Research on Engineering Structures & Materials
www.jresm.org
Research Group

Research Article

Influence of surface treatment techniques of attapulgite lightweight aggregate on performance of light weight self-compacting concrete

Lamyaa Ghanim Salim [*,1,2,a], Ali H. Nahhab [1,b]

[1]*Dept. of Civil Eng., University of Babylon, Iraq*
[2]*Dept. of Building and Construction Eng. Techniques, Al Furat Al Awsat Technical University, Iraq*

Article Info

Article History:

Received 19 Apr 2026
Accepted 26 June 2026

Keywords:

Lightweight self-Compacting concrete;
Attapulgite lightweight aggregate;
Surface treatment;
Compressive strength;
Cement and adhesive ceramics impregnation;
Gloss enamel paint;
Polyvinyl acetate

Abstract

Attapulgite lightweight aggregate is characterized by high water absorption due to its porous structure, which may adversely affect the fresh and mechanical properties of lightweight self-compacting concrete (LWSCC). Although several surface treatment techniques have been applied to conventional lightweight aggregates, limited information is available regarding their application to attapulgite aggregate. Therefore, this study investigates the effectiveness of four surface treatment methods, namely cement paste impregnation, ceramic adhesive coating, gloss enamel paint, and polyvinyl acetate (PVA) solution, on the properties of attapulgite aggregate and the resulting LWSCC. The physical properties of the treated aggregates, including water absorption and specific gravity, were evaluated together with the fresh properties and compressive strength of LWSCC mixtures. The results showed that polymeric coating achieved the highest reduction in water absorption (approximately 46%), followed by ceramic adhesive coating (31%) and cement paste impregnation (27%) however, PVA treatment showed no measurable influence on water absorption. Also, a slight increase in specific gravity was observed after treatment due to partial pore filling by treatment products. Cement paste impregnation provided the best overall performance, where the compressive strength increased by approximately 7% and 4% at 7 and 28 days, respectively, compared with the reference mixture. On the other hand, the other treatment methods resulted in lower compressive strength due to weaker interfacial bonding between the aggregate and cement matrix. The findings indicate that cement paste impregnation is the most effective treatment technique for enhancing the overall performance of attapulgite-based LWSCC while maintaining the characteristics of structural lightweight concrete.

1. Introduction

Lightweight self-compacting concrete (LWSCC) has attracted considerable attention in recent years owing to its ability to combine the advantages of lightweight concrete (LWC) and self-compacting concrete (SCC). Conventional concrete remains the most widely used construction material because of its strength, durability, and versatility; however, its relatively high density contributes significantly to the dead load of structures, particularly in high-rise buildings and long-span structural elements. To overcome this limitation, lightweight concrete was developed to reduce structural weight while maintaining adequate mechanical performance. On the other hand, self-compacting concrete possesses the ability to flow, fill formwork, and pass through congested reinforcement under its own weight without the need for external vibration, thereby improving construction efficiency and ensuring uniform concrete quality. The combination of these two

---

*Corresponding author: eng315.lmyaa.ganem@student.uobabylon.edu.iq , lamyaa@atu.edu.iq
[a]orcid.org/0000-0002-8682-4486; [b]orcid.org/0000-0002-0300-8302

DOI: http://dx.doi.org/10.17515/resm2026-1622ma0419rs

technologies resulted in the development of lightweight self-compacting concrete (LWSCC), which offers reduced self-weight, enhanced workability, and improved structural efficiency [1, 2] Several types of natural and artificial lightweight aggregates are used in LWSCC but LWSCC is mostly prepared with artificial aggregates, although the use of waste materials such as POC, EPS, COK, rubber, coconut shale, and plastic shows notable potential to be used as LWA [3].

Attapulgite-based lightweight aggregate has emerged as a promising material due to its local availability and suitability for producing structural lightweight concrete. Attapulgite is a fibrous hydrated magnesium–aluminum silicate clay mineral with the chemical formula $Si_8Mg_5O_{20}(OH)_2(OH_2)_4{\cdot}4H_2O$ [4]. Lightweight aggregate can be produced from Iraqi attapulgite clay through exposure to high-temperature sintering. During the firing process, physically and chemically bound water is released from the clay structure, generating an internal porous network that significantly reduces aggregate density and enables the production of lightweight aggregate suitable for structural applications [5, 6]. Despite these advantages, attapulgite lightweight aggregate possesses a highly porous structure and interconnected pore system, resulting in relatively high water absorption compared with conventional aggregates. Structural lightweight aggregates commonly exhibit water absorption values ranging from 5% to more than 25% after 24 h according to ASTM C127 and ASTM C128, whereas normal-weight aggregates typically exhibit absorption values below 2% [7]. Excessive water absorption by lightweight aggregates may reduce the effective water-to-binder ratio, impair workability, increase the risk of segregation, and adversely affect the quality of the interfacial transition zone (ITZ) between the aggregate and cement paste. Consequently, controlling the water absorption characteristics of lightweight aggregates is essential for achieving satisfactory fresh and hardened properties in LWSCC [8].

Several studies have demonstrated that surface treatment techniques can effectively improve the performance of lightweight aggregates by reducing water absorption and enhancing the aggregate–paste bond [9].[10] reported that hydrophobic polymer coatings such as polyvinyl acetate (PVA) and styrene–butadiene rubber (SBR) reduced aggregate water absorption by up to 82%, increased slump flow, and improved compressive strength by approximately 21% while producing a denser ITZ. Similarly,[8] found that cement paste pre-coating reduced water absorption by up to 52% and significantly enhanced the compressive strength of lightweight aggregate concrete. Other researchers have also reported that grout impregnation and polymer coating techniques effectively improve the physical and mechanical performance of lightweight aggregate concrete through pore sealing and enhancement of the aggregate surface characteristics. Also, [11] investigated surface modification through a new grout soaking technique with varying water\cement ratios (w/c) of 0.6, 0.8, 1.0, and 1.2. A new technique for the current development of LWPA is discovered through this investigation. The workability of lightweight plant-based aggregate (LWPA) increased considerably after surface modification. Moreover, LWPA concrete strength enhanced greatly after surface modification. [9] study the lightweight concrete mix designs, a partial substitution of polyester-coated coarse pumice aggregates with uncoated aggregates at different proportions of 0%, 25%, 50%, 75%, and 100% were used. Based on the results, it can be concluded that the specific gravity of the aggregates increased substantially with a reduction in water absorption capacity up to 85%, and despite the reduction in the compressive strength of the concrete samples caused by the coated aggregates. Although extensive research has been conducted on the surface treatment of lightweight aggregates such as pumice, LECA, scoria, and expanded shale, limited information is available regarding the treatment of attapulgite lightweight aggregate and its influence on the behavior of lightweight self-compacting concrete. Therefore, the present study aims to investigate the effectiveness of different surface treatment techniques for Iraqi attapulgite lightweight aggregate, including cement impregnation, ceramic adhesive impregnation, gloss enamel paint coating, and polyvinyl acetate (PVA) coating. The effects of these treatments on aggregate physical properties, including water absorption and specific gravity, as well as on the fresh and mechanical properties of LWSCC, represented by slump flow, T50 flow time, and compressive strength, are comprehensively evaluated. The findings of this study are expected to contribute to the development of sustainable and high-performance LWSCC utilizing locally available lightweight aggregate resources. Although several studies have investigated lightweight concrete incorporating attapulgite aggregate, most of the available research has focused on the production and basic characterization of attapulgite lightweight aggregate. Limited attention has been given to improving its performance through surface treatment techniques aimed at reducing its high-water absorption and enhancing the aggregate–paste bond. Furthermore, no comprehensive study has been found comparing different surface treatment methods, including cement impregnation, ceramic adhesive impregnation, gloss enamel paint coating, and polyvinyl acetate (PVA) coating, within lightweight self-compacting concrete (LWSCC). In addition, the influence of these treatments on fresh properties, density characteristics, compressive strength, alkali–silica reactivity, and microstructural behavior has not been systematically evaluated. Therefore, this study addresses this research gap by conducting a comparative assessment of various attapulgite aggregate surface treatments and their effectiveness in improving the performance of LWSCC.

1.1 Research Significance

Previous studies have extensively investigated the effect of surface treatment techniques on lightweight aggregates such as LECA, pumice, scoria, and plant-based aggregates, demonstrating significant improvements in water absorption, workability, and mechanical performance. However, limited research has been conducted on the application of these treatment techniques to attapulgite lightweight aggregate, particularly in lightweight self-compacting concrete (LWSCC). In addition, comparative evaluation of cementitious and polymeric surface treatments for attapulgite aggregate remains insufficiently addressed in the available literature. Therefore, this study aims to investigate the effectiveness of different surface treatment techniques on the physical properties of attapulgite aggregate and their influence on the fresh and compressive strength properties of LWSCC. This study utilizes locally available coating materials, including cement impregnation, ceramic adhesive impregnation, gloss enamel paint, and polyvinyl acetate (PVA).

2. Materials and Methods

2.1 Materials

2.1.1 Portland Cement

Ordinary Portland Cement (OPC), commercially known as Al-Mass cement, was used throughout this study. The cement was manufactured by Al-Mass Company in the Kurdistan Region of Iraq and complies with the requirements of Iraqi Specification IQS No. 472/2019. The chemical composition and physical properties of the cement were determined experimentally through laboratory testing in accordance with IQS No. 472/2019, and the obtained results are presented in Table 1.

