Journal of Asian Concrete Federation
Vol. 6, No. 2, pp. 37-49, December 2020
ISSN 2465-7964 / eISSN 2465-7972
https://doi.org/10.18702/acf.2020.12.6.2.37

Technical Paper

Appraisal of geopolymer lightweight aggregates sintered by microwave radiations

Nimra Saleem, Khuram Rashid*, Noor Fatima, Sadia Hanif, Ghinwa Naeem, Aamna Aslam, Miral Fatima, Kiran Aslam

(Received May 15, 2020; Revised November 6, 2020; Accepted December 26, 2020; Published December 31, 2020)

Abstract: This work was designed for the production of geopolymer based lightweight aggregate (LWA) using industrial by-products. Combination of fly ash (FA) and silica fume (SF) were used as precursors, whereas, combination of sodium hydroxide and sodium silicate were used as activator. Small amount of sodium bicarbonate was also used for surface hardening and early strength development. Pellets of different sizes were crafted manually and cured by microwave radiations just for 5 minutes. The physico-mechanical properties of produced pellets (LWA) were discussed in light of: morphology, density, water absorption, specific gravity, porosity, aggregate impact value, and particle crushing strength. The properties of LWA were also compared with literature reported synthetic LWAs cured with different techniques. The water absorption and specific gravity of LWAs were within the specified range provided by ACI standard. Mechanical strength properties briefed that the produced LWAs were strong enough to resist compressive load comparable to natural LWAs and many other synthetic LWAs. Thus, proposed curing method, microwave irradiation, has been found to be a sustainable and fast curing technique than conventional energy-intensive curing regimes. The results also confirmed that produced LWAs have potential to replace natural LWAs both in cast-in-place and precast concrete elements with possible economic, environmental, and technical benefits.

Keywords: Geopolymer lightweight aggregates; geopolymerization; pellets; microwave radiations; physical and mechanical properties.

1 Introduction

The construction industry is considered to be one of the most important indicators of economic state of a country and concrete is the major and most widely used construction material in civil engineering field. Bulk concrete production, however, leads to both environmental pollution and excessive resources consumption [1]. Growing industrial wastes such as fly ash (FA), ground granulated blast furnace slag (GBFS), and silica fume (SF) can be utilized as construction materials, which is considered a healthy and sustainable practice to dispose the waste off and conserve the available resources for future generations [2]. The incorporation of these industrial by-products as a partial replacement of cement is done in order to reduce huge CO_2 emissions from cement production [3]. On the other hand, it is well known that self-weight of concrete structures considerably influences the design load and economy of structures. Since, aggregate phase occupies 60-80% of total volume of concrete [4]. Therefore, the utilization of artificial LWAs, manufactured from waste and by-products, in concrete production has attracted significant research interest. The use of artificial LWAs as an alternative to natural aggregates not only reduces the dead load of structures but can also lead to many positive environmental consequences including (1) the preservation of natural resources; (2) conservation of energy required for quarrying processes [5];

Corresponding author Khuram Rashid *is an Associate Professor in the Dept. of Architectural Engineering and Design, University of Engineering and Technology, Lahore, Pakistan.*
Nimra Saleem *is a student in the Dept. of Architectural Engineering and Design, UET, Lahore, Pakistan.*
Noor Fatima *is a student in the Dept. of Architectural Engineering and Design, UET, Lahore, Pakistan.*
Sadia Hanif *is a student in the Dept. of Architectural Engineering and Design, UET, Lahore, Pakistan.*
Ghinwa Naeem *is a student in the Dept. of Architectural Engineering and Design, UET, Lahore, Pakistan.*
Aamna Aslam *is a student in the Dept. of Architectural Engineering and Design, UET, Lahore, Pakistan.*
Miral Fatima *is a student in the Dept. of Architectural Engineering and Design, UET, Lahore, Pakistan.*
Kiran Aslam *is a student in the Dept. of Architectural Engineering and Design, UET, Lahore, Pakistan.*

(3) conversion of waste into value-added products [6].

Generally, LWAs can be classified into two major categories: natural LWAs (pumice, scoria, diatomite, volcanic cinders, sawdust and rice husk) and artificial LWAs (foamed slag, bloated clay, expanded shales and slate, sintered fly ash and expanded perlite) [7]. LWAs have been produced artificially due to its significant demand and to avoid the depletion of natural LWA resources [8-10]. Generally, artificial LWAs are produced through agglomeration which involves granulation or compaction of powdered waste materials into fresh pellets with the desired shape and size. The raw materials are pelletized by mixing with liquid as a binding agent to get the desired size and consistency. In agglomeration process by granulation, different types of pelletizer machines can be used such as disc or pan type, drum type, cone type or mixer type [11]. The fresh pellets are then cured, either by autoclaving, sintering, cold bonding processes or by microwave radiations [6]. Sintering process is based on the creation of a ceramic matrix. The matrix consists of alumina silicates and the sintering temperature for alumina silicate fly ashes is typically in the range of 1100-1200 ℃ [8]. Many researchers have developed LWAs by sintering, as high engineering properties can be obtained depending on agglomerated material's properties and process efficiency. Requirement of high temperature in sintering process leads to CO_2 emissions. Thus, it comes up with the drawback of environmental harms along with high production cost [12]. Autoclaving process involves the mixing of chemical such as cement, lime or gypsum with source material at agglomeration stage. After that, the specimen is exposed to autoclaving or cured in pressurized saturated steam at a temperature of 140^{o}C for several hours [13]. Cold bonding method is normal water curing at ambient temperature to bind the mixing materials. In this method, the materials are stabilized at granulation stage using any binder such as cement, lime or alkali activation mechanisms like geo-polymerization at ambient temperature evading high temperature requirements, which is a significant advantage of cold bonding over sintering process [14]. Autoclave or steam curing process is less efficient to enhance LWA properties in comparison to water curing. This process does not show significant difference in strength and durability properties like ordinary water curing [15]. Since curing method plays a significant role in determining the LWA properties, economy, and sustainability, it must be selected wisely. A prospective and competitive solution to conventional methods of curing is the usage of microwave radiations.

Microwave radiations are the electromagnetic radiations covering both electric and magnetic fields oscillating in the direction of propagation at right angles [16]. A significant difference between microwave cured and conventionally cured material is internal microstructure. Materials cured with microwave possess more consistent external and internal structure and present better strength than conventionally-cured materials. The properties of fly ash based LWAs synthesized using microwave radiations have been studied experimentally. Compared with sintering and autoclaving, microwave heating does not introduce thermal cracking, thermal stresses, and provides durable aggregates [8]. The microwave irradiation has potential to reduce both time and energy required for processing materials due to brisk, efficient, and quick energy transfer mechanism [16]. Therefore, microwave radiation can be used as a cost-effective and fast curing method for LWAs.

