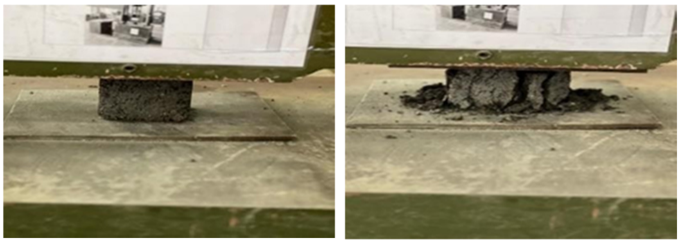

Fig. 1. Compressive strength test.

TABLE IX. RESULTS OF COMPRESSIVE STRENGTH TEST

Mix symbol	**7 days (MPa)**	**28 days (MPa)**	**60 days (MPa)**
LR	7.40	8.40	10.0
LP	7.80	9.70	11.0
LPN1	8.70	10.4	11.5
LPN2	9.10	11.2	12.6
LPN3	10.2	12.5	13.5

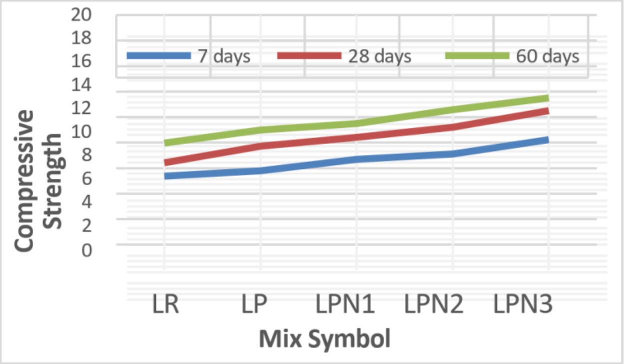

Fig. 2. Relationship between compressive strength and mix compositions at 7, 28, and 60 days.

The LECA substitution in concrete with plastic waste decreases the compressive strength due to the weak link strength and hydrophobic properties, limiting the water mobility during cement hydration, which is consistent with [26, 27]. NS enhances the compressive strength in concrete containing plastic by occupying the voids, increasing the density, and strengthening the cement paste-plastic bonds, mitigating the strength loss, complying with [28, 29, 33].

B. Flexural Strength Test

As per ASTM C293/C293M-16 [30], a flexural strength test was conducted to determine the flexural strength of the concrete, using prism specimens measuring 100 × 100 × 400 mm, as depicted in Figure 3.

Fig. 3. Flexural strength test.

TABLE X. RESULTS OF FLEXURAL STRENGTH TEST

Mix symbol	**7 days (MPa)**	**28 days (MPa)**	**60 days (MPa)**
LR	1.08	1.26	1.44
LP	0.54	0.81	0.90
LPN1	0.72	1.08	1.44
LPN2	0.90	1.22	1.60
LPN3	1.26	1.62	1.98

The LR (100% LECA) demonstrated increased strength over time, while the LP (90% LECA + 10% UPVC) experienced a decrease in the flexural strength due to the weaker bonding between the plastic particles and cementitious mixture, complying with [31, 32]. The addition of nanoparticles to a plastic mixture resulted in the highest strength, with the 1% addition showing a decrease of 0.27 MPa in strength. The 1.5% addition improved the cohesion and structural density, achieving the highest strength, which is consistent with [34].

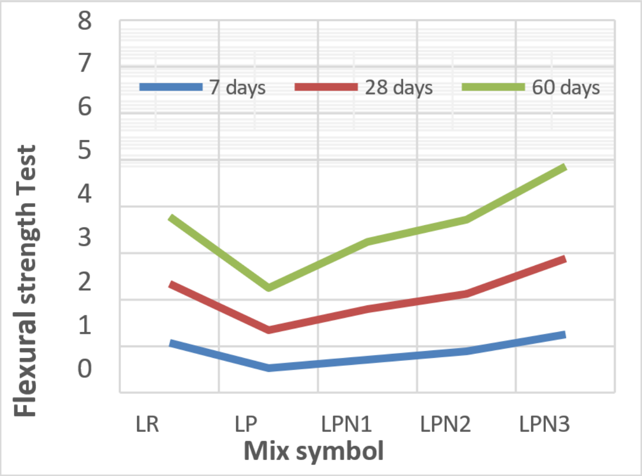

Fig. 4. Relationship between flexural strength and mix compositions at 7, 28, and 60 days.