Table 1. Chemical analysis (according to IQS No.472/2019)

Oxide %	Ordinary Portland Cement (OPC)	Limits IQS No. 472/2019
CaO	60.41	…………….
SiO_2	21.84	…………….
AL_2O_3	4.72	…………….
Fe_2O_3	3.60	…………….
MgO	1.50	≤ 5%
SO_3	2.38	≤2.5% if C_3A < 5% or ≤ 2.8% if C_3A >5%
L.O.I	3.27	≤ 4%
Free lime %	1.12	…………….
Insoluble Residue%	1.12	≤ 1.5%
L.S.F	0.83	0.66-1.02
Compounds		
C_3S%	31.74	…………….
C_2S%	38.67	…………….
C_3A%	6.42	…………….
C_4AF%	10.95	…………….
Physical properties		

Initial setting time (hour:min.)	2.08	00:45 (Min.)
Final Setting Time (hour:min.)	4:30	10:00 (Max.)
Fineness (Blaine) in m^2/kg	425	230 (Min.)
Compressive Strength (MPa) At		
3days	16	15 (Min.)
7days	23	23 (Min.)

2.1.2 Sand

All concrete mix designs used natural sand obtained from the Al-Ekhaider region as a fine aggregate have a maximum size of 4.75 mm. Table 2 shows the physical properties of sand; in addition, the applied sand of the sieve analysis and grading curve are given in (Fig. 1). Based on Iraqi Specifications No. 45/1984, Fig. 1 shows that the used sand is in zone two.

Table 2. Physical properties for sand

Tests	Result	Iraq specification No.45/1984 Limits
Bulk Density (Kg/m^3)	1640	-
Specific gravity	2.64	-
Water absorption	2%	-
Sulfate content %	0.344	≤ 0.5%

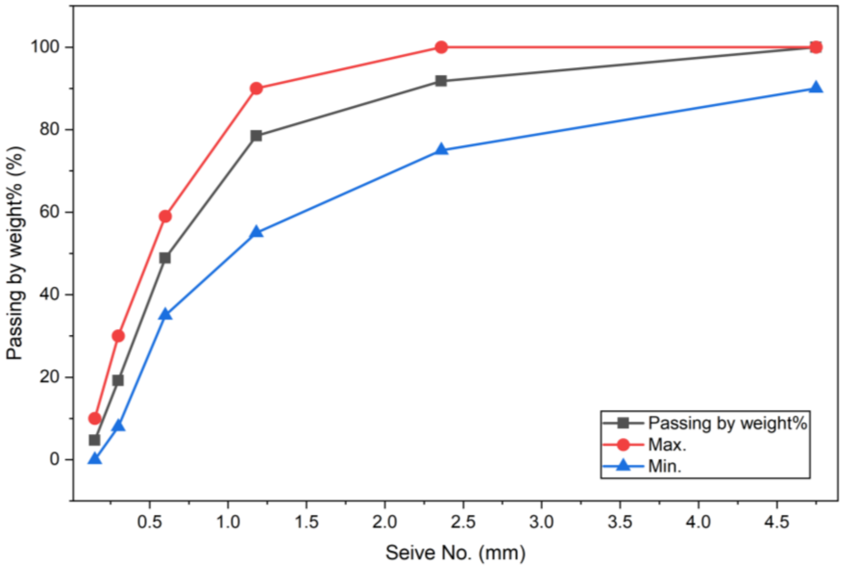


Fig. 1. Grading of sand

2.1.3 Supplementary Cementitious Materials (Fly Ash and Limestone Powder)

Class F fly ash and limestone powder (LP) were utilized as supplementary cementitious materials in this study to improve the performance of LWSCC. The fly ash conforms with ASTM C 618 requirements and it is characterized by a high content of silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3), which cause pozzolanic activity and increase the long-term mechanical and durability properties of concrete. Limestone powder, locally known as Al-Ghubra, was used as a filler material to increase the cohesiveness and improve particle packing of the mixture, due to its high calcium oxide (CaO) content. The combined use of fly ash and limestone powder contributes to improved workability, refinement of the matrix structure, and improve overall performance of LWSCC. Table (4) show the chemical analysis of fly ash type F and lime stone powder.

Table 3. Chemical properties of fly ash and lime stone powder

Test Items	Fly ash %	ASTM 618-05	Lime stone % by weight
SiO_2	50		6.84
Al_2O_3	31		1.12
CaO	5		45.73
MgO	0.28		4.37
SO_3	1.3	≤5%	3.2
Fe_2O_3	7.4		0.24
TiO_2	1.6		
K_2O	1.3		
P_2O_3	0.9		
SiO_2,Al_2O_3 and Fe_2O_3	88	≥70%	
L.O.I	8	≤ 12%	37.12
Activity Index	76	≥75%	

2.1.4 Super-Plasticizer

A high-range water-reducing admixture (HRWRA), commercially known as MasterGlenium® 54, was used as a superplasticizer in this study. The admixture is based on modified polycarboxylic ether (PCE) technology and is designed to provide high workability, improved cement dispersion, and reduced water demand. MasterGlenium® 54 complies with ASTM C494 Type F and Type G requirements as well as BS EN 934-2 specifications. The admixture was incorporated to enhance the flowability and stability of LWSCC mixtures while maintaining a low water-to-binder ratio. According to the manufacturer's technical data sheet, the product is a white-to-straw-colored liquid, relative density of 1.07 and a pH range of 5–8.

2.1.5 Attapulgite Aggregate

The attapulgite aggregate used in this study was obtained from the Tar Al-Najaf area located in Al-Najaf Governorate, Iraq. The raw material was collected from attapulgite-bearing mudstone deposits of the Injana Formation. The collected material was crushed and thermally treated in a furnace at 1000°C, followed by cooling to room temperature to produce lightweight aggregate with a porous internal structure. The produced aggregate was then sieved to obtain particle sizes ranging from 5 to 14 mm in accordance with BS EN 882:1992 requirements for coarse aggregates, as shown in the Fig. (2). The resulting attapulgite lightweight aggregate was used as the coarse aggregate in all LWSCC mixtures. The physical properties of the produced aggregate are presented in Table 5. and the grading of LWA in Fig. (3) below.

Fig.2. Preparation of attapulgite lightweight aggregate

Table 5. Properties of attapulgite aggregate

Tests	Result	Limits	Specification
Loose unit weight dry (Kg/m^3)	866	≤880	ASTM C330
Specific gravity	1.54		ASTM 127-15
Water absorption	26%		ASTM 127-15

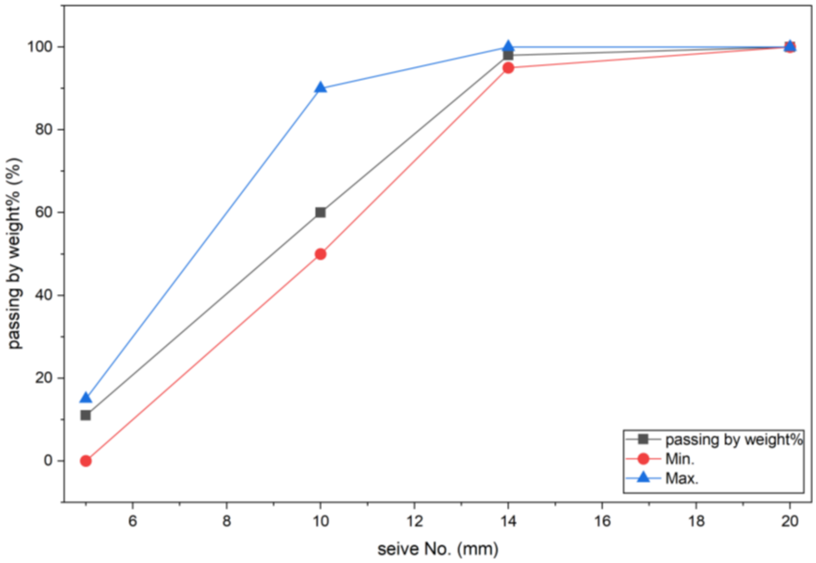


Fig. 3. Grading of LWA

2.1.6 Attapulgite Treatment

The major factors affecting the water absorption of LWA include the particle pore structure and its surface texture. Basically, there are two types of pores in a LWA particle: closed-pore and open-pore. In general, LWA with an isolated holes or vitrified surface often don't absorb much water, while the one with connected or open pores will be able to absorb more water into the pore structure because of capillary absorption [7].

The treatment of attapulgite lightweight aggregate was conducted to reduce water absorption, improve specific gravity, and enhance the aggregate–paste interfacial bond. These improvements were targeted to increase the stability and workability of LWSCC mixtures and to enhance their compressive strength performance**.** The aggregate was treated with different method as follows:

- Treatment with Cement Impregnation:

According to [11]**,** cement paste impregnation was carried out by using Ordinary Portland Cement (Al-Mass Cement) and tap water with a water-to-cement ratio of 0.6. Prior to the treatment process, the attapulgite lightweight aggregate was oven-dried at 100 ± 10°C for 24 h to eliminate residual moisture. The dried aggregate was immersed in the grout and mixed using a mechanical mixer for 5 min to ensure uniform distribution of the coating over the aggregate surface. Subsequently, the coated aggregate was transferred to a mesh basket to drain excess grout and then spread on a non-absorbent horizontal surface until the initial setting of the cement paste was achieved. Finally, the treated aggregate was cured under the same curing conditions adopted for concrete specimens for a period of three days before being used in concrete production.