With this background, the aim of this work is to manufacture geopolymer based LWAs using microwave radiations. FA and SF are used as precursors. Physical properties (density, void's ratio, specific gravity, water absorption, percentage expansion, porosity, and morphology) and mechanical properties (particle crushing strength and aggregate impact value) have been examined for produced LWAs and are compared with natural LWAs and previously formulated LWAs.

2 Experimental methodology

The methodology adopted to achieve the target was divided into two sub-goals. The first section covered the specifications of materials used in this work and production of geopolymer LWAs (A_{GP}). In the second section, testing was done to examine the properties of A_{GP} like morphology, density, porosity, water absorption, particle crushing strength, and aggregate impact value. The summary of research methodology adopted for production and experimentation of A_{GP} is shown in Figure 1.

2.1 Materials and specimen preparation

The materials used in this study for production of A_{GP} were coal fly ash (FA), silica fume (SF), alkaline activators (NaOH and Na_2SiO_3), and sodium bicarbonate ($NaHCO_3$) as shown in Figure 2. Precursors used for the manufacture of geopolymer based LWAs were FA and SF. FA was obtained from DG Cement Pakistan and its chemical composition resembled with Class-F FA according to ASTM C618 [17]. The amount of oxides and other chemical constituents of FA and SF are presented in Table 1. Alkaline activators used were the solutions of NaOH and Na_2SiO_3. White crystalline flakes of NaOH and alkaline solution of Na_2SiO_3 were purchased from Akbari Mandi (Lahore, Pakistan).

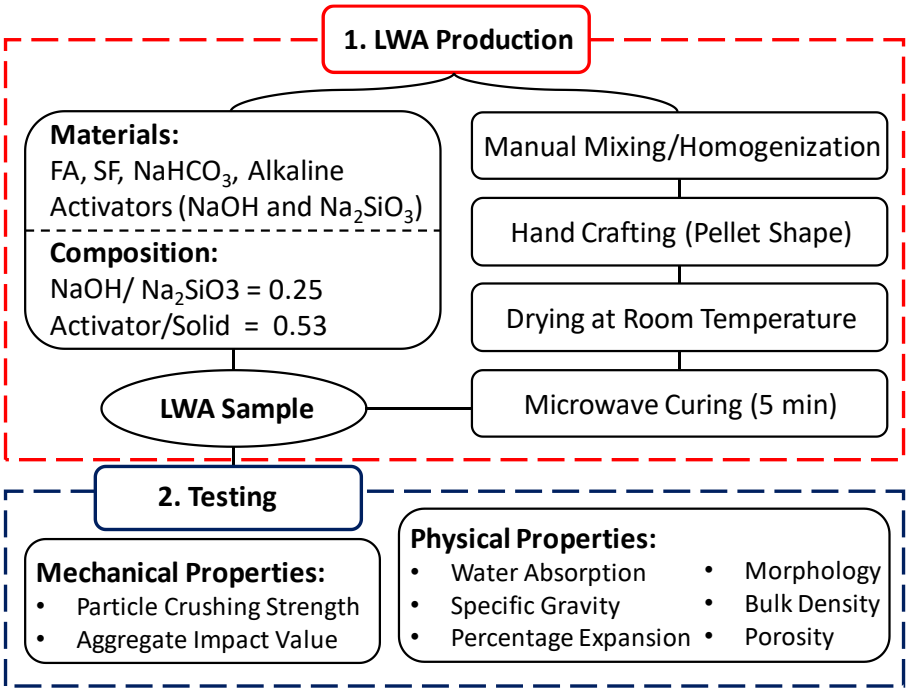

Fig. 1 – Curing condition II and III

Fig. 2 – Materials used in research work: (a) FA, (b) SF, (c) $NaHCO_3$, (d) NaOH, (e) Na_2SiO_3

400g of NaOH pellets were used to prepare 1 liter of 10M NaOH solution. $NaHCO_3$ (baking soda) having molecular mass of 84g/mol and density of 2.1 g/cm^3 was used for surface hardening of aggregates, which acts as an accelerator to decrease the setting time of geopolymer paste [18]. The selection of mix proportion for the production of A_{GP} was based on hit and trial method and on previous research knowledge. The proportion of the A_{GP} for three types of pellets have been mentioned in Table 2. FA and SF were used in amounts of 90% and 10% of total weight of solid materials, respectively. 1% $NaHCO_3$ of solid materials was used as an accelerator. One mixture was selected (FA20-80SF) and their corresponding properties were investigated in detail. Mixture of two alkaline solutions, 10M NaOH and Na_2SiO_3, was used such that the ratio of two solutions ($NaOH/Na_2SiO_3$) was kept 0.25. The alkaline activator to solid ratio selected was equal to 0.53.

Calculated amounts of materials were dry mixed first for about 1-2 minutes. Further mixing was carried out for 1-2 minutes on adding 50% of the alkaline solution. After that, the remaining half of the alkaline solution was added, and the mixing was continued for the same duration in order to ensure fine blending.

Table 1 – Composition of oxides present in FA and SF

Material	**Oxides (%)**							**Cl**	**LOI**	**Moiture Content**
	CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	K_2O	Na_2O	(%)	(%)	(%)
FA	9.02	56.34	23.08	1.70	6.43	0.56	0.28	0.025	< 3	< 1
SF	0.27	93.65	0.28	0.25	0.58	0.49	0.02	3.62	<5	-

Table 2 – Mixing proportion for production of A_{GP}.

Aggregate Type	Pellets Designation	Binding Material (% by total solid)			Alkaline Activator (% by total liquid)		Liquid /Solid
		FA	SF	$NaHCO_3$	Na_2SiO_3	NaOH	
A_{GP}	FA20-80SF	89	10	1	80	20	0.53
	FA30-70SF	89	10	1	70	30	0.53
	FA40-60SF	89	10	1	60	40	0.53

