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Cold-Bonded Lightweight Synthetic Aggregate Involving High Reactive Attapulgite at Different Curing Conditions

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HIGHLIGHTS

- SLA was fabricated using HRA and PC via a cold-bonded process
- Different percentage levels of HRA and PC were used
- SLA with a density of 793 kg/m^3 can be produced

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ABSTRACT

This study aimed to develop an eco-friendly, lightweight, and synthetic aggregate (SLA) based on clay suitable for use in structural lightweight concrete. The researchers utilized the cold-bonded pelletization process to agglomerate pozzolanic materials, specifically attapulgite extracted from a quarry, and crushed into a fine filler. The appropriate calcination temperature for manufacturing this clay as a pozzolanic material is 750°C. A total of 22 mixes were created using a combination of high reactive attapulgite (HRA) and cement (PC), with the attapulgite replacement rate varying from 100-50% by a 10% decrement. Different types of curing methods, including oven-dry, oven-water, room-water, and room-room, were applied. The aggregate properties were evaluated to determine density, specific gravity, water absorption, aggregate impact value, crushing strength, and compressive strength. The results revealed that it could produce lightweight synthetic aggregate from clay-based materials with a bulk density of 793 kg/m^3 with suitable physical and mechanical properties. As the percentage of cement in the mixture increased, the specific gravity and density were increased to 18.12% and 36.61%, whereas impact and crushing values of aggregate improved by 81.83%. This, in turn, leads to a significant boost in compressive strength up to 100.94%. Furthermore, there is a noticeable decrease in absorption. Moreover, the aggregate held under oven water positively impacts the strength development of cement-based composites.

1. Introduction

Aggregate is a crucial concrete component, making up 75% of the mixture. It serves various purposes as a building material and can be found in nature as inorganic aggregate or created as synthetic aggregate. Aggregate plays a vital role in not just the mechanical properties but also concrete's physical and durability properties. Recently, the production of synthetic aggregate, particularly lightweight aggregate, has become a highly studied topic in the construction industry [1].

Many researchers have used waste materials to produce lightweight aggregates (LWAs), such as fly ash and GGBS. This positively affects the community, the construction industry, and the environment. As a result, the characteristics of lightweight concrete are strongly influenced by the volume and characteristics of the lightweight aggregates incorporated into the mixture [2].

Furthermore, significant advancements have been made in the cement industry by developing supplementary cementitious materials (SCMs) and blending materials from natural sources. These mineral additives' two most notable features are the pozzolanic and filler effects. Various products have been utilized as cementitious materials, each with a wide range of chemical components that fall within the SiO_2, CaO, and Al_2O_3 ternary phase diagram [3]. The availability of these SCMs is limited due to their production through blast furnace industries or as byproducts of power stations. As a result, a growing trend is to find new, inorganic binding replacements from local sources for use in concrete structures. Earth-based raw materials are promising options for inexpensive and environmentally friendly construction materials. Among these materials, clays are abundant and can be effective as mineral additives or blended concrete in many regions worldwide. Clays are a rich source of silica and alumina that can trigger a pozzolanic reaction under appropriate conditions. Therefore, clays in their raw, calcined,

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and modified forms are crucial cement replacement substitutes for sustainable concrete development, with minimal environmental impacts and lower costs [4].

Synthetic lightweight aggregate (SLA) is produced using pozzolanic waste through three standard methods: cold bonding, sintering, and autoclaving. Of these methods, the cold-bonding method is the most cost-effective and easy to implement in the production of SLA. Additionally, this method requires significantly less energy than the other methods. An inclined revolving pan is necessary to agglomerate the powdered pozzolans to carry out the process. Water is used as the wetting agent in the production process, which involves coagulating the pozzolan powder particles [2,5,6]. Pozzolanic materials require a hydraulic binding to create the C-S-H structure for forming stiff cement pellets. Occasionally, lime is also used as part of this process [7, 8]. A decrease in the compressive strength of concrete results from the replacement of natural aggregates with SLA particles because their strength is lower than that of the natural aggregate particles, according to earlier researchers on the impact of SLA produced by cold-bonding pelletization of pozzolanic materials[9-11]. Many attempts have been made in recent years to eliminate the weakness of artificial lightweight aggregate particles, such as changing the pozzolanic material fineness or using different types of pozzolanic materials with various chemical compositions altering the cement content[12,13].In the literature, many kinds of research have been published in which artificial pozzolans like slag, fly ash, silica fume, sodium and calcium bentonite, and other waste materials or by-products of heavy industrial operations were used in the manufacturing of LWA [13]. The cold bonding process is commonly employed to repurpose various waste materials and create lightweight aggregates for use in concrete. Many studies in the literature have examined various types of waste materials, including municipal solid waste incinerator fly ash [14,15], bottom ash [16,17], granulated blast furnace slag [2], a combination of copper slag and fly ash [18], quarry dust [19], calcined kaolin and metakaolin [20], expired cement and fly ash [21], quartz [22].

High reactive attapulgite is obtained by thermally activating attapulgite clay with a high alumino-silicate content. This process allows for the production of attapulgite with desired characteristics, such as high reactivity and/or proper fineness, as it is not a waste material or by-product and can be produced in a controlled manner [23-25].

In a study [13], the production of 28 different types of lightweight synthetic aggregate (LWA) was investigated using cement, fly ash, hydrated lime, metakaolin, slag, sodium, and calcium bentonite. The physical and mechanical properties of the aggregate mixtures were examined while the aggregate particles were hardened using the cold-bonded technique. The results showed that the synthetic aggregate made with cement and hydrated lime had lower impact strength, while the mixture made with GGBS and hydrated lime had the highest crushing strength of individual pellets and the lowest water absorption capacity values. Consequently, it was determined that the varied binder contents have a varying effect on the engineering features of such aggregate.

Ibrahim et al. studied the features of artificial aggregate properties such as density, water absorption, specific gravity, and impact value of aggregate produced [16]. Several percentages of ash replacement were chosen, ranging from 10% to 50%. Aggregate pellets were treated with four curing conditions namely: room-room, oven-room, water-room, and oven water. They showed that exposing the aggregate in-room water condition is the most efficient curing regime. The ideal aggregate was chosen at 20%, meeting the necessary 739.5 kg/m^3 density, and was given impact value (AIV) 14 classification as strong aggregate.

Given the foregoing, the current study has designed a comprehensive experimental program to evaluate the novelty of manufacturing aggregate from thermally treated attapulgite (TTA) and evaluate its effects on curing conditions on the density, water absorption, specific gravity, impact value, and crushing strength of the lightweight synthetic aggregate. The cold-bonded pelletization technology was used in the production of SLA. Specific replacement levels and different curing regimes were assigned for this purpose. Impure local attapulgite was calcined in commercial kilns to obtain sufficient pozzolanic activity. Twenty-two different alternative aggregate types were created, and four different curing conditions were applied to this aggregate to determine the efficiency of the curing on the properties of such aggregate. In the second phase of the research, 22 different concrete mixtures were created by replacing the lightweight aggregates with standard coarse aggregates. A water-cement ratio of 0.4 was utilized in the formulation of the concrete. Afterward, the hardened lightweight concrete specimens were evaluated for compressive strength at 28 days.

2. Experimental Program

2.1 Materials

The theoretical section extends the analytical background of the article and develops a new formulation of the problem. Calculations are achieved here using the developed equations, and the modifications should be pointed out.