C. Thermal Conductivity Test

The thermal conductivity (k) was measured using 100 × 100 × 100 mm specimens in accordance with ASTM C1113-09 (2019) [34], as illustrated in Figure 5.

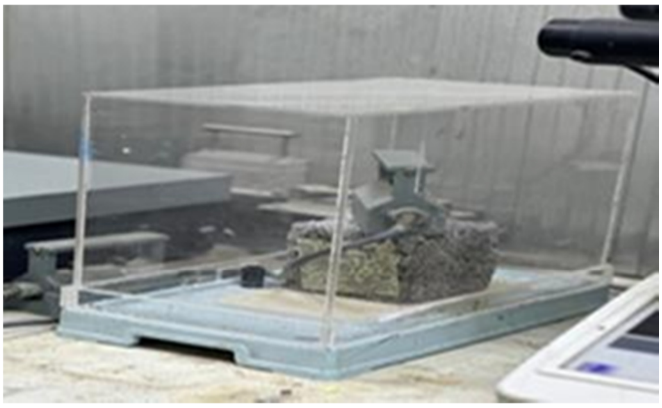

Fig. 5. Thermal conductivity test.

TABLE XI. RESULTS OF THERMAL CONDUCTIVITY TEST

Mix symbol	28 days (W/mK)
LR	0.1786
LR	0.1795
LPN1	0.1823
LPN2	0.1935
LPN3	0.2082

The study revealed that adding UPVC to LECA slightly increased the thermal conductivity, while Incorporating 1% NS further enhanced the thermal insulation, highlighting the need for an optimal balance, as supported by the findings in [35, 36].

D. Apparent and Bulk Density, Absorption, and Void Ratio

The examination was conducted in accordance with ASTM C642-2013 [37]. The results of the bulk density, absorption, and void ratio tests are presented in Figures 7-9, while Table XII provides a summary of these results.

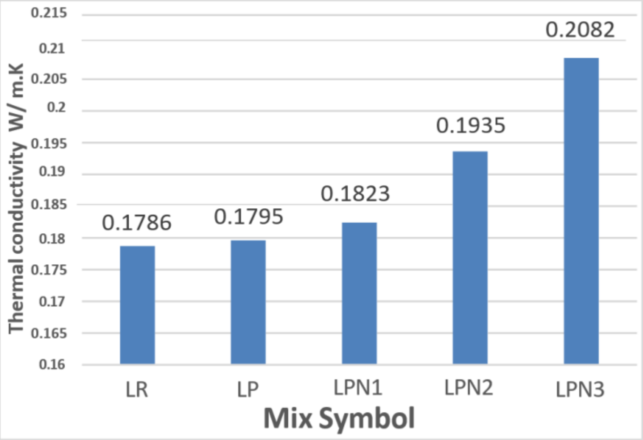

Fig. 6. Relationship between thermal conductivity and mix compositions at 28 days.

TABLE XII. DRY BULK DENSITY , ABSORPTION, AND VOID RATIO TEST RESULTS

Mix symbol	Dry bulk density (kg/m^3)	Absorption after immersion (%)	Voids (%)
LR	1119.4	6.2	14.9
LP	1191.3	3.7	13.7
LPN1	1241.5	3.2	13.1
LPN2	1241.8	2.7	12.2
LPN3	1310.7	1.6	11.9

As shown in Table XIII and Figures 7-9, the inclusion of UPVC significantly increased the bulk density by replacing the porous LECA with non-porous particles, which reduced the voids. As UPVC is non-porous, the absorption decreased significantly from the LR to the LPN3, which is consistent with the findings in [38].