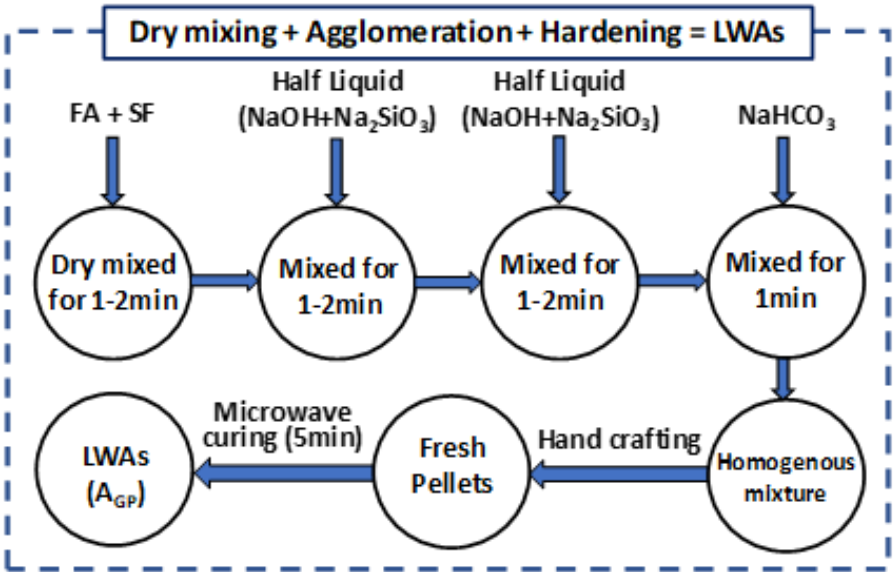

Fig. 3 – A_{GP} pellet formation process

After the formation of homogenous mixture, aggregates were shaped by hands in laboratory having size range about 11-17mm in diameter. Then, pellets were cured under single curing regime that was microwave radiation curing. Aggregates were placed in mud pot and cured for about 4-5 minutes in microwave. The process for the manufacturing of aggregates is illustrated in Figure 3. After the process of curing, the aggregates were wrapped in plastic bags to avoid the penetration of moisture so that it may not alter the test results. The pellets designation such as FA20-80SF is explained as: first two alphabets tell the primary precursor (Fly ash as FA), after alphabets, first two numerals tell the percentage of NaOH; next two numerals tell the percentage of Na_2SiO_3, and last two alphabets are for secondary precursor (Silica fume abbreviated as SF).

2.2 Testing

LWAs were tested for physical and mechanical properties in accordance with the respective standards. Figure 4 shows the procedure of different tests performed on A_{GP} in this work.

2.2.1 Physical properties

To examine the physical properties of LWAs, bulk density, water absorption, specific gravity, porosity, and expansion tests were performed on developed pellets. The morphological features of LWAs were also examined. The particle shape and color were observed from naked eye. Surface texture was examined by touching the surface of LWAs and size of A_{GP} was computed by passing aggregates through sieves as well as Vernier calipers. The bulk density and percentage void test were carried out in accordance with ASTM C29 [19]. The loose and compacted bulk densities were determined by weighing LWAs in a cylinder of known volume and were obtained from Eq. (1) and Eq. (2). From loose and compacted bulk densities, percentage of voids (spaces between LWAs) was determined by using Eq. (3).

$$LBD = \frac{w_{LA+C} - w_C}{V_C} \quad (1)$$

$$CBD = \frac{w_{CA+C} - w_C}{V_C} \quad (2)$$

$$\text{Percentage Voids} = \frac{CBD - LBD}{CBD} \times 100 \quad (3)$$

Relative density (specific gravity) is used in the computation of voids in aggregate. Saturated surface dry (SSD) specific gravity is used if the aggregate is wet, that is, if its absorption has been satisfied. Conversely, the oven dried (OD) specific gravity is used for computations when the aggregate is dry or assumed to be dry. Apparent relative density pertains to the solid material making up the constituent particles, not including the pore space within the particles

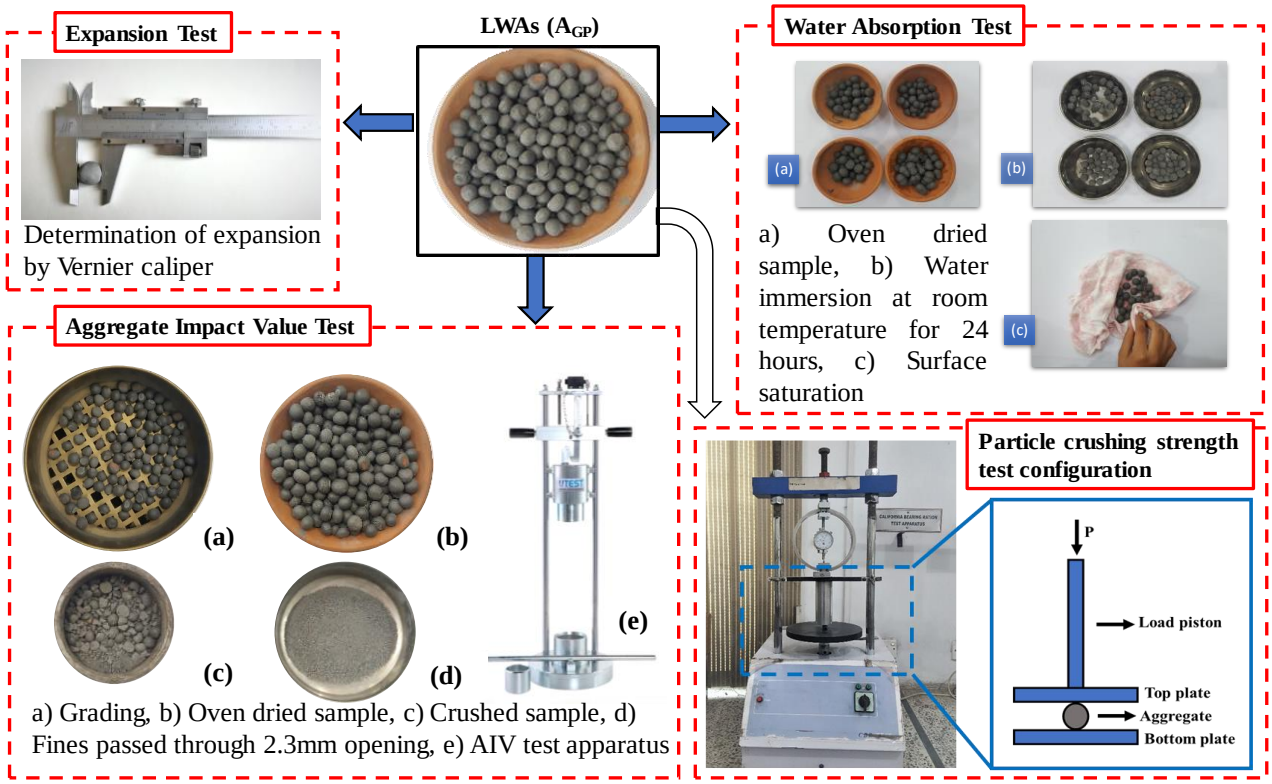

Fig. 4 – Pictorial views of different tests performed on produced LWAs (A_{GP})

which is accessible to water. Absorption values are used to calculate the change in the mass of an aggregate due to water absorbed in the pore spaces within the constituent particles, compared to the dry condition. For water absorption measurement, aggregates retained on 4.75mm opening (Sieve # 4) were immersed in water for 24 hours according to ASTM C128-15 [20]. The relative density (specific gravity) and water absorption values of LWAs were determined by means of equations (Eq. (4); Eq. (5); Eq. (6) and Eq. (7)) given as follows:

$$Relative\ Density\ (OD) = \frac{m_{OD}}{m_{SSD} - m_{AP}} \quad (4)$$

$$Relative\ Density\ (SSD) = \frac{m_{SSD}}{m_{SSD} - m_{AP}} \quad (5)$$

$$Apparent\ Specific\ Gravity = \frac{m_{OD}}{m_{OD} - m_{AP}} \quad (6)$$

$$Absorption = \frac{m_{SSD}}{m_{SSD} - m_{OD}} \times 100 \quad (7)$$

LWAs contain pores which contribute to volume of aggregates. Therefore, it is necessary to determine the true porosity of LWAs, which is the percentage of total pore volume of bulk sample relative to its own volume; it includes the volume of the sealed pores also.

