

Artificial Lightweight Aggregates Made from Pozzolan Material

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Contributor: Dickson Chuan Hao Ling , Dumitru-Doru Burduhos-Nergis , Rafiza Abdul Razak , Marwan Kheimi , Zarina Yahya , Mohd Mustafa Al Bakri Abdullah , Hamzah Fansuri , Alida Abdullah

Production of artificial lightweight aggregate incorporating waste materials or pozzolan materials is advantageous and beneficial in terms of being environmentally friendly, as well as lowering carbon dioxide emissions. Moreover, additives, such as geopolymer, have been introduced as one of the alternative construction materials that have been proven to have excellent properties.

artificial lightweight aggregate

aggregate crushing value

thermal properties

1. Lightweight Aggregate

A lightweight aggregate (LWA) is a solid substance having a particle density of less than 2.0 g/cm^3 and a loose bulk density of less than 1.2 g/cm^3 (BS EN 13055-1, 2002) [1]. LWAs are porous and granular materials that have been widely used in architecture, landscaping, and geotechnics [2]. In addition, it can provide better sound absorption and thermal insulation [3]. Lightweight aggregates are ecologically friendly construction materials made from a variety of wastes and frequently produced through high-temperature burning [4]. There are two types of lightweight aggregate, which are natural lightweight aggregate and artificial lightweight aggregate. The following are the two types of lightweight aggregate:

- Aggregates that occur naturally and can only be used after mechanical treatment, such as pumice and scoria aggregates [5].
- Artificial aggregates are made up of waste materials, such as fly ash, husks, or volcanic form and ground granulated blast-furnace slag (GGBS) [6].

Various types of lightweight aggregate have been widely utilized as construction materials in the construction field. Considering aggregate makes up approximately 70% of the concrete mixture, substituting natural aggregate with lightweight aggregate manufactured from waste materials will be an efficient method to minimize nonrenewable resource usage [7]. Lightweight aggregate has been discovered as significant in the formation of lightweight concrete by lowering greenhouse emissions in buildings and decreasing the self-weight of the structure [8]. Application of LWA in concrete will enhance thermal insulation characteristics, decrease structural dead load, allowing larger structures to be built with the same foundation size, and lead to lower CO_2 emissions [9]. Furthermore, LWA is a critical component in the construction of earthquake-resistant buildings [10]. Due to the larger

amount of internal pores in lightweight aggregate, absorption of moisture from cement paste is more rapid than in normal-weight aggregate, which makes the concrete less workable and lower in strength performance than the concrete prepared with normal aggregate [11]. Regardless of the performance when compared to natural aggregate concrete, LWA is worthwhile to be explored specifically for enhancing the performance towards minimizing environmental problems, alongside maintaining long-term sustainability by improving water quality or as a growth medium for green roofs to mitigate the urban heat island effect [12].

Lightweight Aggregate with Inclusion of Geopolymer

The inclusion of geopolymer in lightweight aggregate has become more concerning due to its advantages in improving the properties of lightweight aggregate. The strength of activated fly ash-based artificial lightweight aggregate by inclusion of geopolymer is comparable to that of commercialized expanded clay lightweight aggregate [7]. In addition, the inclusion of geopolymer in lightweight aggregate produced from fluidized bed combustion (FBC) fly ashes and mine tailings showed excellent mechanical properties in mortar and concrete as compared to the application of commercialized aggregate (LECA) [13]. The inclusion of geopolymer in the lightweight aggregate manufactured from recycled silt and palm oil fuel ash meets the demand for high-strength lightweight concrete and can be utilized for lightweight construction or insulating concrete [8]. In addition, the inclusion of geopolymer in lightweight aggregate that is produced from the combination of fly ash and silica fume can be used for heavy-duty floors due to its high strength [14]. Therefore, the inclusion of geopolymer in lightweight aggregate brings advantages in the construction field, especially in the structural components. However, the use of geopolymer in lightweight aggregate is still limited, and more research is needed to identify lightweight aggregate properties.

2. Manufacturing of Lightweight Aggregate

The manufacturing process of artificial aggregate consists of three stages, which are the mixing of raw materials, pelletization, and hardening. In the first stage, which is mixing, the well-proportioned ingredients are mixed until the mixture achieves consistency. In a disc-based pelletizer machine, the mixture of the raw materials undergoes the pelletization process by the agglomeration of the fine particles using a suitable binder. Some previous studies used pozzolanic materials as binders, such as metakaolin and bentonite [11][12][15]. Meanwhile, alkaline activators are commonly used as binders for the production of geopolymer aggregate [2][12][13][14]. Depending on the angle of the disc, the speed of the pelletizer, and the moisture content, the appropriate size of pellets will be collected in the disc. The hardening of the fresh pellets can be accomplished by using sintering, cold bonding, or autoclaving in order to gain the strength of the aggregate.

By Punlert et al. (2017) [16], lightweight concrete was manufactured using fly ash lightweight aggregates instead of coarse aggregates, resulting in a much lower density and good strength compared to conventional concrete. Furthermore, when sintered at around 1100 °C, lightweight aggregate made from sewage sludge and river sediment achieved high density, low water absorption, and high strength. However, the existence of air voids in fly ash lightweight aggregates, which are crucial for absorbency, leads to difficulty in producing lightweight aggregate

concrete, especially in the mix design, which requires further insight to enhance the properties [17]. For this purpose, additional binders or additives are introduced as one of the alternatives towards improving the properties of lightweight aggregate.