In the production of SLA, CEM I 42.5R type ordinary Portland cement (Taslujah) that meets the requirements of I.Q.S No 5, 2019 with a Blaine fineness of 328 m^2/kg, a specific gravity of 3.15 and particle size diameter of 517.2 nm was used, as shown in Figure 2a. The raw material for producing high-reactive attapulgite was obtained from a local Tar Al-Najaf, Najaf, Iraq quarry. The Iraqi clay was treated to become a pozzolanic material (HRA) after removal from the quarry, then it was crushed and ground to a filler. HRA was obtained through special heat treatment at a calcination temperature of 750℃ for 30 minutes, as shown in Figure 1, with a specific gravity of 2.2 and particle size diameter of 303.8 nm, as shown in Figure 2b, as well as the strength activity index (S.A.I) at 28-day of HRA was 107.2 according to ASTM C311[26]. A liquid foaming agent produced the SLA with a specific gravity of 1.02. The chemical properties of cement and HRA are presented in Table 1.

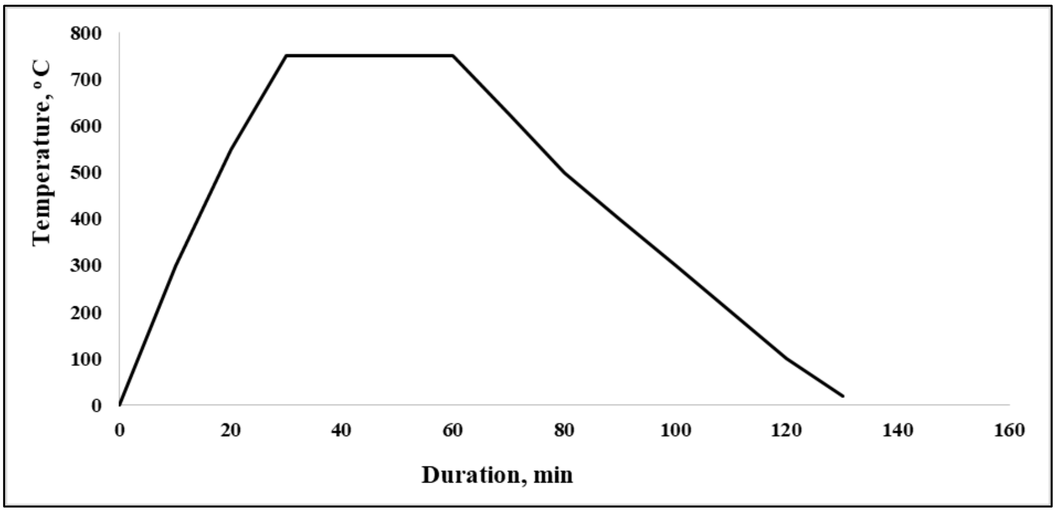
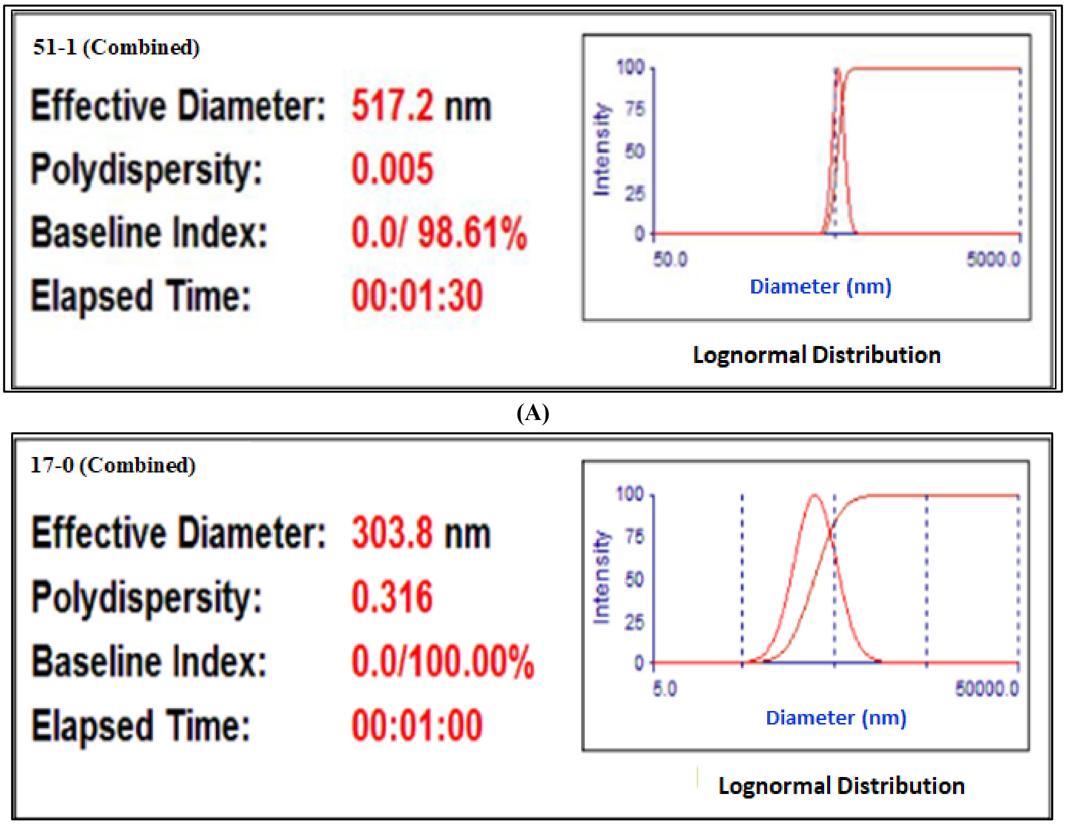


Figure 1: Heating and cooling system for thermal treatment (calcining) of attapulgite



51-1 (Combined)

Effective Diameter: 517.2 nm
Polydispersity: 0.005
Baseline Index: 0.0/ 98.61%
Elapsed Time: 00:01:30

(A)

17-0 (Combined)

Effective Diameter: 303.8 nm
Polydispersity: 0.316
Baseline Index: 0.0/100.00%
Elapsed Time: 00:01:00

(B)

Figure 2: Particle size distribution for (A) Portland cement (B) High reactive attapulgite

Table 1: XRF analysis of PC and HRA

Major components (%)	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	L.O.I	Blaine Fineness (m^2/kg)	S.A.I	S.G
Cement	63.21	19.86	4.18	2.79	1.29	2.62	0.33	0.17	2.99	328	-	3.15
HRA	21.78	51.91	11.80	7.1	6.76	0.77	2.13	2.52	0.19	2010	107.2	2.2

2.2 Natural Fine Aggregate

According to Iraqi standard No. 45/1984, natural fine aggregate with a maximum size of 4.75 mm and specific gravity of 2.65 from (Al-Ukhaider) was utilized in the mix design. Zone 2 has been employed. The grading, physical, and chemical characteristics of natural sand are presented in Tables 2 and 3 respectively.