Aggregate volume density, true density and true porosity were determined by using Eq. (8), Eq. (9) and Eq. (10) respectively, where true density is the weight of one cm^3 of fine powder of aggregate without any air in its open pores and its value was determined with the help of pycnometer as given in literature [21]. Expansion of LWAs was also determined for five different sizes of LWAs through Vernier caliper to evaluate the increase in diameter of aggregates after microwave oven curing. Eq. (11) was used to determine the percentage of expansion.

$$Aggregate\ Volume\ Density\ (\rho_b) = {}^{m_1}/_{v_1} \quad (8)$$

$$True\ Density\ (\rho_d) = \frac{w_2 - w_1}{w_2 - w_3} \times density\ of\ water \quad (9)$$

$$True\ Porosity = \left(1 - \frac{\rho_b}{\rho_d}\right) \times 100 \quad (10)$$

$$\%\ Expansion = \frac{D_2 - D_1}{D_1} \times 100 \quad (11)$$

2.2.2 Strength properties

Aggregate impact value (AIV) and particle crushing strength tests were carried out to establish the mechanical properties of A_{GP}. AIV test, which gives the strength of A_{GP} under sudden or impact loads, was carried out in accordance with BS 812-112 [22] on oven dried sample. Similarly, particle crushing strength test was performed on California Bearing Ratio (CBR) apparatus to determine the crushing value of LWAs in order to compute their

ability to take compressive load. The capacity of load ring was 10 kN. The crushing strength of individual pellet was determined in accordance with previous researches [23, 24], where pellets of about 12-16mm in size were placed between two parallel plates individually and loaded diametrically until failure occurred. For more reliable estimate, 5 pellets of different sizes were tested using strength index formula [11]. Equations used to find aggregate impact value (Eq. (12)) and particle crushing strength value (Eq. (13)) are as follows:

$$AIV = \frac{M_2}{M_1} \times 100 \quad (12)$$

$$\textit{Individual crushing strength of pallet} = \frac{2.8\,P}{\pi\, d^2} \quad (13)$$

where: M_1 = weight of sample before compaction (g), M_2 = weight of sample passing through 2.36mm opening or sieve # 8 (g), P = failure load (kN), d = distance between two plates (m).

3 Results and discussion

The physical and mechanical properties of synthesized and natural LWAs obtained from literature are presented in Table 3.
The results obtained from the tests performed on produced LWAs are presented in Table 4. The results are also compared with natural and synthetic LWAs which justify our approach towards objective of this research.

3.1 Physical properties

3.1.1 Morphological features

The LWAs produced in this study were round in shape as shown in Fig. 5. Before microwave curing, A_{GP} were shiny with smooth surface texture. After microwave curing, A_{GP} remained smooth textured with small exposed pores, however, large number of pores were generated inside the A_{GP}. It was observed that before microwave curing the color of A_{GP} was dark grey, while after microwave curing, a slight change in color was observed with internal dark grey core. Since, grading determines the activator requirement and binder content for geopolymer concrete; various sizes of A_{GP} were produced in this study as shown in Fig. 6. It was observed that average particle size for A_{GP} was 13.2 mm, with the smallest and largest size of 11 mm and 17 mm, respectively. Moreover, all the produced aggregates were coarse aggregates as they retained on 4.75 mm opening (Sieve # 4).

3.1.2 Density and percentage void

Aggregate density is considered to be a conclusive parameter for determining the unit weight of concrete and consequently, the dead load of concrete structures. The loose and compacted bulk densities of A_{GP} were found to be 699kg/m^3 and 738 kg/m^3 respectively. The compacted bulk density greatly depends upon the shape and size of aggregates, determining the degree of compaction and presence of voids between aggregates; the percentage of voids was found to be 5.58% for produced LWAs. It was observed that loose bulk density of specimen was less than benchmark (880 kg/m^3) given by ACI 213R-03 [36], which verified their applicability as LWA. It was also noted that: (1) LWAs manufactured in this study were lighter than many previously

Fig. 5 – Particle shape, color, and surface texture of (A_{GP})

Fig. 6 – Grading of (A_{GP})

Table 3 – Raw materials, binders, physical and mechanical properties of natural and synthetic LWAs briefed in literature

Ref.	Binder	Alkaline Activators	Size	LBD	WA	SG		PCS	AIV	Curing Method
			(mm)	(kg/m^3)	(%)	OD	SSD	(MPa)	(%)	
[11]	FA + Metakaolin	NaOH (8M)	12	794	29.75	1.16	1.50	2.07 (12mm), 2.03 (10mm)	----	Cold bonding
[11]	FA + Bentonite	NaOH (8M)	14	867	30.90	1.49	1.96	3.26. (14mm), 2.96 (16mm)	----	Cold bonding
[25]	FA + Cement	----	4-12.5	840	15.00	1.46		8.7	----	Sintering at (>900ºC)
[26]	FA + Cement	----	----	830	16.80	1.40		----	27.78	Sintering at (1000-1200ºC)
[27]	FA + Cement	NaOH, Na_2SiO_3	8.125	878	20.25	----		----	22.10	Oven curing at 70ºC for 24 h
[27]	FA + GBFS	NaOH, Na_2SiO_3	8.125	809	28.30	----		----	27.90	Cold bonding
[28]	FA	NaOH, Na_2SiO_3	9.5-19	789	25.50	1.30	1.63	3.70	----	Cold bonding
[28]	FA	NaOH, Na_2SiO_3	9.5-19	933	0.70	1.56	1.57	12	----	Sintering
[10]	FA	NaOH, Na_2SiO_3	8-10	783	18.19	----	----	----	----	Sintering
[28]	FA	NaOH, Na_2SiO_3	9.5-19	936	0.70	1.59	1.60	9.60	----	Cold bonding
[29]	FA + GBFS	NaOH, Na_2SiO_3	10-20	903	10.60	----		5.70	----	Cold bonding
[29]	FA + GBFS	NaOH, Na_2SiO_3	10-20	1002	8.30	----		15.50	----	Cold bonding
[30]	BA + Cement	----	----	938	25.00	1.48		4.00	35.70	Sintering
[30]	BA + Cement	----	----	1017	21.50	1.57		5.35	29.20	Sintering
[31]	FA + Bentonite	----	----	933	0.7	1.56		12	28.00	Cold bonding
[31]	FA + Glass powder	----	----	936	0.7	1.59		9.6	30.00	Cold bonding
[32]	Diatomite		----	500	7.6	----		----	----	Natural
[33]	Pumice		----	475	25.00	0.80		----	----	Natural
[33]	Expanded perlite		----	40	70.00	2.20		----	----	Natural
[34]	Pumice		----			0.82-2.17		1.49-1.96	----	Natural
[26]	Natural LWA		----	1490	0.90	2.65		----	15.63	Natural
[35]	Calcined diatomite aggregate		4.75-12.5	417	112.0	2.45		----	----	Natural