- Treatment with Adhesive Ceramics:

The ceramic adhesive treatment was performed using Royal ceramic adhesive mixed with water at an adhesive-to-water ratio of 1:2 by weight. Prior to treatment, the attapulgite lightweight aggregate was oven-dried at 100 ± 10°C for 24 h to remove residual moisture. The adhesive grout was then prepared and mixed thoroughly to obtain a uniform consistency. The dried aggregate was immersed in the grout and mechanically mixed for 5 min to ensure complete coating of the aggregate particles. Subsequently, the coated aggregate was transferred to a mesh basket to remove excess grout and spread on a non-absorbent horizontal surface until the initial setting occurred. Finally, the treated aggregate was cured under the same curing conditions used for concrete specimens for three days before use. Figure 5 illustrates the final appearance of the aggregate after ceramic adhesive treatment.

Fig. 4. Attapulgite lightweight aggregate after cement paste impregnation treatment, showing the formation of a cementitious coating on the aggregate surface prior to curing

Fig. 5. Attapulgite lightweight aggregate coated with ceramic adhesive after curing, illustrating the surface sealing effect of the treatment

- Treatment with Polymeric Coating:

Gloss enamel paint (Al-Margan Paint) was used as a polymeric coating material for the surface treatment of attapulgite lightweight aggregate. Prior to treatment, the aggregate was oven-dried at 100 ± 10°C for 24 h to remove residual moisture. The dried aggregate was then immersed in the paint until complete surface coverage was achieved, which required less than 5 min. Subsequently, the coated aggregate was removed using a mesh basket to drain excess paint and spread on a non-absorbent horizontal surface. The treated aggregate was then allowed to dry at room temperature for two days to ensure complete drying and hardening of the coating layer before use. Figure 6 illustrates the final appearance of the gloss-enamel-treated aggregate**.**

Fig. 6. Attapulgite lightweight aggregate after gloss enamel paint treatment, showing the formation of a continuous surface coating after two days of drying

Fig. 7. Attapulgite lightweight aggregate after PVA treatment, showing the surface coating formed after drying at room temperature for two days

- Treatment with polyvinyl Acetate (PVA):

Polywed's PVA Bond, supplied as a ready-to-use product, was used as a polymeric surface treatment for the attapulgite lightweight aggregate. Prior to treatment, the aggregate was oven-dried at 100 ± 10°C for 24 h to remove residual moisture. The dried aggregate was then immersed directly in the PVA solution and maintained under immersion for 15–20 min to ensure complete surface coverage. Subsequently, the coated aggregate was removed using a mesh basket to drain excess PVA and spread on a non-absorbent horizontal surface. The treated aggregate was then allowed to dry at room temperature for two days before use. The treatment procedure was adopted according to the method reported by [12]. Figure 7 illustrates the final appearance of the aggregate after PVA treatment

3. Mix Design

The mix design methodology used in LWSCC in this research work is based on IS 10262: 2019 which includes a dedicated section for self-compacting concrete (Section 4) which satisfies requirement target slump flow of (660-750) mm mix with presoaking aggregate for 24 hours (N) was considered as a reference; four types of treatment were used. The quantities of mixed materials are displayed in Table 6.

Table 6. The quantities of mixed materials (by weight kg\m^3)

Treatment type	Symbol	cement	Fly ash	Limestone (kg\m^3)	water	w\c	Fine Aggregate	Coarse Aggregate	Super Plastizer Sp
presoaking Attapulgite (reference)	N	450	50	20	155	0.31	500	600	1.2%
cement impregnation	NC	450	50	20	155	0.31	500	600	1.4%
adhesive ceramics (Royal) impregnation	NR	450	50	20	155	0.31	500	600	1.3%
gloss enamel paint	NP	450	50	20	155	0.31	500	600	1.2%
Polyvinyl Acetate (PVA)	NPV	450	50	20	155	0.31	500	600	1.2%

As shown in Table 6, the superplasticizer dosage was not kept constant but ranging from 1.2% to 1.4% by weight of cementitious materials because the different aggregate treatment methods changed the absorption characteristics and surface texture of the attapulgite aggregate, thus that effect on concrete workability. Therefore, slight adjustments in superplasticizer content were required to obtain the target slump flow range of 660–750 mm for all mixtures.

4. Mixing, Casting, and Curing Procedure of Concrete

The high-water absorption amount of attapulgite lightweight aggregate can significantly reduce the free water available for cement hydration and flowability of LWSCC mixtures. To minimize this effect and maintain a consistent water-to-cement ratio, the aggregate was pre-soaked in water for approximately 24 h and subsequently brought to a saturated surface dry (SSD) condition before mixing. In order to obtain the SSD condition, after the aggregate was soaked in water for 24 h, subsequently spread it on flat surface to air-dried on a flat surface. SSD was achieved when the particle surfaces appeared dry and free from visible moisture, while the internal pore structure remained saturated. After achieving the SSD condition, all materials were mixed in a 0.04 m^3 pan mixer. First, the fine and coarse attapulgite aggregates were dry-mixed for 30 s. Subsequently, half of the mixing water was added and mixing continued for 1 min. The mixture was then left for 1 min to allow water absorption by the aggregate particles. Thereafter, cement, fly ash, and limestone powder were added and mixed for 1 min. Finally, mixed superplasticizer with the remaining mixing water and then adding to the mixture was introduced and mixing was continued for 3 min. Then, the mixture was allowed to rest for 2–3 min, after which it was remixed for an additional 2 min before casting to ensure uniform distribution of all constituents and adequate homogeneity of the LWSCC mixture To prevent adhering of the concrete to the moulds, each mould had to be cleaned and oiled before casting. As can be seen in Fig. (8), a single layer of fresh concrete needs to be placed without creating any vibration for casting in the case of a cylinder, cube, and prism. After completing the casting activity, a steel trowel was used to level the surface and left in the lab for a whole day. After casting, the specimens were left in the molds for 24 h at laboratory conditions. Subsequently, the specimens were demolded and immersed in a curing water tank until the designated testing ages of 7and 28days. The details regarding the number of specimens prepared for each test are presented in the corresponding testing procedures.

Fig. 8. Steel molds used for casting LWSCC specimens, including cubes, cylinders, and prisms for the different experimental tests

5. Testing Methods

5.1 Physical Properties

The specific gravity and water absorption of untreated and treated attapulgite aggregates were determined in accordance with ASTM C127-15. The aggregate samples were first oven-dried at 110 ± 5°C until a constant mass was achieved and then cooled to room temperature before recording the dry mass. Subsequently, the samples were immersed in water at room temperature for 24 ± 4 h to ensure full saturation. After soaking, the aggregates were removed from the water and surface moisture was eliminated using an absorbent cloth until a saturated surface-dry (SSD) condition was attained.

Fig. 9. Main steps of the specific gravity and water absorption test for attapulgite aggregate

The SSD mass (A) was then measured. Thereafter, the apparent mass in water (B) was determined by suspending the sample in water maintained at 23 ± 2°C while carefully removing any entrapped air bubbles. Finally, the samples were re-dried in an oven at 110 ± 5°C to a constant mass and weighed to obtain the oven-dry mass used in the calculations. The sequence of the test procedure is illustrated in (Fig. 9). Calculate the relative density (specific gravity) from eq (1) and absorption from eq (2):

$$Relative\ density\ (specific\ gravity) = \frac{C}{A-B} \tag{1}$$

$$Absorption\ \% = \frac{A-C}{C} * 100 \tag{2}$$

Where, A: mass of the saturated-surface-dry test sample in air (gram), B: apparent mass of saturated test sample in water (grams), C: mass of the oven-dried test sample in air (gram)

5.2. Testing of Fresh Properties

In the present study, the evaluation of fresh properties was focused on slump flow, T500 time, and fresh density tests. The L-box and V-funnel tests were not performed because of the main objective was to investigate the influence of aggregate surface treatment on the flowability characteristics of LWSCC mixtures. Therefore, these tests were considered beyond the scope of the present investigation.

5.2.1. Slump Flow, T500mm

The slump flow and T500 tests were conducted to evaluate the flowability characteristics of the developed LWSCC mixtures in accordance with EFNARC guidelines. The tests were performed immediately after mixing. Abram’s cone has a standard dimension with a height of 300 mm, a top diameter of 100 mm, and a bottom diameter of 200 mm was positioned on a smooth, non-absorbent steel plate and lightly moistened before testing. The cone was filled with fresh concrete in a single layer without compaction or vibration. Subsequently, the cone was lifted vertically, allowing the concrete to spread freely under its own weight. The slump flow diameter was determined as the average of two perpendicular diameters (D1 and D2) measured after the concrete ceased flowing, and the result was expressed in millimeters (mm), from eq (3) determine the slump flow. The T500 time was recorded as the elapsed time from lifting the cone until the leading edge of the concrete spread reached a circle with a diameter of 500 mm. Fig. (10) illustrates the measurement procedure for determining the slump flow diameter and T500 time of the developed LWSCC mixtures.

$$Slump\ Flow = \frac{D1 + D2}{2} \tag{3}$$

Where, D 1: Largest diameter of the flow spread (mm),D 2: diameter of the flow spread at right angle to D1. (mm).