Table 2: Grading of fine aggregate

Sieve Size (mm)	Passing by weight %	Limitation of the specification No.45/1984 Zone (2)
4.75	100	90-100
2.36	89	75-100
1.18	71.5	55-90
0.60	58	35-59
0.30	24.8	8-30
0.15	4.3	0- 10

Table 3: Fine aggregate properties: physical and chemical

Physical properties	Test result	Test result Limit of Iraqi specification No.45/1984
Specific gravity	2.65	
Sulfate content %	0.17	specification requirements ≤ 0.5% (max)
Absorption %	3.76	
Bulk density Kg/m3	1663	

2.3 SLA Manufacturing Mixture Proportions and Curing Regimes

The study used the cold-bonded pelletization method to produce a lightweight synthetic aggregate (SLA). It utilized a pelletizer machine with specific components, including a pelletization disc, water pump, switchboard, manual jack, scraping blades, and water spray nozzles. The pelletization disc has a diameter of 800 mm, a depth of 350 mm, a revolving speed of 37 rpm, and an inclination angle of 45 degrees, as shown in Figure 3, based on the values specified by [2]. In the process of creating a lightweight synthetic aggregate, a dry combination of powder pozzolans and cement was placed into a tilting pan. Water as a coagulant was then sprayed onto the powder components. To achieve the lightweight characteristics of the aggregate, the foam was incorporated into the mixture. The foam forms pores, resulting in a less dense material. A protein-based foaming agent was used in a 1:25 dilution ratio, with one part of the foaming agent combined with 25 parts of water. The essential weight of the foam was calculated by calculating the density multiplied by the intended volume of foam to be incorporated. It was then swiftly incorporated into the dry mixtures and thoroughly mixed to create a paste. In general, the amount of water sprayed during the process is approximately 38-45% of the total weight of the powder materials. This results in spherical aggregate through the pelletization process. In this study, a dry mixture containing HRA and PC was prepared in five different percentages with HRA percentages of 10%, 20%, 30%, 40%, and 50%. The process was conducted at room temperature and lasted for a total of 20 minutes. During the first 10 minutes of the manufacturing process, water was sprayed onto the dry powder material to allow for pellets formation. The structure of the pellets was formed during the trial manufacturing process, which took place between 10 and 12 minutes. In the second 10-minute period, the tilted pan continued to revolve to produce stiff, compacted, fresh spherical pellets, as shown in Figures 4 (a, b, c).

The study conducted a free-fall test on freshly manufactured pellets to confirm the production of stiff and compacted aggregate. An average-sized pellet was dropped from a height of 115 cm, and if it did not crush or show visible cracks upon impact, the production process was considered successful [20].

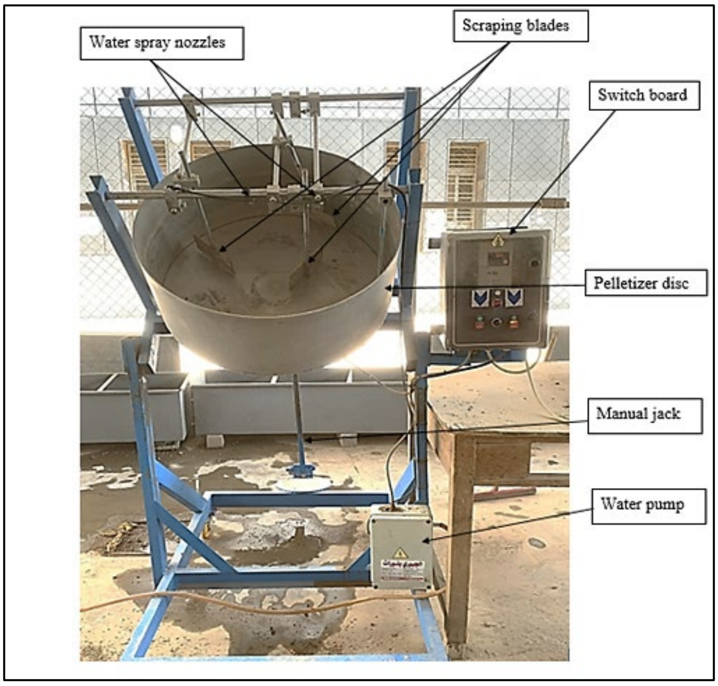


Figure 3: Pelletizer machine

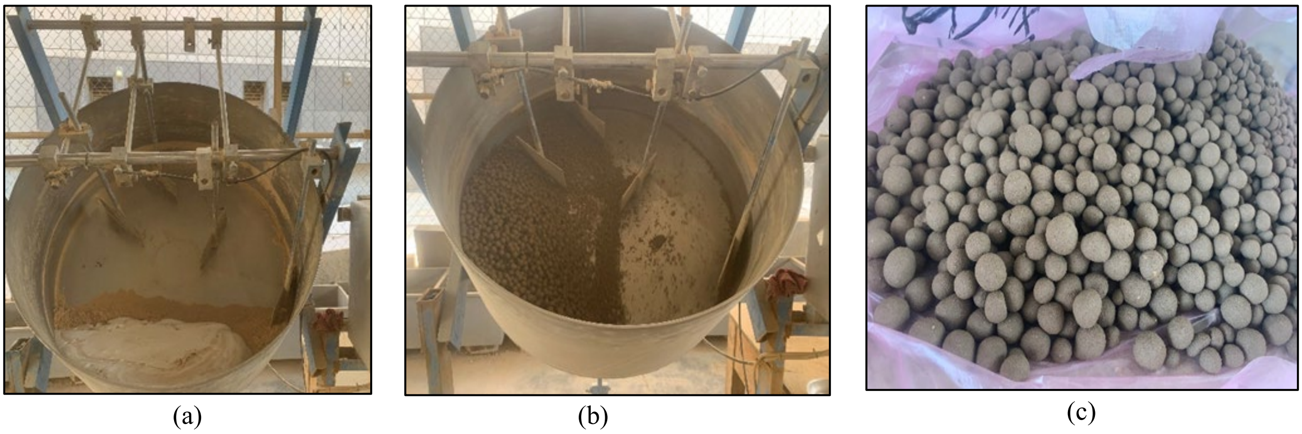

(a) (b) (c)

Figure 4: Lightweight aggregate procedure a) materials in the disc, b) fresh pellets, and c) collecting the fresh pellets

As soon as the production process is finished, the fresh pellets are placed in sealed plastic bags with a relative humidity of 70%, and they are maintained in a curing room at a temperature of 25℃ for 24 hours. Each type of synthetic aggregate was separated into four groups and subjected to specified curing regimes after the initial 24-hour curing time to evaluate the effect of the hardening. The first group was placed in an oven at 100 ± 10ºC, known as the oven-room condition. The second group was kept in a plastic bag in a laboratory environment, curing with moisture, known as room-room curing. The third and fourth groups were held in water at temperatures of 25 and 75°C, respectively, and these curing regimes were dubbed room-water and oven-water, respectively. The aggregate was subjected to various curing environments to assess its physical and mechanical attributes and the efficiency of the curing regimes on the characteristics of SLA. Each curing process took a total of 28 days. Sieve analysis of lightweight aggregate can be seen in Table 4.

Table 4: Sieve analysis of lightweight aggregates used

Sieve size (mm)	**Lightweight coarse aggregate (4-12.5) mm**	**Cumulative passing % ASTM C330** [27]
19	100	100
12.5	95	90-100
9.5	55	40-80
4.75	11	0-20
2.36	0	0-10

2.4 Lightweight Concrete Production

To assess compressive strength, 22 concrete mixtures were meticulously devised using a 0.4 water-to-cement ratio and 410 kg/m^3 of CEM I Portland cement according to the ACI 211.2.98 [28]. The concrete mixture compositions are detailed in Table 5. The composition of the concrete mixes, including water-to-cement ratio, cement content, proportions of coarse and fine aggregates, and superplasticizer content, was consistent across all mixtures. The only difference was in the type of lightweight coarse aggregate utilized. To attain a slump of 150 ± 30 mm, 22 concrete mixtures were designed, utilizing an appropriate quantity of superplasticizer during casting. The proportions of the concrete mixture for a volume of 1 cubic meter can be located in Table 5. The production of LWCs necessitates a specialized technique, owing to the high water absorption characteristics of the lightweight aggregates; therefore, the aggregates underwent a pre-soaking period of 30 minutes before mixing. All the concrete mixes containing a lightweight synthetic aggregate of less than 880 kg/m^3 can be classified as lightweight concrete.