Table 4 – Physical and mechanical properties of produced LWAs (FA20-80SF)

Property	Value	Property	Value
Loose bulk density (kg/m^3)	699	Aggregate size	11-17mm
Compacted bulk density (kg/m^3)	738	Aggregate impact value (%)	10.24
Voids (%)	5.58	Particle crushing strength (MPa)	3.96 (max)
Porosity (%)	31.93	Specific Gravity (OD, SSD)	(1.4, 1.7)
Water absorption (%)	18.98		

reported densities of artificial LWA cured by other methods, where densities ranged between 789-1017kg/m^3 (Table 3); and (2) they were heavier than some natural LWAs like pumice, expanded perlite and diatomite with densities equal to 475kg/m^3 [33], 40kg/m^3 [33] and 500kg/m^3 [32], respectively. A graphical comparison of natural LWAs, synthetic LWAs from literature and produced LWAs (A_{GP}) is shown in Fig. 7.

3.1.3 Porosity

Aggregate total porosity test roots for determining the percentage of total pores in aggregate. Total porosity of prepared pellets was determined, and the observed values are presented in Table 5. LWAs are exposed to heating process during their formation which causes the expansion of LWAs [37]. This expansion leads towards the introduction of closed pores in aggregate's inner anatomy, causing a significant increase in its total or true porosity. The total porosity of prepared pellets was found to be 31.93% with true density of 2010kg/m^3. Maximum total porosity of LWAs can be up to 67% as given in literature [38]. Thus, A_{GP} porosity fell in the range of prescribed true porosity for LWAs. It can be observed that A_{GP} exhibited greater value of true porosity than literature-reported LWAs having true porosity in the range of 6.20-31.10% [28]. Literature has shown that some natural LWAs like pumice and scoria have true porosity equal to 59.06% and 49.04%, respectively [39]. Therefore, it can be deduced that A_{GP} are heavier than natural LWAs because porosity and density are inversely related to each other [27] as shown in Fig. 8.

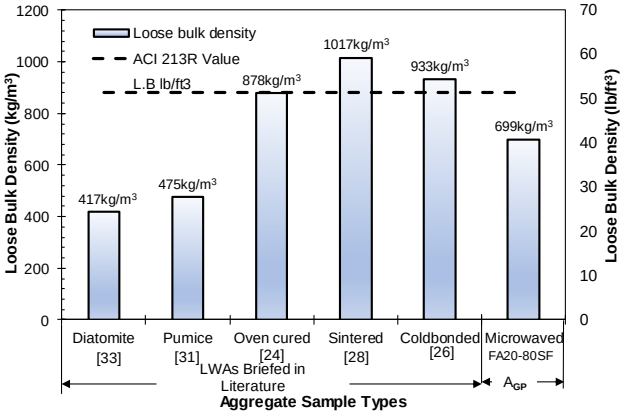

Fig. 7 – Comparison of loose bulk densities of produced LWAs and previous LWAs

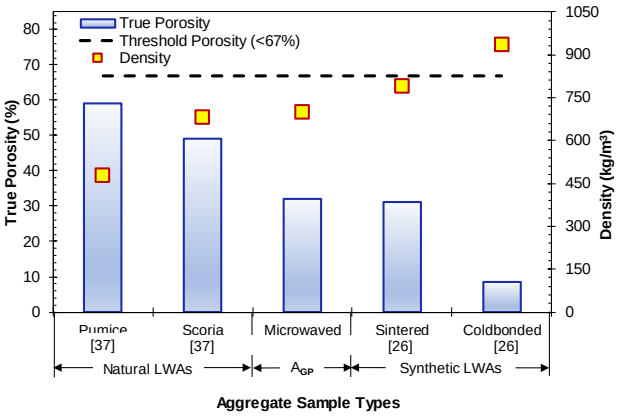

Fig. 8 – Comparison between porosity and density of different LWA

Table 5 – Observations for aggregate porosity test

Mix	Density		True density		True porosity
	g/cm^3	kg/m^3	g/cm^3	kg/m^3	%
FA20-80SF	1.367	1367	2.013	2012	31.93

Table 6 – Observations of specific gravity and water absorption

Mix Type	Specific gravity			Water absorption
	OD	SSD	Apparent	%
FA20-80SF	1.4	1.7	2.0	18.98

3.1.4 Water absorption and specific gravity

Water absorption (WA) of prepared pellets with different aggregate sizes ranging between 11-17mm was calculated after 24 h immersion in water, and the observations are presented in Table 6. The WA of A_{GP} was found to be 18.98% which was within the normal range for LWAs (<25%) in accordance with ACI-213R [36]. It was observed that WA of many previously synthesized LWAs lies in the range of 0.70-30.90% as shown in Figure 9. It was seen that A_{GP} exhibited lesser WA and higher density as compared to the natural LWAs like expanded perlite and pumice, as their WA values were equal to 70.00% and 25%, respectively [33]. Thus, more water absorption of aggregates is associated to lesser density of aggregates, which is an indication of porous microstructure as shown in Figure 10. However, most of the commercial artificial LWAs exhibit water absorption within 10-18% [40].

Specific gravities (oven dry (OD), saturated surface dry (SSD) and apparent) of A_{GP} were calculated using Eq. (4), Eq. (5) and Eq. (6), respectively. Specific gravity (OD) of A_{GP} was found to be 1.4 which was within the range of 1.16-1.59 of literature-reported synthetic LWAs as shown in Table 3. According to ACI-213R [36], the specific gravity of LWAs is 1/3 to 2/3 of normal weight aggregates. So, the manufactured LWAs fulfill the requirements of AC1-213R. A_{GP} showed greater specific gravity as compared to natural LWA (pumice) having specific gravity (OD) equal to 0.82 [34]; concluding, natural LWAs exhibit lower specific gravities as compared with synthetic ones as evident from Figure 11.