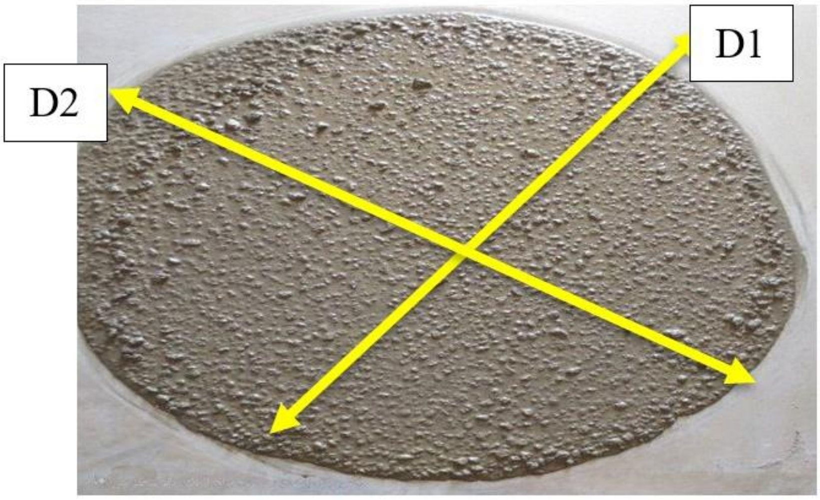


Fig. 10. illustrates the measurement procedure for determining the slump flow diameter and T500 time of the developed LWSCC mixtures

5.2.2. Fresh Density

The fresh density of LWSCC mixtures was determined in accordance with ASTM C138/C138M-08. A steel cube mould with dimensions of 100 × 100 × 100 mm and a known volume was used as the measuring container. The empty mould was first weighed, then filled with freshly mixed concrete immediately after mixing without vibration, and its surface was leveled. The filled mould was subsequently weighed, and the fresh density was calculated by dividing the net mass of concrete by the mould volume by using the eq (4). The reported value for each mixture represents the average of three specimens.

$$Density\ (D) = \frac{M}{V} \tag{4}$$

Where, D: The density of fresh concrete (kg\m^3), M: The mass of fresh concrete (kg), V: The volume of cube measure (m^3**)**

5.3. Testing of Hardened Concrete

5.3.1. Compressive Strength

Compressive strength tests were conducted on 100 × 100 × 100 mm cube specimens in accordance with BS 1881: Part 116 (1989). Three specimens were tested for each mixture at the ages of 7 and 28 days, and the reported compressive strength values represent the average of the three measurements, Figure 11 shows the compressive strength testing setup**.**

Fig. 11. Compressive strength testing setup

5.3.2. Equilibrium Density

The cylinders used in this test have dimensions of 100mm diameter x 200mm height, and they were tested based on ASTM C 567-05 standards. After 24 hours but not more than 32 hours, the cylindrical samples were removed from their molds. When hanging and submerged cylinders in water, the cylinders' apparent mass in water was designated as (A) as shown in Fig12(a). The cylinders were removed from the water, drained for one minute, and wiped with a damp cloth to remove *e*xcess surface water and achieve saturated surface-dry (SSD) condition. The saturated surface-dry (SSD) mass of the cylinders was designated as (B). Consequently, the cylinders were oven-dried at 110 °C for a period of 72 h. Upon completion of drying, the specimens were removed from the oven then cooled to room temperature, and weighed the specimens. This procedure was repeated every 24 h until the variation in mass was less than 0.5%. The mass of the oven-dried cylinders was designated as (C). (Fig. 12) explains the test steps for determining the equilibrium density. The oven-dry density (O_m) was calculated using the following Eq. (5):

$$Om = \frac{C * 997}{B - A} \tag{5}$$

Where, $O_{m:\ Oven}$-dry density (Kg\m³), A: Apparent mass of cylinder submerged in water (kg), B: Saturated surface-dry mass of cylinder in air (kg), C: Oven-dry mass of cylinder (kg). Then, calculated equilibrium density by using the following eq (6):

$$Ed = O_m + 50(Kg\backslash m^3) \tag{6}$$

Where, Ed: Calculated equilibrium density (kg/m³), O_m: Oven-dry density (kg/m³).

(a) (b)

Fig. 12 (a) Apparently submerged mass (A), (b) Oven-dry mass (C)

5.4 Alkali silica Reaction (ASR)

Attapulgite is a naturally occurring fibrous silicate clay mineral with and acidic properties which contribute to its high adsorption capacity and catalytic potential. chemically the attapulgite formula is $Mg_5Si_8O_{20}(OH)_2(OH_2)_4.4H_2O$ and contains aluminum silicate minerals and hydrous magnesium and adsorbed water within its crystalline system. Alkali silica Reaction (ASR) determine whether attapulgite aggregate used in LWSCC mixture could experience an ASR that might cause internal expansion thus deteriorate the concrete as indicated in[5]. According to ASTM 1260-07, Three mortar bars with dimension (25*25*285) mm were used for this test. The test procedure includes:

- Crushed attapulgite aggregate and sieved to meet the grading requirements of the standard specification as shown in the Fig.13(a), then dried the aggregate and cool it to room temperature
- Prepare the mortar mixture test by mixing 1part of Portland cement with 2.25 parts of graded aggregate with w\c ratio 0.47 by mass then cast the mortar bars as shown in the Fig.13(b).
- After casting, the specimens were covered by nylon sheets and stored for 24 h at room temperature, then remove the specimens from its mold and immersed in water at 80°C for 24 h.
- After recorded the initial length by using length comparator, the mortar bars specimens were transferred to immersed a 1 N NaOH solution maintained at 80±2C° as shown in the Fig.13(c).
- Length change measurements were reading at specified intervals with at least three intermediate readings 3, 7, 10 and 14 days. The expansion recorded at age 14 days was used to evaluate the alkali–silica reactivity of the attapulgite aggregate as shown in the Fig.13(d), the expansion was calculating from eq (7).

$$Expansion\ \% = \frac{Lx - Li}{G} \tag{7}$$

Where, Lx: Comparator reading at the required age, Li: Initial comparator reading, G:Gauge length of specimen (250 mm)

(a) (b) (c) (d)

Fig. 13. Main stages of the ASR test: (a) aggregate grading, (b) casting mortar bars, (c) curing and immersion at 80°C, and (d) length measurement using a comparator

6. Results and Discussion

6.1. Specific Gravity and Absorption

According to [13], the range of coarse LWA specific gravity corrected to the dry condition is from about 1/3 to 2/3 that of normal weight aggregates. The specific gravity for normal weight concrete with a range of (2.4-2.9) (ACI E1-16). Thus, the specific gravity for LWA is ranged (0.8-1.9). As illustrated in the Table 9. and (Fig.14) all the experimental values obtained from this study fell within the limits of [13]. The specific gravity of aggregate treated with cement impregnation (NC) and adhesive ceramics impregnation (NR) is higher than the reference aggregate (N) treated by presoaking attapulgite. This increment can be attributed to increased weight of treated aggregate gain from deposit treatment materials within the pores increased the attapulgite aggregate density and reduced the volume of internal voids that agreed with results reported by [14] reached to similar finding but for pumice aggregate and [10] for Leca and scoria lightweight aggregates. The aggregates treated with gloss enamel paint (NP) and polyvinyl acetate (PVA) (NPV) exhibited specific gravity values that were very close to that of the untreated control aggregate (N). This behavior may be attributed to the formation of thin coating layers on the aggregate surface without significant penetration into the internal pore structure of the highly porous attapulgite aggregate. Consequently, these treatments mainly modified the external surface characteristics while producing only a marginal effect on the overall density and specific gravity of the aggregate, similar observations were reported by [15].

Table 9. specific gravity and water absorption results

Attapulgite Treatment Type	Absorption %	Specific Gravity (S.G)
Treatment by presoaking attapulgite	26%	1.54
Treatment by cement impregnation	19%	1.60
Treatment by adhesive ceramics impregnation	18%	1.75
Treatment by gloss enamel paint	14%	1.55
Treatment with poly vinyl Acetate (PVA)	26%	1.54

According to [13] after soaking for 24 hr. lightweight aggregates absorbed water from 5 to 25% or more by mass of dry aggregate. As illustrated in Table 9 and Fig. (15), the water absorption reduced about 27%,31%,46% for (NC), (NR) and (NP) respectively compared with (N) which showed an absorption of 26%. s shown in (Fig. 15), the water absorption of aggregates treated with cement impregnation (NC), adhesive ceramics impregnation (NR), and gloss enamel paint (NP) decreased by approximately 27%, 31%, and 46%, respectively, compared with the untreated aggregate (N). For NC, the reduction in absorption can be attributed to the penetration of cement slurry into the surface pores, followed by the formation of hydration products that partially blocked the pore network and limited water ingress. In the case of NR, the adhesive ceramic material effectively filled and sealed a considerable portion of the interconnected pores, thereby reducing the accessible void volume available for water absorption. Also, the NP treatment exhibited the lowest absorption value because the gloss enamel paint formed a continuous hydrophobic film around the aggregate particles, acting as a physical barrier that restricted water penetration into the porous structure. Similar trends have been reported by [8]and [16]. For the PVA-treated aggregate (NPV), no noticeable change in water absorption was observed. This behavior may be attributed to the limited penetration of the PVA solution into the internal pore structure of the aggregate. , This behavior may indicate that dust was present on aggregate surface, Similar trends have been stated by [17] [18] or the smooth surface (glassy) of aggregate resulting from aggregate exposed to high temperature as the results obtained by [5].