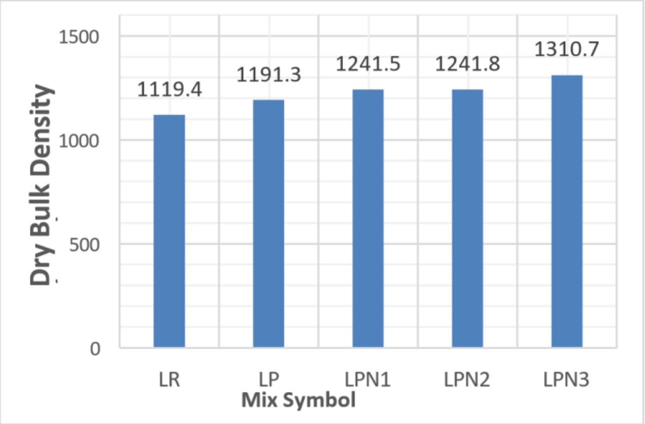

Fig. 7. Relationship between dry bulk density and compositions at 28 days.

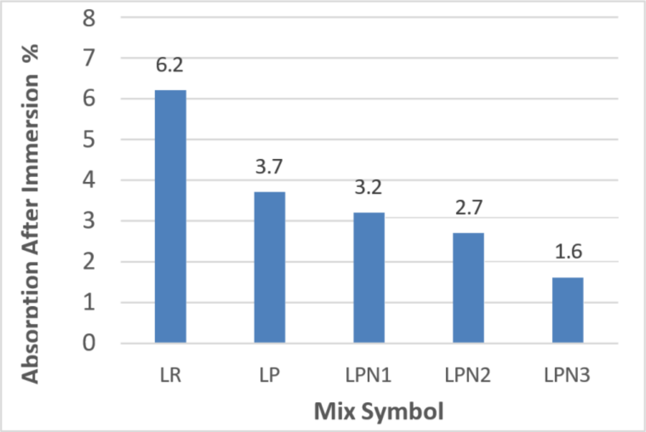

Fig. 8. Relationship between absorption after Immersion and compositions at 28 days.

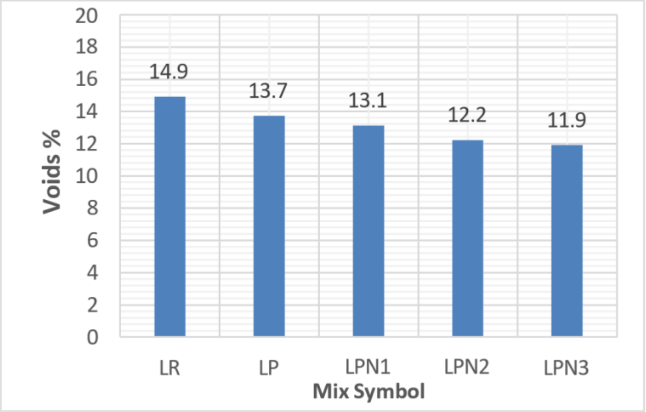

Fig. 9. Relationship between voids and compositions at 28 days.

IV. CONCLUSION

The incorporation of nanomaterials, specifically Nano-Silica (NS), demonstrated an improvement in the compressive strength, flexural strength, and thermal conductivity in Lightweight Concrete (LWC) samples. Among the tested mixes, the sample containing 2% NS (LPN3) exhibited the most pronounced performance gains, suggesting that this dosage offers an optimal balance between the particle dispersion and pozzolanic activity. Furthermore, the positive effects of NS became more evident with an extended curing time, with the peak splitting tensile strength observed at 60 days. These findings highlight the potential of NS as a performance-enhancing additive in LWC, especially when combined with recycled materials, such as Unplasticized Polyvinyl Chloride (UPVC), contributing both to improved sustainability and structural efficiency in the construction applications. Future studies could explore the long-term durability aspects and the behavior of such composites under varying environmental conditions.

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