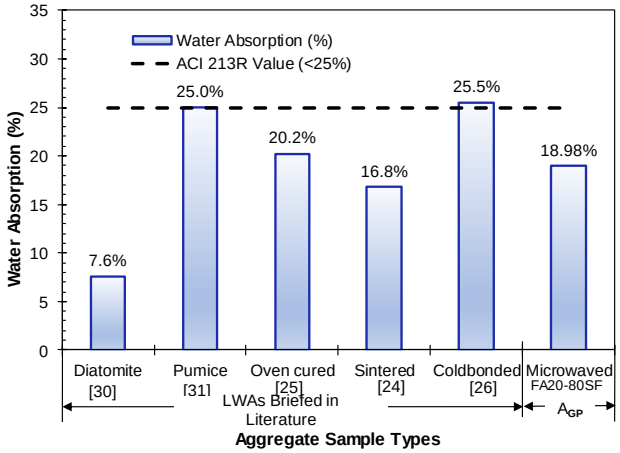

Fig. 9 – Comparison of water absorption of produced LWAs and previous LWAs

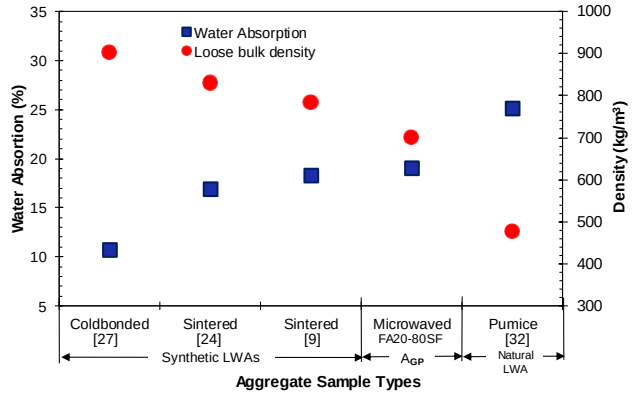

Fig. 10 – Comparison between water absorption and density of various LWAs

3.2 Mechanical properties

3.2.1 Particle crushing strength

Particle crushing strength test was conducted on a range of produced LWAs (13-17mm) as shown in Table 7. The highest crushing strength of 3.96 MPa was recorded for particle size of 15mm. It was observed that particle crushing strength increased as the size of aggregate increased. However, inconsistency was witnessed in predicting the trend for particle size of 17mm, which might be there due to non-uniformity of particle shape. It was examined that particle crushing strength of produced LWAs fell in the range of 2.03-12.00 MPa observed for literature-reported LWAs with particle sizes ranging between 10-20mm as shown in Table 3. In addition, particle crushing strength of produced LWAs was greater than that of natural LWAs (1.49-1.96 MPa) [26]. As natural LWAs (lighter in nature) have lesser strength thus, it can be deduced conclusively that density and strength are directly related with each other as shown in Figure 12.

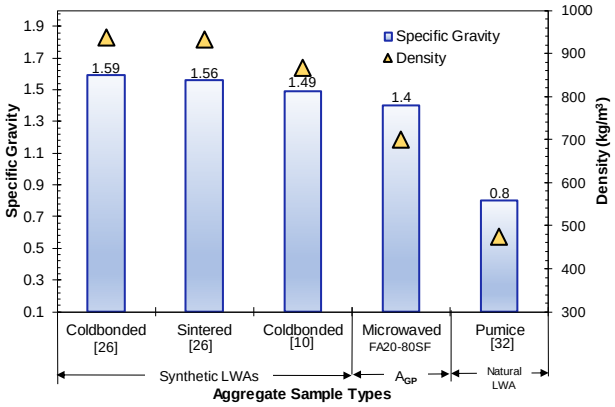

Fig. 11 – Comparison between specific gravity and density of LWAs

Table 7 – Observations of particle crushing strength test

Particle size (mm)	Aggregate strength (MPa)
13	3.66
14	3.94
15	3.96
17	3.08

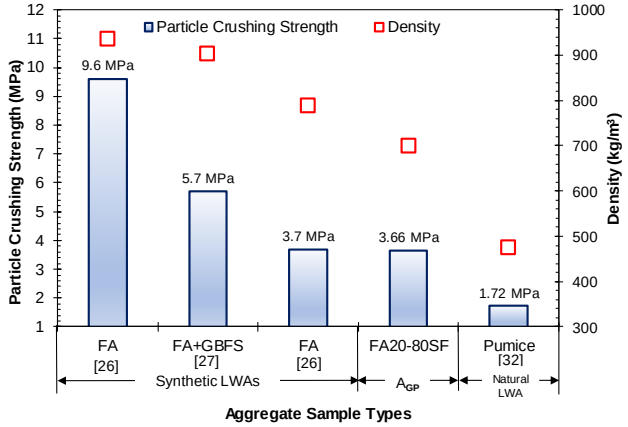

Fig. 12 – Comparison between particle crushing strength and density of LWAs

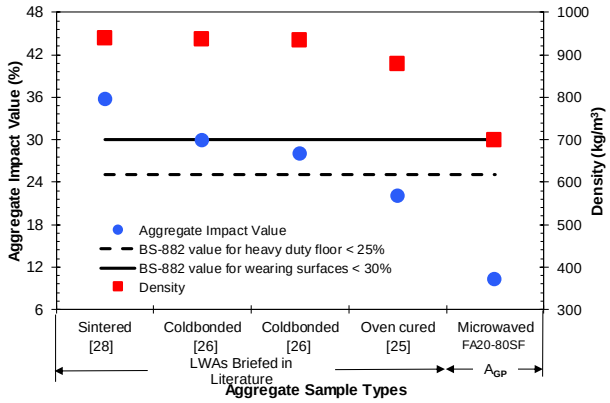

Fig. 13 – Comparison between aggregate impact value and density of LWAs

3.2.2 Aggregate impact value

The aggregate impact value (AIV) test was carried out on produced LWAs. The lower the impact value is, better will be the resistance of aggregates against impact loads. BS 882-1992 [41] describes the maximum impact value as 25% when aggregate is to be used in heavy duty floors, 30% when aggregate is to be used in concrete for wearing surfaces, and 45% for other concrete applications. A_{GP} exhibited good impact value of 10.24% and they were envisaged to be comparatively stronger than LWAs formulated and reported in previous research works having AIV in the range of 22.10-35.70% as shown in Figure 13. It was observed that A_{GP} appeared to be stronger than natural LWA having AIV equal to 15.63% [26] and this was because of their greater density relative to natural LWA as shown in Figure 13.

4 Conclusions

In this work, LWAs were produced through geopolymerization by using FA and SF as precursors. Microwave heating (5 min) was adopted as curing regime. Physical and mechanical properties of prepared LWAs were investigated and compared with other synthetic LWAs as well as natural LWAs. The main conclusions obtained from the experimental work can be summarized as follows:

(1) The aggregates presented smooth surface with small tiny pores. Physical properties such as density, water absorption and specific gravity of produced LWAs followed the specified ranges of ACI standard for LWAs.