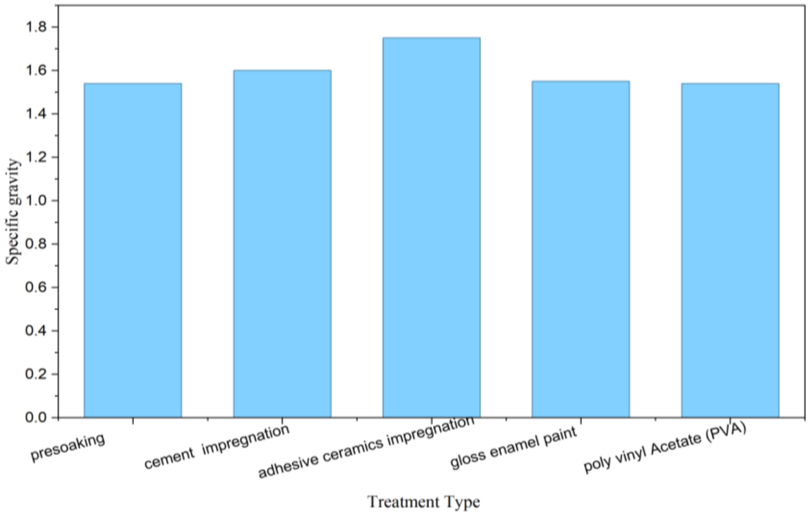


Fig. 14. Specific gravity results

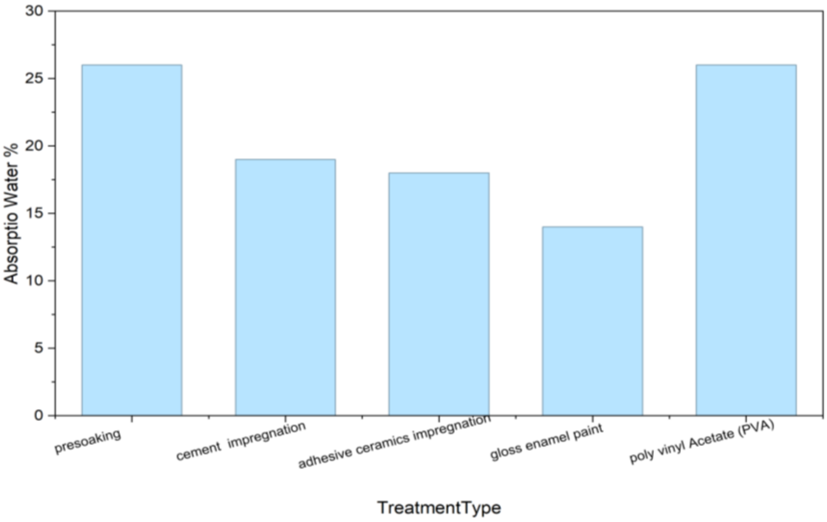


Fig.15. Absorption results of treated attapulgite

6.2. Fresh and Equilibrium Density

As presented in Table 10 and (Fig. 16), all equilibrium density values ranged between 1713 and 1774 kg/m^3, satisfying the requirements of structural lightweight concrete according to ASTM C567. The highest equilibrium density was recorded for the adhesive ceramic impregnation treatment (NR), reaching 1774 kg/m^3, followed by the polyvinyl acetate treatment (NPV) and the untreated aggregate (N), with values of 1768 and 1761 kg/m^3, respectively. The increase observed in the NR mixture can be attributed to the penetration of the impregnation material into the interconnected pore network of the attapulgite aggregate, leading to partial pore filling and a reduction in internal void volume. Similar observations were reported by Domagała et al., who found that impregnation of lightweight aggregates improved particle tightness and increased density through pore sealing and internal densification.

Table 10. Results of equilibrium density

Aggregate treatment type	Symbol	Fresh Density (kg\m^3)	Equilibrium density (Kg\m^3)
Treatment by presoaking attapulgite	N	1923	1761
Treatment by cement impregnation	NC	1974	1744
Treatment by adhesive ceramics impregnation	NR	1989	**1774**
Treatment by gloss enamel paint	NP	1950	**1713**
Treatment with poly vinyl Acetate (PVA)	NPV	1947	**1768**

The cement impregnation treatment (NC) exhibited an equilibrium density of 1744 kg/m^3, which was lower than that of NR but still higher than the NP mixture. This behavior may be associated with the formation of hydration products within part of the pore structure, resulting in a denser aggregate skeleton that confirm with previous study by [8]. In contrast, the gloss enamel paint treatment (NP) produced the lowest equilibrium density (1713 kg/m^3). Although the paint coating reduced water absorption, its effect was mainly limited to the external surface of the aggregate and did not substantially modify the internal pore structure. Therefore, the increase in solid volume inside the aggregate remained limited. Similar findings were reported [10, 19] for surface-coating treatments. The equilibrium density of the polyvinyl acetate-treated aggregate (NPV) reached 1768 kg/m^3 and remained close to that of the untreated aggregate. This result suggests that the PVA coating had a limited ability to penetrate the internal pore system of the attapulgite aggregate. Although a thin polymer film may have formed around the aggregate particles, its contribution to internal densification was relatively small. Similar observations regarding PVA-based coatings were reported in studies on coated lightweight aggregates [10, 20].

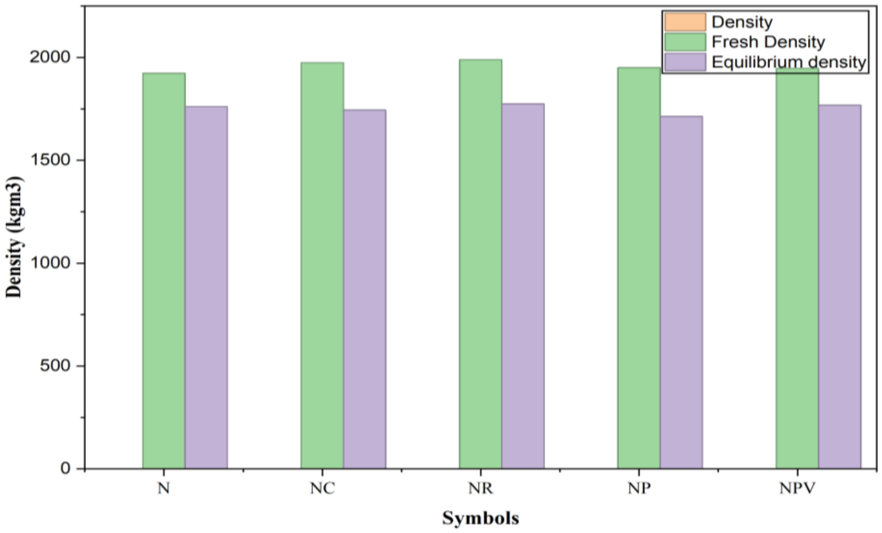


Fig. 16. Fresh and equilibrium density results

6.3. Fresh Properties (Slump Flow and T500Mm)

As presented in Table 11, all mixtures satisfied the EFNARC requirements for self-compacting concrete, with slump flow values ranging from 715 to 735 mm and T50 times between 2.53 and 2.94 s. The fresh properties were noticeably influenced by the surface treatment method applied to the attapulgite lightweight aggregate. The control mixture (N) exhibited the highest slump flow value of 735 mm. In contrast, the cement-impregnated aggregate (NC) and adhesive ceramic-impregnated aggregate (NR) reduced the slump flow to 720 and 715 mm, respectively. This reduction can be attributed to the increased surface roughness and higher friction between the treated aggregate particles and the surrounding cement paste, which restricted the free movement of the concrete during flow. Similar observations were reported by [21].

The influence of the treatments was also reflected in the T50 values. Although the NR mixture exhibited the lowest slump flow (715 mm), its T50 value remained relatively low (2.78 s), indicating that once flow was initiated, the mixture maintained adequate mobility. The NC mixture recorded the highest T50 value (2.83 s), suggesting a slightly higher viscosity due to the presence of cement hydration products deposited within the aggregate pores. Similar effects of pore-filling treatments on fresh-state rheology have been reported [22, 23]. On the other hand, the gloss enamel paint treatment (NP) achieved a slump flow of 730 mm and the lowest T50 value of 2.53 s among all mixtures. This behavior may be attributed to the formation of a smooth coating layer around the aggregate particles, which reduced surface friction and facilitated particle movement during flow. Consequently, the mixture exhibited improved flowability and lower viscosity compared with the other treated aggregates. Similar trends have been reported [2, 21].