2.5 Testing Procedure

After the curing process, the aggregate density was calculated using the standard method specified in [27]. ASTM C127 [29], was followed to determine the specific gravity of the aggregate at SSD state, and this standard was also used to calculate the aggregates' water absorption capacity. In addition, to the 24-hour water absorption, the 10-minute, 30-minute, 60-minute, 100-minute, 1-day, and 7-day absorption capacities were also measured.

The aggregate impact value is necessary to classify the strength of the aggregates generated in this study, as explained by [30]. The strength of the manufactured aggregate will be represented by the value of the AIV, which is defined as the weight of friction passing through the 2.36 mm sieve size divided by the total weight of the aggregate.

The aggregate samples were tested with a hammer blow 15 times from a height of 350 mm with a hammer weight of 14 kg and then sieved through a sieve of 2.36 mm. Equation 1 can be used to calculate AIV:

$$\text{AIV} = \frac{B}{A} * 100\% \tag{1}$$

where: A= Aggregate net weight (g). B= Aggregate crushing weight via 2.36 mm sieve.

The crushing strength of aggregate was determined in compliance with BS-EN 1097-2 2010 [31] employing a comprehensive test procedure. Aggregate pellets of varying dimensions, specifically between 6 and 14 mm, were selected for the test. The test consisted of positioning a solitary aggregate pellet between two parallel plates and exerting a diametrical force on the particle to measure its strength. After measuring the load, the final result was recorded as the average of 5 pellets' readings. The crushing strength of spherical particles squeezed from two opposing points was calculated using the Equation below:

$$\sigma\_crushing = 2.8F/\pi X^{2} \qquad (2)$$

where: F: the crushing load (in N), X: pellet diameter between loading point (in mm).

To conduct scanning electron microscope (SEM) analysis, standard portions of 1 cm in size recovered from the core of the samples were put in an oven for 24 hours at 105±5°C to eliminate any evaporable moisture. These pieces were then placed on alloy stubs and sputter-coated before being subjected to the electron beams from Axia-Chemi SEM. The experiments have been carried out with the desired magnification.

Table 5: Mix design proportion for 1 m^3

Mix designation	w/b	Cement	Water	*SP	Fine agg	*SLA	Fresh density
Control 1 100%HRA(O.R	0.40	410.00	164.00	6.15	736.80	725.70	1978
Control 2 100%HRA(R.R	0.40	410.00	164.00	6.15	736.80	713.20	1969
HRA90, PC10 (O.R)	0.40	410.00	164.00	6.15	736.80	754.87	2092
HRA90, PC10 (O.W)	0.40	410.00	164.00	6.15	736.80	759.04	2055
HRA90, PC10 (R.R)	0.40	410.00	164.00	6.15	736.80	713.17	1987
HRA90, PC10 (R.W)	0.40	410.00	164.00	6.15	736.80	754.87	2016
HRA80, PC20 (O.R)	0.40	410.00	164.00	6.15	736.80	750.70	1993
HRA80, PC20 (O.W)	0.40	410.00	164.00	6.15	736.80	767.38	2012
HRA80, PC20 (R.R)	0.40	410.00	164.00	6.15	736.80	750.70	1996
HRA80, PC20 (R.W)	0.40	410.00	164.00	6.15	736.80	759.04	2071
HRA70, PC30 (O.R)	0.40	410.00	164.00	6.15	736.80	767.38	2083
HRA70, PC30 (O.W)	0.40	410.00	164.00	6.15	736.80	775.72	2088
HRA70, PC30 (R.R)	0.40	410.00	164.00	6.15	736.80	767.38	2059
HRA70, PC30 (R.W)	0.40	410.00	164.00	6.15	736.80	767.38	2066
HRA60, PC40 (O.R)	0.40	410.00	164.00	6.15	736.80	788.24	2088
HRA60, PC40 (O.W)	0.40	410.00	164.00	6.15	736.80	796.58	2099
HRA60, PC40 (R.R)	0.40	410.00	164.00	6.15	736.80	784.07	2091
HRA60, PC40 (R.W)	0.40	410.00	164.00	6.15	736.80	792.41	2090
HRA50, PC50 (O.R)	0.40	410.00	164.00	6.15	736.80	804.92	2152
HRA50, PC50 (O.W)	0.40	410.00	164.00	6.15	736.80	834.11	2128
HRA50, PC50 (R.R)	0.40	410.00	164.00	6.15	736.80	804.92	2121
HRA50, PC50 (R.W)	0.40	410.00	164.00	6.15	736.80	829.94	2156

*SP; Superplasticizer, SLA: lightweight synthetic aggregate.

3. Results and Discussion

3.1 Density and Specific Gravity

The classification of aggregate types will be based on its density, and concrete can be classified as lightweight according to [32] if the measured density is less than 2000 kg/m^3; the ASTM C330 categorizes aggregate as a lightweight aggregate(LWA) if the unit weight was less than 880 kg/m^3. According to Table 6, (75%) of the aggregate produced from this investigation can be categorized as LWA, independent of the curing regime. Only HRA70PC30 with room-room curing, HRA60PC40 with oven-room curing, and HRA60PC40 with oven-water curing obtained densities slightly higher than the standard maximum density by 0.34%, 0.56%, and 1.25%, respectively. It was discovered that HRA50PC50 with oven water had the highest density at 1026 kg/m^3, whereas HRA80PC20 had the lowest density at 793 kg/m^3 with room-room curing. In general, it can be said that a greater percentage of HRA replacement will lead to a lower density of aggregate, as mentioned in [16].

The specific gravity of the aggregate is crucial in mitigating the density of the aggregate. The test results show that almost all aggregate samples have a specific gravity value below 2, except for HRA50PC50 with oven-water curing, which has a specific gravity of 2.02. The synthetic aggregates subjected to room-room curing showed the lowest specific gravity value of 1.710. The aggregate produced through this study has been classified as lightweight aggregate and meets the EN 13055-1 standard.

The specific gravities of the SLA ranged from 1.710 to 2.02. In general, the synthetic aggregate under the condition of oven-dry curing showed the lowest specific gravity values. Among all SLA types, oven-water curing often produced the highest specific gravity values. This is due to the creation of a denser structure in the heat-curing regimes caused by increased hydration kinetics [20]. Meanwhile, this investigation's density and specific gravity values are interconnected. This is because HRA has a lower specific gravity than OPC. Another significant finding from the current study was that the specific gravity values increased consistently due to replacing cement with HRA since the specific gravity of cement is higher than the specific gravity of attapulgite [16].

The specific gravity values obtained in this study were compared to those obtained by [33], it was discovered that denser LWAs were generated in this investigation while their values ranged from 1.58 to 1.97.

The relationship between density and specific gravity can also be considered in terms of curing regimes. The same table shows that the density of SLA is higher when oven-water curing is used as opposed to oven-dry curing. For example, the mix HRA90PC10 with oven-water curing has a higher density of 834 kg/m^3 than the oven-room curing condition with a density of 806 kg/m^3, as SLA with oven-dry has a lower moisture content than SLA in water curing.