(2) The loose and compacted bulk densities of LWAs were found to be 699 kg/m^3 and 738 kg/m^3, respectively, which was within ACI limit (<880 kg/m^3) mentioned for structural LWA. It was ensured that the produced LWAs were lighter than many previously formulated LWAs. However, these were heavier than some natural LWAs such as pumice, expanded perlite and diatomite.

(3) Similarly, total porosity (31.93%) of produced LWAs was lesser than the synthetic LWAs reported in literature, but higher than the natural LWAs. Water absorption of produced LWAs was 18.98% which was lesser than natural LWAs as well as ACI limit (<25%) for structural LWAs. It suggests that LWAs can be used to produce structural concrete. More water absorption of LWAs is attributed towards lesser density, which indicates porous microstructure of LWAs.

(4) The produced LWAs exhibited good mechanical properties. The maximum particle crushing strength was found to be 3.96 MPa for aggregate size of 15 mm. Higher strength characteristics were observed for the produced LWAs in comparison to the natural LWAs thus indicating the direct relation of density and particle crushing strength.

(5) The impact value of 10.24% was observed for produced LWAs, which shows its better resistance against impact load than both previously developed synthetic LWAs and natural LWA -that have been used in concrete. The obtained impact value confirms the applicability of produced LWAs for heavy duty floors and in other concrete applications as well, according to BS 882-1992.

Proposed curing methodology is able to produce LWAs in just 5 minutes and may have a strong potential to be used at industrial scale. Detailed analysis with respect to time savings and energy savings must be carried out and is strongly recommended for future works.

List of Abbreviations

LWA	Lightweight aggregate
FA	Fly ash
SF	Silica fume
GBFS	Ground granulated blast furnace slag
A_{GP}	Geopolymer light weight aggregates
LBD	Loose bulk density (kg/m^3)
CBD	Compacted bulk density (kg/m^3)
SSD	Saturated surface dry
OD	Oven dry
Cl	Chlorine (%)
LOI	Loss on ignition (%)
w_{LA+C}	Weight of loose aggregate and container (g)
w_{CA+C}	Weight of compacted aggregate and container (g)
w_{LA}	Weight of loose aggregate (g)
w_{CA}	Weight of compacted aggregate (g)
w_C	Weight of empty container (g)
V_C	Volume of container (m^3)
m_{OD}	Mass of oven dry test sample in air (g)
m_{SSD}	Mass of surface saturated dry test sample in air (g)
m_{AP}	Apparent mass of saturated test sample in water (g)
m_1	Mass of single aggregate (g)
v_1	Volume of single aggregate having external pores with access of water and internal pores without access of water (m^3)
w_1	Weight of pycnometer filled with water (g)
w_2	Weight of pycnometer filled with water and fine powder aggregate sample (g)
w_3	Weight of pycnometer filled with fine powder aggregate sample and water (g)
D_1	Diameter of aggregate before curing (mm)
D_2	Diameter of aggregate after curing (mm)
AIV	Aggregate impact value (%)
M_1	Weight of sample before compaction (g)
M_2	Weight of sample passing through 2.36mm opening or sieve # 8 (g);
P	Failure load (kN)
D	Distance between two plates (m)
WA	Water absorption (%)
PCS	Particle crushing strength (MPa)
SG	Specific gravity
ρ_b	Aggregate volume density (kg/m^3)
ρ_d	True density (kg/m^3)

References

1. Aslam, M.; Shafigh, P.; Jumaat, M.Z.; and Lachemi M. (2016) "Benefits of using blended waste coarse lightweight aggregates in structural lightweight aggregate concrete," Journal of Cleaner Production, vol. 119, pp. 108-117.
2. Kisku, N.; Joshi, H.; Ansari, M.; Panda, S.; Nayak, S.; and Dutta, S.C. (2017) "A critical review and assessment for usage of recycled aggregate as sustainable construction material," Construction and Building Materials, vol. 131, pp. 721-740.
3. Mannan, M.; and Ganapathy, C. (2001) "Mix design for oil palm shell concrete," Cement and Concrete Research, vol. 31, no. 9, pp. 1323-1325.
4. Oktay, H.; Yumrutaş, R.; and Akpolat, A. (2015) "Mechanical and thermophysical properties of lightweight aggregate concretes," Construction and Building Materials, vol. 96, pp. 217-225.
5. Mohammed, J.H.; and Hamad, A.J. (2014) "Materials, properties and application review of Lightweight concrete," Technical Review of the Faculty of Engineering University of Zulia, vol. 37, no. 2, pp. 10-15.
6. Tajra, F.; Elrahman, M.A.; and Stephan, D. (2019) "The production and properties of cold-bonded aggregate and its applications in concrete: A review," Construction and Building Materials, vol. 225, pp. 29-43.
7. Priyanka, M.; Karthikeyan, M.; and Sri Rama Chand, M. (2020) "Development of mix proportions of geopolymer lightweight aggregate concrete with LECA," Materials Today: Proceedings, vol. 27, pp. 958-962.
8. Bijen, J. (1986) "Manufacturing processes of artificial lightweight aggregates from fly ash," International Journal of Cement Composites and Lightweight Concrete, vol. 8, no. 3, pp. 191-199.