Table.11 Slump flow diameter and T50cm results

Aggregate treatment type	Symbol	Slump (mm)	T50 (sec)
Treatment by presoaking attapulgite	N	**735**	2.94
Treatment by cement impregnation	NC	**720**	2.83
Treatment by adhesive ceramics impregnation	NR	**715**	2.78
Treatment by gloss enamel paint	NP	730	2.53
Treatment with poly vinyl Acetate (PVA)	NPV	720	2.88

The polyvinyl acetate treatment (NPV) resulted in a slump flow of 720 mm and a T50 value of 2.88 s, which were close to those of the control mixture. This indicates that the thin PVA film had a limited influence on the rheological behavior of the fresh concrete. The treatment mainly modified the aggregate surface without substantially altering the internal pore structure or the interaction between aggregate particles and cement paste. Similar findings have been reported for [21, 23]. As shown in Table 6, the superplasticizer dosage varied from 1.2% to 1.4% to maintain the target SCC workability. Despite the slight increase in SP dosage for the NC and NR mixtures, lower slump flow values (720 and 715 mm) were still observed compared with the reference mixture (735 mm). Therefore, the observed changes in slump flow and T500 may be attributed to the combined influence of aggregate surface treatment and superplasticizer dosage. These results compatible with results reported by [24]. For mixture with attapulgite aggregate treatment with PVA solution (NPV), results showed there is no noticeable change in Sp dose compare with N, this attributed PVA formed a thin layer on aggregate surface which reduce surface roughness and thus improves workability.

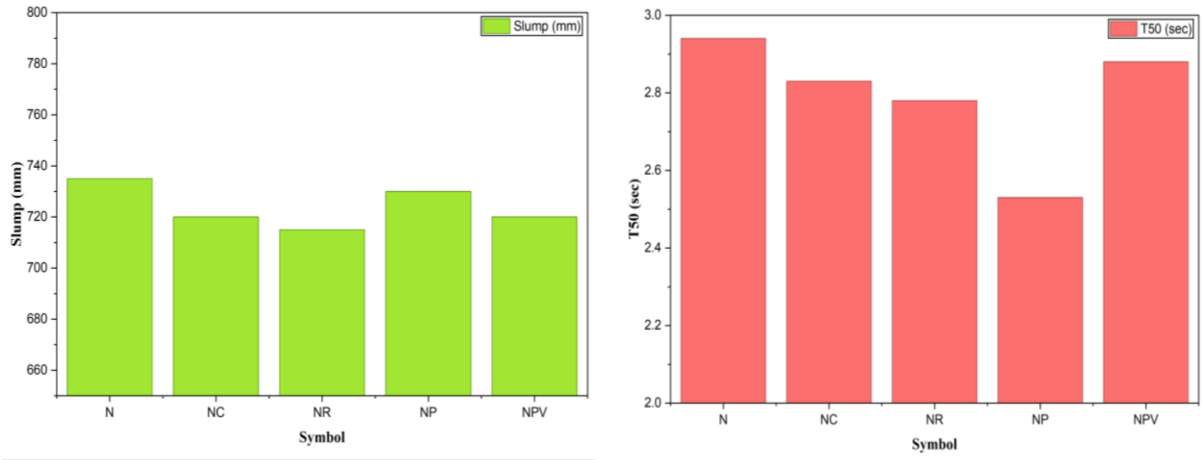


Fig.17. Slump flow and T50cm results

6.4. Compressive Strength

Compressive strength is a major mechanical property of hardened concrete and is widely recognized as a main guide for evaluating its overall mechanical implementation and other related properties. As shown in the table 12 (Fig. 18), the concrete mix (NC) at 7 and 28 days exhibited higher compressive strength than other mixes (NR, NP, NPV) compared with the reference (N). At 7 days, the NC mixture showed increased in compressive strength about 7% compare wit compared with the reference (N) h reference (N) , whereas for NR, NP, NPV, the reduction about 21%, 51%,23% respectively were noted compared with the reference (N). At age 28 days, the experimental results for NC mixture recorded improvement in strength about 4%, while it recorded reductions in strength of about 17%, 47%, and 23% were recorded for the NR, NP, and NPV mixtures respectively compared to the reference concrete.

Table 12. Compressive strength results

Aggregate treatment type	Symbol	Compressive strength (MPa)	
		7 days	28 days
Treatment by presoaking attapulgite	N	25.11	30.03
Treatment by cement impregnation	NC	26.89	31.27
Treatment by adhesive ceramics impregnation	NR	19.74	24.82
Treatment by enamel gloss paint	NP	12.33	15.66
Treatment with poly vinyl Acetate (PVA)	NPV	19.22	23.03

The increase in compressive strength observed for the NC mixture can be attributed to the improved roughness of surface attapulgite aggregate, which improved mechanical interlocking and improves cohesion between the aggregate and the cement paste, in agreement with the conclusions registered by [16] and [25]. In addition, cement impregnation treatment efficiently reduces water absorption of the attapulgite aggregate, helping more cement hydration products. As a result, a higher amount of hydration products develops in the vicinity of the treated aggregate, leading to an increase in the local density at interfacial zone. Based on SEM observations, a denser interfacial transition zone (ITZ) with fewer micro voids and a more compact microstructure was observed around the cement-impregnated aggregate, which may have contributed to the improvement in compressive strength. These results compatible with results reported by [8, 26].

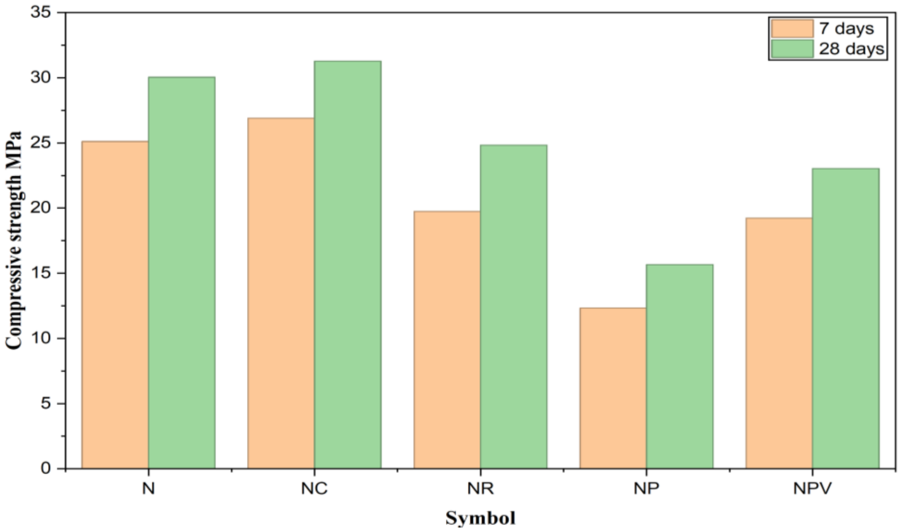


Fig. 18. Compressive strength

In contrast, LWSCC incorporating with pre-wetted or pre-saturated aggregates (N) displayed a weaker interfacial bonding, which adversely affected compressive strength. Also, the NP mixture demonstrated lower strength values, as the enamel gloss paint-treated attapulgite aggregate possessed a smoother surface, resulting in poor cohesion between the enamel-gloss-paint-coated aggregate and the cement paste. This observation is consistent with previous results stated by [27, 28].The use of polyvinyl acetate (PVA) to treated aggregates (NPV) resulted in reduction in compressive strength at both 7 and 28 days, this behavior can be attributed to the formation of a thin film of PVA that does not significantly improved bonding between treated attapulgite aggregate – cement paste, as PVA-based treatments primarily act as adhesive coatings rather than strength-enhancing modifiers as a results reported by [29].

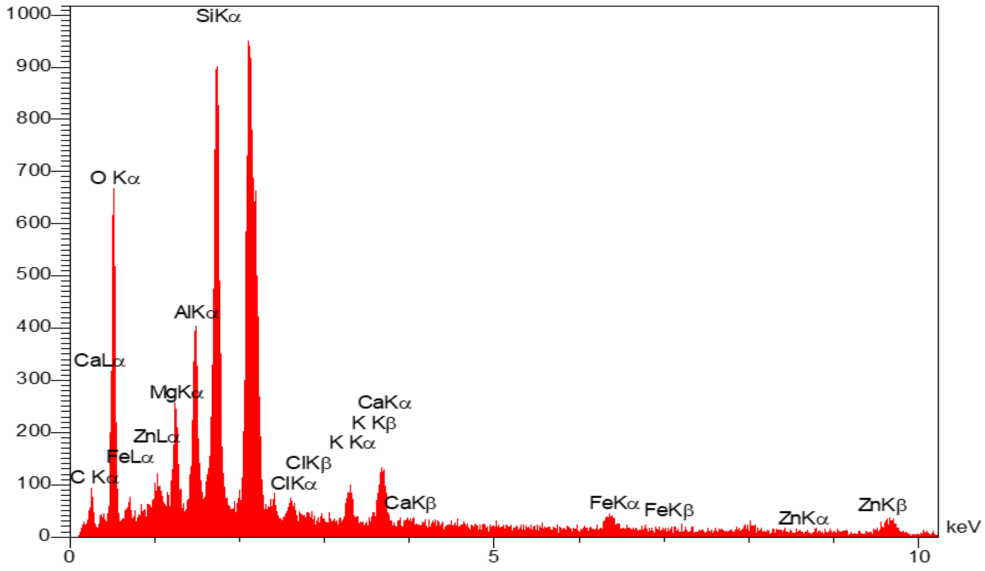
6.5. Alkali – Silica Reactivity (ASR)

The measured expansion value of 0.052% after 14 days is lower than the ASTM C1260-07 limit of 0.10%, indicating that the attapulgite aggregate possesses negligible alkali–silica reactivity. Therefore, the aggregate can be safely used in structural lightweight concrete without significant risk of deleterious expansion, cracking, or long-term durability deterioration associated with ASR. Similar observations have been reported for lightweight aggregates exhibiting expansion values below the ASTM threshold.