Table 6: Density and specific gravity of SLA produced

	Sample ID	**Density kg/m^3**	**Specific gravity**	**Curing conditions**
Series 1	Control 1 (100% HRA)	751	1.74	Oven-Room
	Control 2 (100% HRA)	NA*	NA	Oven-Water
	Control 3 (100% HRA)	699	1.71	Room-Room
	Control 4 (100% HRA)	NA	NA	Room-Water
Series 2	HRA90PC10	806	1.810	Oven-Room
	HRA90PC10	834	1.829	Oven-Water
	HRA90PC10	821	1.795	Room-Room
	HRA90PC10	823	1.815	Room-Water
Series 3	HRA80PC20	818	1.812	Oven-Room
	HRA80PC20	817	1.840	Oven-Water
	HRA80PC20	793	1.802	Room-Room
	HRA80PC20	819	1.824	Room-Water
Series 4	HRA70PC30	866	1.846	Oven-Room
	HRA70PC30	847	1.858	Oven-Water
	HRA70PC30	883	1.845	Room-Room
	HRA70PC30	853	1.846	Room-Water
Series 5	HRA60PC40	885	1.891	Oven-Room
	HRA60PC40	891	1.910	Oven-Water
	HRA60PC40	903	1.889	Room-Room
	HRA60PC40	909	1.908	Room-Water
Series 6	HRA50PC50	955	1.935	Oven-Room
	HRA50PC50	1026	2.020	Oven-Water
	HRA50PC50	949	1.931	Room-Room
	HRA50PC50	965	1.988	Room-Water

* Not available. Water curing caused the degradation of the LWA pellets.

3.2 Water Absorption

The permeability of concrete directly causes problems with durability. Studies on the permeation characteristics of concrete typically focus on proving the cement paste and the interfacial transition zone (ITZ) between cement paste and aggregate, even though not only the cement paste and ITZ but also the aggregate's features are responsible for the entire permeation performance of concrete. However, it is widely recognized that natural aggregates only sometimes exhibit good permeability performance. In general, this is an issue with synthetic aggregate. As a result, resolving or minimizing the high permeability issue of synthetic aggregate would also fix mechanical and durability issues that may be encountered in concrete produced with synthetic aggregate. Figures 5, 6, 7, and 8 present the water absorption capacities with different curing regimes. The findings show that the water absorption values of synthetic aggregate have an increasing tendency with time passed in all types of aggregate regarding the curing regimes, as well as the absorption percentages, increased with increasing HRA volume inside aggregate mixtures.

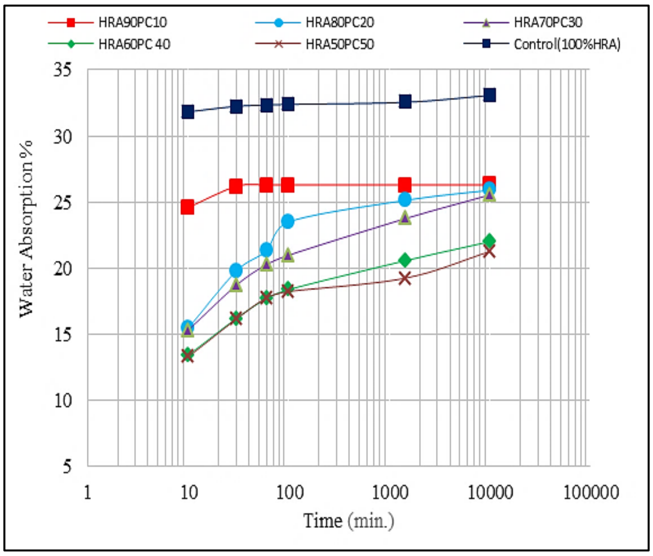


Figure 5: Water absorption capacity oven-room

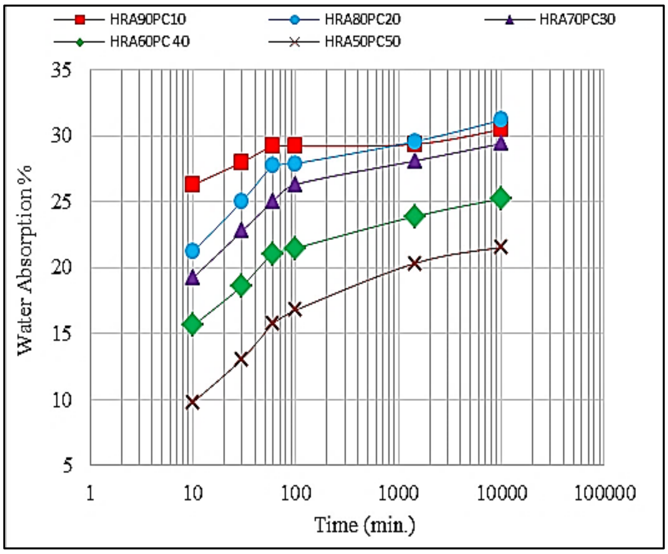


Figure 6: Water absorption capacity oven-room

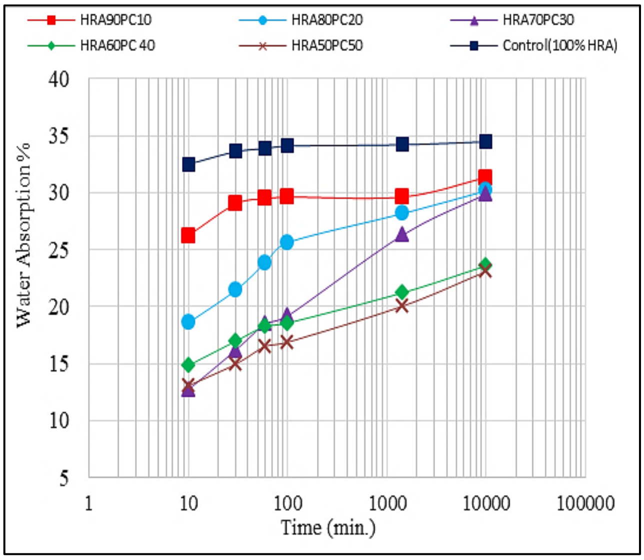


Figure 7: Water absorption capacity oven-room

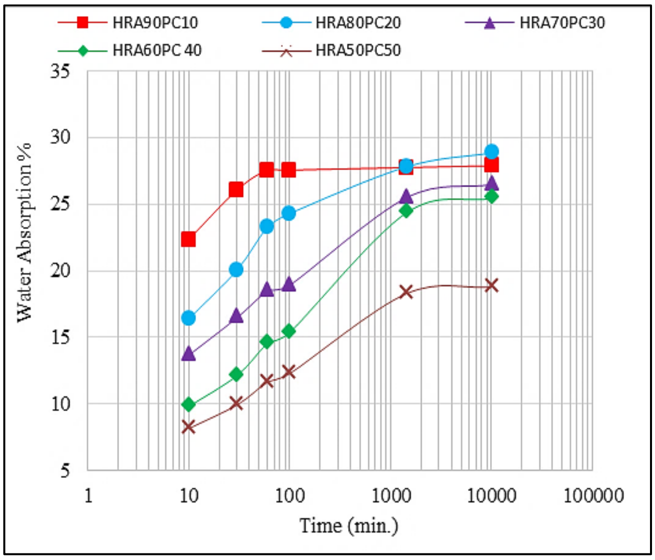


Figure 8: Water absorption capacity oven-room

For instance, the results of 100% to 50% HRA lightweight aggregate with room-room condition decreasing from 32.56% to 19.26% for an absorption capacity of 24-hr. It can be established that as the amount of HRA used in the manufacturing of SLA increases, the greater the water absorption and the lower the strength of the SLA. Increased water absorption negatively affects the strength of SLA-produced concrete. HRA absorbs more water, which reduces the aggregate strength. Additionally, the internal voids created by the foam during the production of LWA also result in increased water absorption levels.