9. Franus, M.; Panek, R.; Madej, J.; and Franus, W. (2019) "The properties of fly ash derived lightweight aggregates obtained using microwave radiation," Construction and Building Materials, vol. 227 pp. 116677.
10. Nadesan, M.S.; and Dinakar, P. (2017) "Structural concrete using sintered flyash lightweight aggregate: A review," Construction and Building Materials, vol. 154, pp. 928-944.
11. Gomathi, P.; and Sivakumar, A. (2014) "Cold Bonded Fly Ash Lightweight Aggregate Containing Different Binders," Research Journal of Applied Sciences, Engineering and Technology, vol. 7, no. 6, pp. 1101-1106.
12. Sharif, S.; Mahmad Nor, A.; Yahya, Z.; Abdullah, M.M.A.B.; Abdul Razak, R.; Jaya Ekaputri, J.; Faris, M.A.; Nur Hamzah, H.; Abdullah, M.M.A.B.; Abd Rahim, S.Z.; Ghazali, M.F.; Mat Saad, N.; Ramli, M.M.; Zainol Murad, S.A.; and Mat Isa, S.S. (2016) "A Review on the Manufacturing of Lightweight Aggregates Using Industrial By-Product," MATEC Web of Conferences, vol. 78, pp. 01067.
13. Domagała, L. (2011) "Modification of properties of structural lightweight concrete with steel fibres," Journal of Civil Engineering and Management, vol. 17, no. 1, pp. 36-44.
14. Topçu, İ.B.; and Uygunoğlu, T. (2007) "Properties of autoclaved lightweight aggregate concrete, Building and Environment, vol. 42, no. 12, pp. 4108-4116.
15. Reddy, M.V.S.; Nataraja, M.; Sindhu, K.; Harani, V.; and Madhuralalasa, K. (2016) "Performance of light weight concrete using fly ash pellets as coarse aggregate replacement," International Journal of Engineering Research and Technology, vol. 9, no. 2, pp. 95-104.
16. Thostenson, E.; and Chou, T.-W. (1999) "Microwave processing: fundamentals and applications," Composites Part A: Applied Science and Manufacturing, vol. 30, no. 9, pp. 1055-1071.
17. C. ASTM, Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete, ASTM Int 4 (2012).
18. Wang, Y.; He, F.; Wang, J.; and Hu, Q. (2019) "Comparison of Effects of Sodium Bicarbonate and Sodium Carbonate on the Hydration and Properties of Portland Cement Paste," Materials, vol. 12, no. 7, pp. 1033.
19. ASTM C29, Standard test method for bulk density ("Unit Weight") and voids in aggregate. American Society for Testing and Materials: West Conshohocken, PA, USA. , (2017).
20. ASTM C127–14, Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate, ASTM International. West Conshohocken, Pennsylvania 19428–2959, United States (2014).
21. Borys, M.; Kurpińska, M.; Ferenc, T.; Czyż, Z.; Falkowicz, K.; Kujawska, J.; Kulisz, M.; and Szala, M. (2017) "Effect of porosity on physical properties of lightweight cement composite with foamed glass aggregate," ITM Web of Conferences, vol. 15, pp. 06005.
22. B. British Standard, Testing aggregates. Method for determination of aggregate impact value (AIV), Vol. BS (1990) 812-112.
23. Alqahtani, F.K.; Rashid, K.; Zafar, I.; and Iqbal Khan, M. (2021) "Assessment of morphological characteristics and physico-mechanical properties of geopolymer green foam lightweight aggregate formulated by microwave irradiation," Journal of Building Engineering, vol. 35, pp. 102081.
24. Li, Y.; Wu, D.; Zhang, J.; Chang, L.; Wu, D.; Fang, Z.; and Shi, Y. (2000) "Measurement and statistics of single pellet mechanical strength of differently shaped catalysts," Powder technology, vol. 113, no. 1-2, pp. 176-184.
25. Van der Wegen, G.; and Bijen, J. (1985) "Properties of concrete made with three types of artificial PFA coarse aggregates," International Journal of Cement Composites and Lightweight Concrete, vol. 7, no. 3, pp. 159-167.
26. Wang, H.-T.; and Wang, L.-C. (2007) "Experimental study on mechanical properties of steel fiber reinforced lightweight aggregate concrete," Jianzhu Cailiao Xuebao(Journal of Building Materials), vol. 10, no. 2, pp. 188-194.
27. Ul Rehman, M.; Rashid, K.; Ul Haq, E.; Hussain, M.; and Shehzad, N. (2020) "Physico-mechanical performance and durability of artificial lightweight aggregates synthesized by cementing and geopolymerization," Construction and Building Materials, vol. 232, pp. 117290.
28. Kockal, N.U.; and Ozturan, T. (2011) "Durability of lightweight concretes with lightweight fly ash aggregates," Construction and Building Materials, vol. 25, no. 3, pp. 1430-1438.
29. Bui, L.A.T.; Hwang, C.L.; Chen, C.T.; Lin, K.L.; and Hsieh, M.Y. (2012) "Manufacture and performance of cold bonded lightweight aggregate using alkaline activators for high performance concrete," Construction and Building Materials, vol. 35, pp. 1056-1062.
30. Saad, M.; Baalbaki, O.; Khatib, J.; El Kordi, A.; and Masri, A. (2019) "Manufacturing of Lightweight Aggregates from Municipal Solid Waste Incineration Bottom Ash and their Impacts on Concrete Properties," 2nd international Congress on Engineering and Architecture, At Marmaris / Turkey, pp. 1638-1649.

31. Bui, L.A.T.; Hwang, C.L.; Chen, C.T.; and Hsieh, M.Y. (2012) "Characteristics of Cold-Bonded Lightweight Aggregate Produced with Different Mineral Admixtures," Applied Mechanics and Materials, vol. 174-177, pp. 978-983.
32. Mehmedi Vehbi GÖ KÇ , E. (2012) "Use of diatomite in the production of lightweight building elements with cement as binder," Scientific Research and Essays, vol. 7. No. 7, pp. 774-781.
33. Karakurt, C.; and Ö zen, U. "Influence of natural lightweight aggregates on the properties of concrete," Journal of the Turkish Chemical Society Section B: Chemical Engineering 1(Sp. is. 2), pp. 9-16.
34. Rashad, A.M. (2019) "A short manual on natural pumice as a lightweight aggregate," Journal of Building Engineering, vol. 25, pp. 100802.
35. Posi, P.; Lertnimoolchai, S.; Sata, V.; and Chindaprasirt, P. (2013) "Pressed lightweight concrete containing calcined diatomite aggregate," Construction and Building Materials, vol. 47, pp. 896-901.
36. Akers, D.J.; Gruber, R.D.; Ramme, B.W.; Boyle, M.J.; Grygar, J.G.; Rowe, S.K.; Bremner, T.W.; Kluckowski, E.S.; Sheetz, S.R.; and Burg, R.G. (2003) "Guide for Structural Lightweight-Aggregate Concrete," ACI 213R-03. American Concrete Institute (ACI), Michigan.
37. Abdulkareem, O.A.; Abdullah, M.; Hussin, K.; Ismail, K.N. and Binhussain, M. (2013) "Mechanical and Microstructural Evaluations of Lightweight Aggregate Geopolymer Concrete before and after Exposed to Elevated Temperatures," Materials, vol. 6, no. 10, pp. 4450-4461.
38. Kurpińska, M.; and Ferenc, T. (2017) "Effect of porosity on physical properties of lightweight cement composite with foamed glass aggregate," ITM Web of Conferences, EDP Sciences, vol. 15, pp. 06005.
39. Kılıc, A.; and Teymen, A. (2009) "The effects of scoria and pumice aggregates on the strengths and unit weights of lightweight concrete," Scientific Research and Essay, vol. 4, no. 10, pp. 961-965.
40. Colangelo, F.; Messina, F.; and Cioffi, R. (2015) "Recycling of MSWI fly ash by means of cementitious double step cold bonding pelletization: Technological assessment for the production of lightweight artificial aggregates," Journal of hazardous materials, vol. 299, pp. 181-191.
41. Manikandan, R.; and Ramamurthy, K. (2008) "Effect of curing method on characteristics of cold bonded fly ash aggregates," Cement and concrete composites, vol. 30, no. 9, pp. 848-853.