6.6. Microstructure Analysis

6.6.1. EDS Analysis of Attapulgite Aggregate Before and After Burning

The EDS spectra presented in Fig.19 and Fig.20 illustrate the elemental composition of attapulgite lightweight aggregate before and after burning, respectively, and clearly demonstrate the influence of thermal treatment on the chemical characteristics of the aggregate surface.

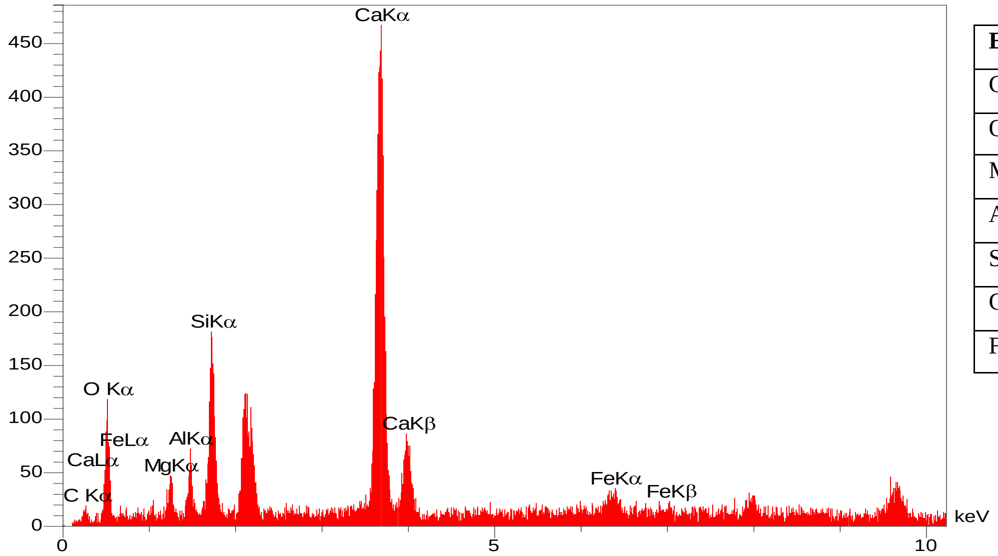


Elt	W%
C	18.84
O	45.77
Mg	4.08
Al	5.93
Si	13.06
Cl	1.35
K	1.54
Ca	2.79
Fe	1.96
Zn	4.67

Figure 19. EDS analysis of attapulgite aggregate before burning

Before burning, the attapulgite aggregate exhibited high contents of oxygen (45.77%), carbon (18.84%), silicon (13.06%), aluminum (5.93%), and magnesium (4.08%). These elements represent the main composition of natural attapulgite, which mainly are formed of hydrated magnesium aluminum silicates. The higher carbon content denotes the presence of volatile compounds, absorbed moisture, and organic impurities within the raw material of lightweight aggregate. Also, the presence of Zn, K, and Cl peaks implies the existence of unstable minor mineral phases associated with the untreated aggregate. Similar elemental compositions for raw attapulgite and porous lightweight aggregates were reported by [30].

After burning, a greater change in elemental distribution were observed. The carbon content (C) decreased significantly from 18.84% to 8.46%, this reduction due to decomposition and elimination of volatile materials and absorbed water during thermal treatment. Moreover, Zn, K, and Cl peaks dissolved completely after burning, confirming that at elevated temperatures unstable impurities were eliminate. At the same time, calcium content increased considerably from 2.79% to 33.64%, while oxygen stilled at the dominant element. This increment may be attributed to the concentration and stabilization of calcium-rich mineral phases after calcination. However, due to dehydration and structural transformation of the attapulgite crystalline network during heating, Mg, Al, and Si contents were decreased. These results indicate that the burning process improved the mineral structure and chemical stability of the attapulgite aggregate surface. The reduction in volatile materials and unstable phases after burning may modify the surface composition and stability of the attapulgite aggregate. In addition, the decrease in internal porosity and water absorption may contribute to improved aggregate performance in LWSCC mixtures [5].



Elt	W%
C	8.46
O	43.56
Mg	1.96
Al	1.85
Si	6.33
Ca	33.64
Fe	4.20

Figure 20. EDS Analysis of attapulgite aggregate after burning

6.6.2. Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) is one of the most important techniques used to study the microstructure of cement-based materials. The SEM micrographs show the microstructural interaction between the treated attapulgite by cement impregnation and the cementitious matrix. As shown in Fig. (21), the surface of the treated attapulgite aggregate is coated with hydration products (C–S–H), forming a fibrous and irregular surface structure. This indicates the penetration and deposition of hydration products within the micro-pores of the attapulgite surface, which improve the bonding between the attapulgite aggregate and the cement matrix. Interfacial transition zone (ITZ) between the treated attapulgite aggregate and the surrounding matrix represents, the treated surface of attapulgite aggregate improves the interfacial bonding with the cement matrix and contributes to a more integrated microstructure, Similar results show by [8, 31].

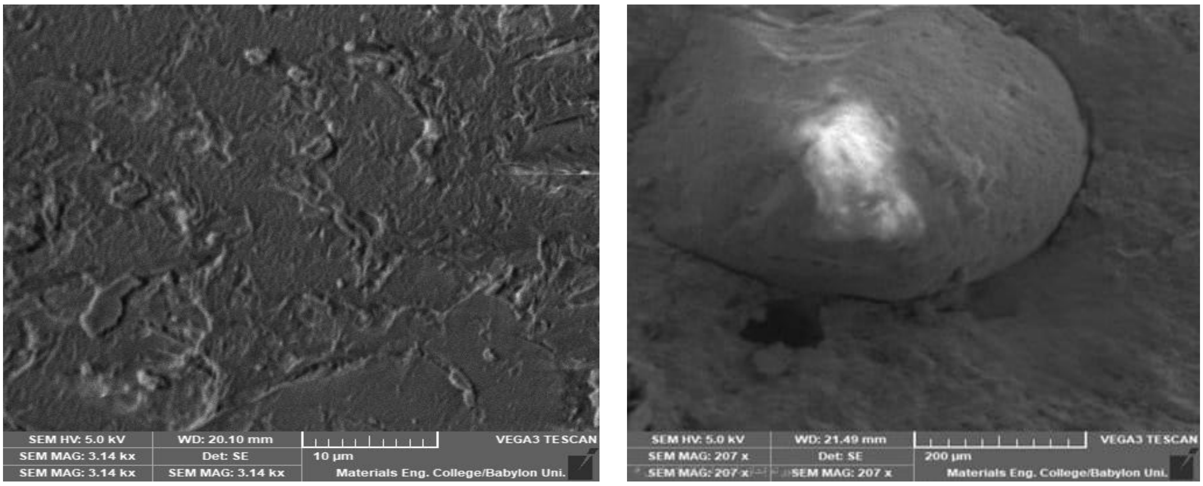


Fig. 21. SEM micrographs of cement-mortar-treated attapulgite aggregate: (a) surface morphology of treated aggregate showing deposited hydration products (C–S–H), and (b) interfacial transition zone (ITZ) between the treated aggregate and cement

7. Conclusion

In this research, four types of attapulgite aggregate surface treatment were used: cement impregnation, adhesive ceramics impregnation, gloss enamel paint, and poly vinyl Acetate PVA, the conclusions from experiments are as follows:

- Surface treatment exhibited a reduction in the water absorption of attapulgite aggregate for the cement impregnation (NC), ceramic adhesive impregnation (NR), and gloss enamel paint (NP) treatments, resulting in reductions of approximately 27%, 31%, and 46%, respectively, compared with the reference aggregate. In contrast, the polyvinyl acetate (NPV) treatment showed no noticeable effect on water absorption.
- Specific gravity was influenced by the effectiveness of pore filling and the reduction of internal porosity. Cement impregnation (NC) and ceramic adhesive impregnation (NR) increased the specific gravity due to the deposition of solid materials within the pore structure of the attapulgite aggregate. In contrast, gloss enamel paint (NP) and polyvinyl acetate (NPV) mainly formed surface coatings, resulting in limited changes in specific gravity despite their influence on water absorption behavior.
- All LWSCC mixtures satisfied the requirements of structural lightweight concrete according to ACI 213R-14, with equilibrium density values ranging from 1713 to 1774 kg/m^3. The applied surface treatment methods influenced the density values to varying degrees; however, none of the treatments altered the classification of the produced concrete as structural lightweight concrete.
- The fresh properties were influenced by both aggregate surface treatment and the corresponding superplasticizer dosage. The reference mixture (N) exhibited a slump flow of 735 mm and a T50 time of 2.94 s using 1.2% SP. The cement-impregnated mixture (NC) and ceramic adhesive mixture (NR), despite using higher SP dosages of 1.4% and 1.3%, respectively, recorded lower slump flow values of 720 mm and 715 mm, indicating that the increased surface roughness and internal friction dominated the flow behavior. In contrast, the gloss enamel paint mixture (NP) achieved a slump flow of 730 mm and the lowest T50 value of 2.53 s with only 1.2% SP, suggesting improved particle mobility. The PVA-treated mixture (NPV) showed a slump flow of 720 mm and a T50 value of 2.88 s, remaining close to the reference mixture.
- Cement impregnation treatment (NC) achieved the highest compressive strength among the investigated mixtures, with increases of approximately 7% and 4% at 7 and 28 days, respectively, compared with the reference mixture. This increment was due to improved cohesion at the interfacial transition zone (ITZ). non-cementitious treatments (NR,NP,NPV) resulted in notable strength reductions at ages 7 and 28days.
- SEM and EDS analyses indicated that the cement mortar treatment modified the surface characteristics of the attapulgite aggregate through the deposition of hydration products. The EDS results indicated higher concentrations of calcium and silicon on the treated aggregate surface after treatment. However, the presence of C–S–H phases cannot be confirmed solely based on EDS analysis. These observations indicate a denser interfacial region and improved aggregate–paste interaction compared with the untreated aggregate, which may contribute to the enhanced mechanical performance of the treated mixtures.

Acknowledgement

The author would like to express their sincere appreciation to their supervisor, Prof. Dr. Ali Hassoun, for his/her invaluable guidance, continuous support, and insightful advice throughout this research.

References

[1] Nahhab AH, Ketab AK. Influence of content and maximum size of light expanded clay aggregate on the fresh, strength, and durability properties of self-compacting lightweight concrete reinforced with micro steel fibers. Constr Build Mater. 2020;233:117922. https://doi.org/10.1016/j.conbuildmat.2019.117922

[2] Pavithran S, Praveen M, Preethi M, Kumar MA. An Experimental Investigation of Lightweight Self Compacting Concrete with Replacement of Coarse Aggregate as Pumice Stone-A Review. Mater Res Proc. 2022;23. https://doi.org/10.21741/9781644901953-22

[3] Adhikary SK, et al. Lightweight self-compacting concrete: A review. Resour Conserv Recycl Adv. 2022;15:200107. https://doi.org/10.1016/j.rcradv.2022.200107
[4] Carroll D. Clay minerals: a guide to their X-ray identification. Geological Society of America; 1970. https://doi.org/10.1130/SPE126-p1
[5] Qais JF, Waleed AA, Mahdi JH. Producing lightweight concrete aggregate from Iraqi attapulgite. In: Proceedings of the 2nd Australasia and South East Asia Structural Engineering and Construction Conference; 2014; Bangkok, Thailand. p. A9-A14. https://doi.org/10.14455/ISEC.res.2014.132
[6] Abdulhussein FK, Beddu S, Nazri F, Al-Hubboubi S, Aljalawi N. Effect of using Fly Ash and Attapulgite Lightweight Aggregates on Some Properties of Concrete. Eng Technol Appl Sci Res. 2024;14(5):17280-17285. https://doi.org/10.48084/etasr.8452
[7] Tang CW. Effect of presoaking degree of lightweight aggregate on the properties of lightweight aggregate concrete. Comput Concr. 2017;19(1):69-78. https://doi.org/10.12989/cac.2017.19.1.069
[8] Domagała L, Podolska A. Effect of lightweight aggregate impregnation on selected concrete properties. Materials. 2021;15(1):198. https://doi.org/10.3390/ma15010198
[9] Miranda A, et al. High-Performance Concrete from Rubber and Shell Waste Materials: Experimental and Computational Analysis. Materials. 2024;17(22):5516. https://doi.org/10.3390/ma17225516
[10] Vahabi MY, Tahmouresi B, Mosavi H, Fakhretaha Aval S. Effect of pre-coating lightweight aggregates on the self-compacting concrete. Struct Concrete. 2022;23(4):2120-2131. https://doi.org/10.1002/suco.202000744
[11] Yew MK, et al. Effect of pre-soaking treatment method of plant-based aggregate on the properties of lightweight concrete-preliminary study. Coatings. 2023;13(5):864. https://doi.org/10.3390/coatings13050864
[12] Thong C, Teo D, Ng C. Application of polyvinyl alcohol (PVA) in cement-based composite materials: A review of its engineering properties and microstructure behavior. Constr Build Mater. 2016;107:172-180. https://doi.org/10.1016/j.conbuildmat.2015.12.188
[13] Akers DJ, et al. Guide for structural lightweight-aggregate concrete. ACI 213R-03. Michigan: American Concrete Institute (ACI); 2003.
[14] Bideci ÖS, Bideci A, Gültekin AH, Oymael S, Yildirim H. Polymer coated pumice aggregates and their properties. Compos Part B Eng. 2014;67:239-243. https://doi.org/10.1016/j.compositesb.2013.10.009
[15] Ünal M, et al. Physical and mechanical properties of pre-treated plant-based lightweight aggregate concretes: A review. Constr Build Mater. 2024;444:137728. https://doi.org/10.1016/j.conbuildmat.2024.137728
[16] Mahmmod LMR, Dulaimi A, Bernardo LFA, Andrade JMdA. Characteristics of Lightweight Concrete Fabricated with Different Types of Strengthened Lightweight Aggregates. J Compos Sci. 2024;8(4):144. https://doi.org/10.3390/jcs8040144
[17] Kandhal PS, Motter JB. Criteria for accepting precoated aggregates for seal coats and surface treatments. Pennsylvania Department of Transportation, Bureau of Construction and Materials; 1987.
[18] Lopez E, Rung M, Adwani D, Masad A, Hazlett D, Bhasin A. Developing Guidelines for Precoating of Aggregates Used in Seal Coats [Report]. Center for Transportation Research, University of Texas at Austin; 2022.
[19] Yahya MQ, Ibrahim EK. Evaluation of coating materials used to enhance the properties of lightweight aggregate. Kufa J Eng. 2026;17(2):476. https://doi.org/10.30572/2018/KJE/170229
[20] Pang C, Zhang C, Li P. Improvement of core-shell lightweight aggregate by modifying the cement-EPS interface. Materials. 2023;16(7):2827. https://doi.org/10.3390/ma16072827
[21] Güneyisi E, Gesoglu M, Ghanim H, İpek S, Taha I. Influence of the artificial lightweight aggregate on fresh properties and compressive strength of the self-compacting mortars. Constr Build Mater. 2016;116:151-158. https://doi.org/10.1016/j.conbuildmat.2016.04.140
[22] Ibrahim H, Abbas W. Fresh properties of self-consolidating expired cement-fly ash cold bonded lightweight aggregate concrete with different mineral admixtures. Eng Technol J. 2023;41(5):734-744. https://doi.org/10.30684/etj.2023.139260.1424
[23] Jamal Hamasalh B, Jalal Khoshnaw G. Fresh properties of lightweight concrete and lightweight self compacting concrete produced with pumice aggregate. Eurasian J Sci Eng. 2020;6(2):11-20. https://doi.org/10.3390/eajse.v6i2p11
[24] Abbas WA, Frayyeh QJ, Al Obaidey SJ. Fresh and hardened properties of lightweight self compacting concrete containing attapulgite. Eng Technol J. 2016;34(9):1767-1781. https://doi.org/10.30684/etj.34.9A.5
[25] Zhao Z, Wang S, Lu L, Gong C. Evaluation of pre-coated recycled aggregate for concrete and mortar. Constr Build Mater. 2013;43:191-196. https://doi.org/10.1016/j.conbuildmat.2013.01.032
[26] Chen HJ, Lin CK, Tsai WP, Liu TH. A Study of Interfacial Transition Zone in Lightweight Aggregate Concrete. Adv Mater Res. 2011;194:935-941. https://doi.org/10.4028/www.scientific.net/AMR.194-196.935

[27] Tuncer M, Bideci A, Çomak B, Durmuş G, Sallı Bideci Ö. Experimental investigation of durability properties of polymer coated pumice aggregate lightweight concretes. Polymers. 2025;17(2):253. https://doi.org/10.3390/polym17020253
[28] Akyuncu V, Sanliturk F. Investigation of physical and mechanical properties of mortars produced by polymer coated perlite aggregate. J Build Eng. 2021;38:102182. https://doi.org/10.1016/j.jobe.2021.102182
[29] Ohama Y. Polymer-based admixtures. Cem Concr Compos. 1998;20(2-3):189-212. https://doi.org/10.1016/S0958-9465(97)00065-6
[30] Zeng Y, Yang X, Zhang C, Yu J. Analytical Solution for the Steady Seepage Field of a Foundation Pit in an Anisotropic Layer. Buildings. 2024;14(4):1055. https://doi.org/10.3390/buildings14041055
[31] Zhang L, Zhang Y, Liu C, Liu L, Tang K. Study on microstructure and bond strength of interfacial transition zone between cement paste and high-performance lightweight aggregates prepared from ferrochromium slag. Constr Build Mater. 2017;142:31-41. https://doi.org/10.1016/j.conbuildmat.2017.03.083