3.3 Impact Test

The Aggregate Impact Value (AIV) is used to measure aggregate strength. According to Figure 9, it can be seen that the aggregate impact value increases proportionally with the percentage of HRA utilized in LWA manufacturing. For instance, it is concluded that the AIV value increases from 17.39 to 26.09 as the percentage of HRA decreases from 90% to 50% for room curing conditions. [16] Claimed that any aggregate with an Aggregate Impact Value (AIV) greater than 20% is unsuitable for concrete production, and any aggregate with an AIV exceeding 30% is considered extremely weak. This conclusion is consistent with the requirement stated in IS: 2386 that the AIV for aggregates must not exceed 25% for heavy-duty concrete applications. The findings of this study demonstrate that a reduced AIV was produced when HRA was employed in SLA production at a higher rate. Moreover, the AIV might also be explored concerning each curing circumstance. From Figure 9, it can be seen that the most effective curing for AIV of aggregate produced is oven-water curing. For instance, the series of HRA90PC10 decreased from 34.62, 26.09, and 28.03 for oven-room, room-room, and room-water, respectively.

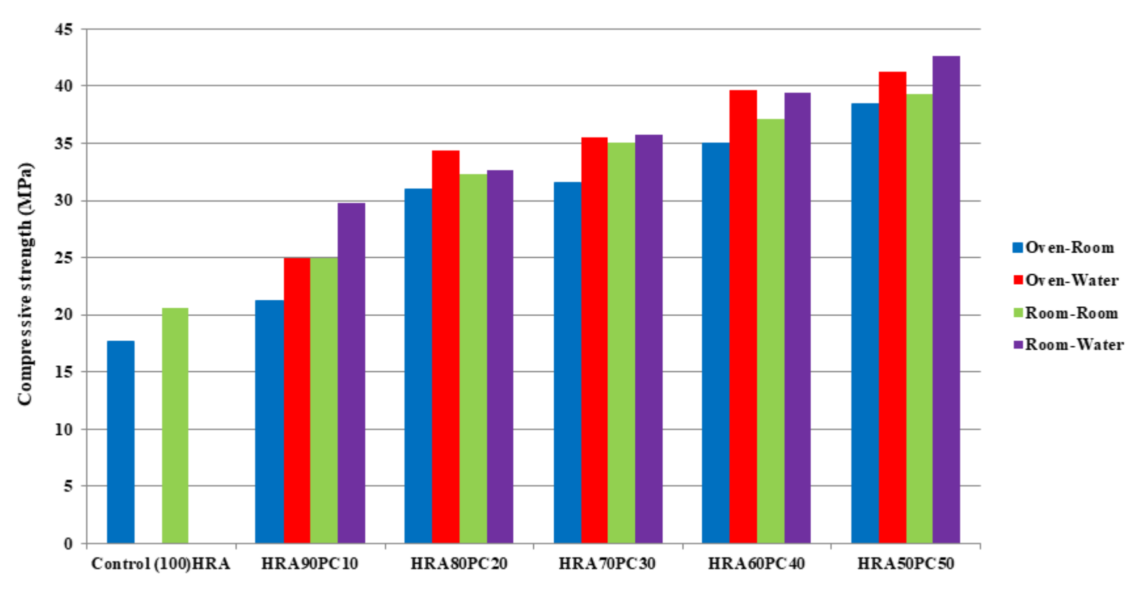


Figure 9: Aggregate impact value of synthetic lightweight aggregate

3.4 Crushing Strength Test

The crushing strength of synthetic aggregate particles is important because the strength of concrete is closely related to the strength of the aggregate particles, cement paste, and the transition zone between them. Table 7 illustrates the crushing load values recorded for synthetic aggregate particles of various diameters.

The table shows the crushing loads on synthetic aggregate that were kept under different curing regimes, including oven-room, oven-water, room-room, and room-water, which are represented respectively. The results showed that larger particles diameter resulted in higher crushing load values. Table 7 illustrates that a rise in cement content enhances the aggregates' strength, primarily due to the hydraulic cement reaction impacting the strength of the SLA. The results of the crushing strength test for the SLA align with the recorded values for specific gravity and water absorption. Aggregates with higher specific gravity, lower water absorption, and lower AIV were stronger. Additionally, the study revealed that the curing regime significantly impacted the crushing load values. Generally, the lowest values were obtained for aggregates kept under oven-room curing conditions regardless of the cement content and aggregate size. However, the aggregates held under water and hot water curing regimes had similar values to those held under moisture curing conditions. This indicates that wet curing positively impacts the strength development of cement-based composites.

As the crushing load values are converted to strength through the relation outlined in Equation 2, SLA's strength decreases as the particle size increases, regardless of the ingredient content and curing conditions. Simply put, the smaller the particle size, the higher the strength.

3.5 Mineralogy and Microstructure

Figure 10 illustrates the microstructure of all the cold-bonded synthetic aggregate pellets using scanning electron microscopy (SEM). The SEM images in Figure 10 show the microstructure and mineralogy of the different percentages and curing regimes used to manufacture aggregates that exhibit different patterns of pores. The main difference between the artificial aggregate types produced by this method is the presence of voids. Some pores are uneven, round, and disconnected, while others are elongated and interconnected.

The microstructural study suggests that oven water and room water as a curing regime may lead to a solid structure, possibly due to a continuous reaction between minerals and calcium hydroxide, as shown in Figure 10. During hydration, Ca $(OH)_2$ reacts with the ingredients in HRA to form calcium silicate hydrate (C-S-H), which helps fill voids. Calcium hydroxide (portlandite) crystals are long with slender ettringite needles and C-S-H crystals, as shown in Figure 10 c. Aggregates made with HRA50PC50 have a denser structure than those as the percentage of attapulgite increases.

The elevated temperature led to more uniform matrices for all aggregate types, regardless of the cement content. Aggregates made with 90% HRA and 10% PC have larger voids. When the temperature applied is too high, continuous pore formation will occur. Among all the types of aggregates, the aggregate made with oven-water curing and 50 percent of ATT has the least number of pores, which increases its binding capacity.

Table 7: Crushing load value for SLA

Aggregate type	**Crushing load value N**				
	Diameter mm				
	6	***8***	***10***	***12***	***14***
Control 1 (Oven room Curing) only HRA	27	39.12	43	44.3	47
HRA90PC10	113.28	199.32	217.44	249.15	271.8
HRA80PC20	249.19	302.62	469.31	527.05	687.44
HRA70PC30	416.76	453	634.2	724.8	815.4
HRA60PC40	463.18	659.26	691.8	843.12	933
HRA50PC50	543.6	906	815.4	996.6	1087.2
Control 2 (Oven water curing) Only HRA	NA	NA	NA	NA	NA
HRA90PC10	226.5	237.82	294.45	430.35	566.25
HRA80PC20	261.3	338.1	406	603.75	805.65
HRA70PC30	317.1	498.3	543.6	815.4	915.06
HRA60PC40	483.56	688.15	742.71	922.23	1062.78
HRA50PC50	634.2	838.05	906	985.27	1200.45
Control 3 (Room-room curing) Only HRA	32	43.8	47	51	51
HRA90PC10	253.68	271.8	317.1	280.86	294.45
HRA80PC20	331.01	349.89	423.35	458.56	543.45
HRA70PC30	430.35	462.06	543.6	670.44	747.45
HRA60PC40	454.63	541.05	649.58	824.25	862.59
HRA50PC50	520.95	611.55	770.1	996.6	960.36
Control 4 (Room-water curing) Only HRA	NA	NA	NA	NA	NA
HRA90PC10	203.85	226.5	389.58	317.1	430.35
HRA80PC20	285.76	389.37	499.45	581.26	624.52
HRA70PC30	441.67	566.25	679.5	781.42	860.7
HRA60PC40	513.28	651.53	767.28	939.96	1099.85
HRA50PC50	588.9	724.8	915.06	1132.5	1359

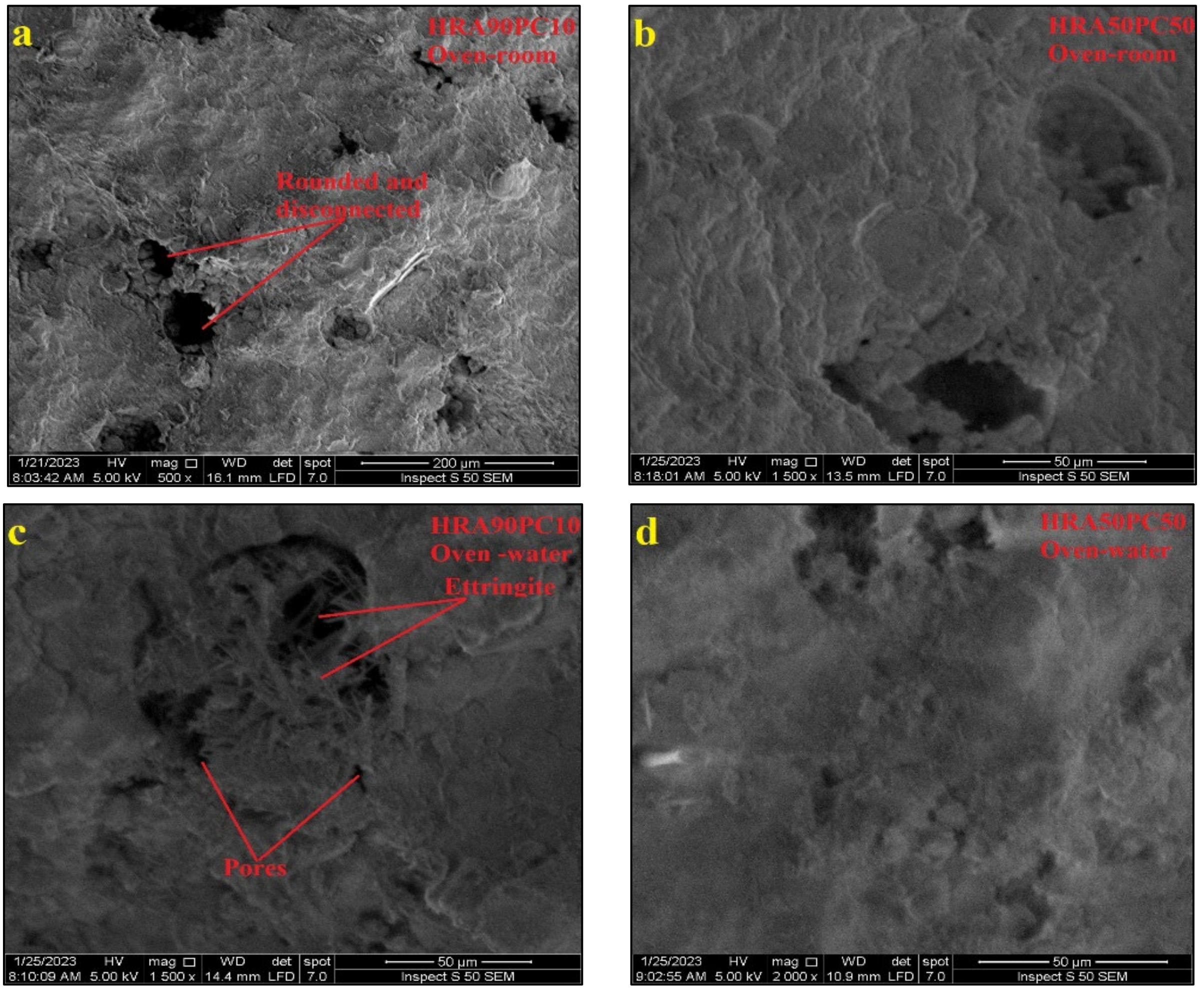


Figure 10: Microstructure of SLA

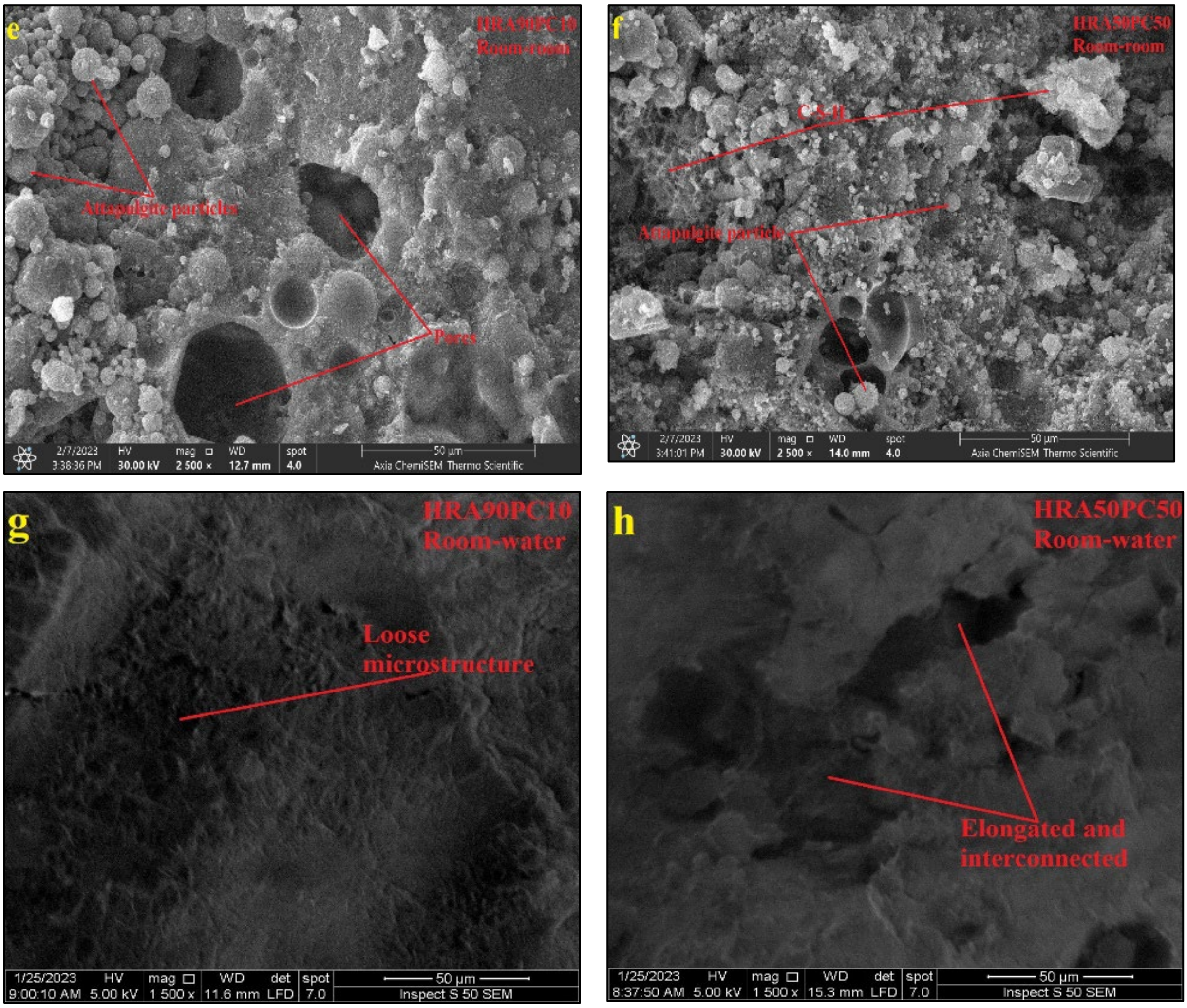


Figure 10: Continued

3.6 Compressive Strength Test

The compressive strength of LWC cannot be determined solely by the density of LWA, as the strength of LWC is not necessarily proportional to its density [34]. The porosity of LWA greatly influences the strength of LWC. [8] Established that the compressive strength of LWC is contingent upon the water absorption capacity, strength, and particle size distribution of the LWA used. The test results of compressive strength at 28 days can be seen in Figure 11. The compressive strength of lightweight concrete (LWC) is affected by the specific gravity, porosity, and crushing strength of lightweight aggregates (LWAs), given that the W/c ratio and cement dosage remain constant.

Although the SSD specific gravity of HRA90PC10 and HRA80PC20 of oven curing, or HRA90PC10 of room-water curing, are similar, the concrete produced using these aggregates demonstrated a significant difference in compressive strength. The concrete made with HRA90PC10 LWA had a compressive strength of 21.2 MPa at 28 days, while the concrete made with HRA80PC20 LWA had a compressive strength of 31 MPa with the same oven-room curing. Similarly, the concrete made with HRA90PC10 of oven-room and water-room curing LWAs had compressive strengths of 21.2 MPa and 29.8 MPa, respectively. This result indicates that the crushing strength of the LWAs primarily determines the compressive strength of LWCs. As the cement content in the production of lightweight aggregates increases, the compressive strength of lightweight concretes also increases due to the stronger crushing strength of the aggregates. Of the 22 lightweight concretes studied, the one made with an aggregate containing 50% HRA and 50% cement had the highest 28-day compressive strength of approximately 42.6 MPa. However, the 28-day compressive strength of the concrete made with the control-high reactive attapulgite lightweight aggregate and cured at oven room temperature was the lowest, with a value of approximately 17.7 MPa. The results of this study demonstrate that the effect of cement content in the lightweight aggregates (LWAs) on the compressive strength of LWCs is highly pronounced, as evidenced by the crushing tests performed.

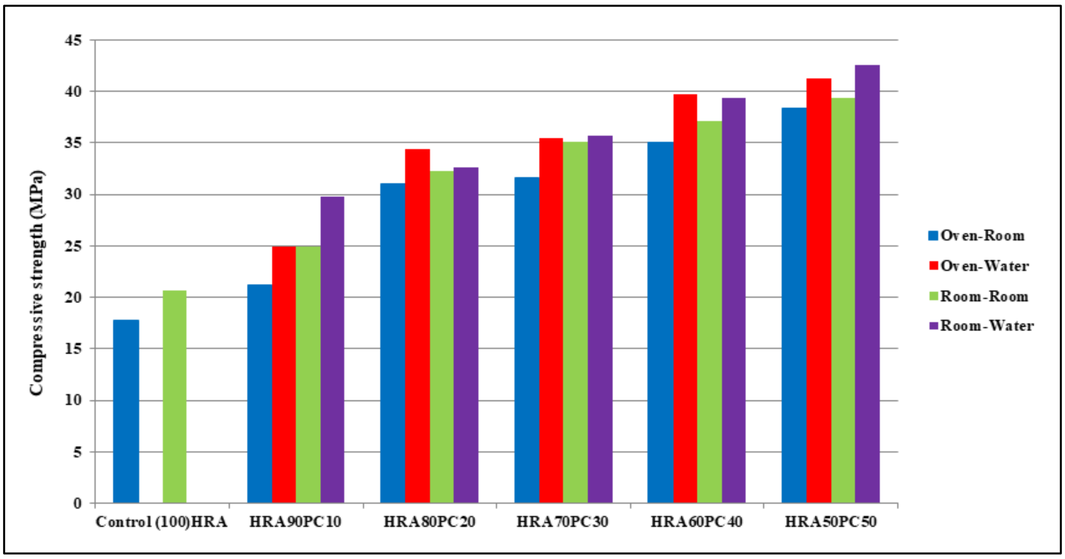


Figure 11: Compressive strength of LWC

4. Conclusion

The following inferences can be derived from the above observations:

1) It is possible to produce lightweight synthetic aggregate through a pelletization process using clay-based material, specifically HRA, with a unit weight of less than 880 kg/m3. Based on these findings, using these lightweight synthetic aggregates may present a new opportunity to produce lightweight structural concrete.
2) To achieve maximum pelletizing efficiency in a pelletizer machine with a diameter of 800 mm and a depth of 350 mm, the rotational speed should be set at 37 rpm, and the tilt angle should be set at 45º. The optimal water percentage for this process is between 0.38-0.45 by the total weight of the binder. As the percentage of HRA increases, the percentage of water demand also increases.
3) The most optimal pelletizing results were attained with a blend of 80% (HRA) and 20% (PC), leading to a nearly complete conversion of the powder material in the disc pan into Lightweight Aggregates (LWA).
4) As the percentage of cement in the mixture increases, the aggregate's specific gravity, density, impact, and crushing values also increase. This, in turn, leads to a significant boost in compressive strength. Furthermore, there is a noticeable decrease in absorption.
5) The study found that using aggregate held under oven water improved cement-based composites' strength, specific gravity, density, impact, and crushing values, significantly increasing compressive strength and reducing absorption. Room-room curing was identified as the most cost-effective and easy-to-apply curing method, yielding acceptable water absorption rates, specific gravity, and strength. The optimal mix is 80% HRA, 20% PC, cured using the room-room method, based on density measurements.
6) The study suggests that the compressive strength of lightweight concrete is determined by the impact value and crushing strength of the lightweight aggregate used. As the amount of cement in aggregate production increases, the concrete's strength also increases.
7) Finally, using cold-bonded high reactive attapulgite aggregate as a substitute for traditional aggregate can result in a more sustainable and environmentally conscious approach to construction. Integrating these aggregates into lightweight structural concrete can also mitigate the negative effects of fly ash produced by thermal coal-fired power plants and reduce the depletion of scarce natural resources.

Author contributions

Conceptualization, M. Abbas and W. Abbas; Methodology, M. Abbas and W. Abbas; Validation, M. Abbas and W. Abbas; Resources, M. Abbas and W. Abbas; Data curation, M. Abbas and W. Abbas; Writing - original draft, M. Abbas; Visualization, M. Abbas and W. Abbas; Project administration, M. Abbas; Supervision, W. Abbas; All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data supporting this study’s findings are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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