From the previous results, the salt additives (NaCl) resulted in less viscosity and produced wider internal pores, which allowed the production of ultralight aggregates. However, the use of Na_2CO_3 as an additive, which is low cost and low corrosion hazard, allows the creation of ultra-lightweight aggregates [4]. Reported by Ren et al. [18], addition of coke particles in the manufacturing of lightweight aggregate will help to reduce the apparent density of the aggregate produced. The use of styrene butadiene rubber (SBR) improves the microstructure of lightweight aggregate, thus improving the aggregate's mechanical properties [19]. In addition, the inclusion of waste glass powder causes the pozzolan material to inflate, resulting in a more efficient lightweight aggregate by enhancing the porosity of lightweight aggregate and decreasing water absorption [20].

In addition, pozzolan materials with high SiO_2 , Al_2O_3 , and CaO content have a high potential to be utilized in producing artificial aggregates with the addition of an alkaline activator [8]. The usage of alkaline activator as an additive for pozzolan materials will help to influence the formation of C-S-H binding gel and sodium aluminosilicate hydrates during the geopolymerization process [21]. The formation of geopolymer aggregate by mixing pozzolan material with alkaline activator will decrease the porosity of aggregate and improve the strength due to the extra C-S-H and calcium reaction during the reaction process alongside the denser microstructure produced [22]. Furthermore, the NaOH molarity will affect the strength of the geopolymer aggregate. For instance, low sodium hydroxide content leads to improper dissolution of fly ash, thus causing the inter-particle spaces of the participating gels to not be entirely filled [19]. It is critical to investigate the optimization of mix designation for each kind of material utilized in the manufacturing of lightweight aggregate-based geopolymer.

To summarize, recently, it has shown that fly ash is the common material that had been chosen to produce the lightweight aggregate due to their excellent properties. In the future, alternative pozzolan materials should be studied to establish their suitability in the manufacturing of lightweight aggregate. In addition, it showed that additional additives will improve the properties of lightweight aggregate in terms of specific gravity, strength, and water absorption. Furthermore, the use of geopolymer in lightweight aggregate has been shown to increase the porosity and strength of the aggregate, making it a viable option for lightweight aggregate manufacturing. Various methods can be used to manufacture lightweight aggregate, which are sintering, cold bonding, and autoclaving, which have been reported previously. The sintering and cold bonding methods are the methods that have been used wisely due to the excellent properties of aggregate. Despite the fact that the sintering technique consumes a lot of energy, the quality of the lightweight aggregate generated is excellent, with good strength at a low density. Because of the considerable energy required in the sintering procedure, cold bonding has grown popular because it does not require any additional sintering or heating. This process can create various grade aggregates, depending on the density of the aggregate produced. Generally, aggregate with high density will have a high strength. As a result, the use of a foaming agent may be necessary to make the aggregate lighter. There is relatively limited research on autoclaving methods, necessitating more inquiry to assess the possible application of autoclaving methods in the manufacturing of lightweight aggregate. The strength and water absorption capabilities

of lightweight aggregate generated by the autoclaving technique were good, and the incorporation of geopolymer improved the properties. As a result, greater research into autoclaving procedures is needed, particularly in terms of simplifying the process so that it can be commercialized.

2.1. Sintering

Sintering is a process that consumes high energy to produce artificial aggregate with enhanced properties. As reported by Sun et al. (2021) [23], raw materials with a high amount of SiO_2 and Al_2O_3 commonly use sintering. When the pellets in the disc pelletizer are shaped, the pellets will dry for a day before undergoing the sintering process at a temperature of between 1180 °C and 1200 °C [24][25]. In some cases, some of the pellets are fused at a temperature above 1200 °C for optimum properties [6][26]. Most of the previous research used a similar drying method prior to sintering [27][28]. Chen et al. [29] also reported a similar method where the pellets undergo a drying stage, followed by preheating at 500 °C expanding temperature of a temperature between 1100 °C and 1150 °C for the sintering process.

Meanwhile, according to Grygo and Pranevich [30], the aggregate produced through the sintering process is lighter and has high strength performance. The sintering process is a popular application for mass manufacture of lightweight aggregates that does not require a long-term curing process [31]. Lytag, Pollytag, LECA, and liapour are some of the commercially sintered lightweight aggregates around the world. The factory that manufactured LECA has three lightweight aggregate production lines with a total capacity of 750,000 cubic meters per year [32]. Sintered artificial lightweight aggregate is one of the possible materials to make concrete lighter than the standard aggregate concrete [15]. In addition, Tian et al. (2021) [33] state that sintering aggregates with the help of geopolymerization reactions can have higher aggregate strength and low density. However, the sintering process involves a high level of energy during pelletization, which results in higher manufacturing costs [26]. Aside from that, the sintering process generates a large amount of pollutants, which will cause environmental problems. The sintering method needed a lot of energy regardless of its potential engineering properties with respective mix design applied [34].

In short, the lightweight aggregate produced at the temperature of 1200 °C provides the best properties of the aggregate. To acquire the best features of lightweight aggregate, the suggested sintering temperature for metakaolin is 900 °C, 1100 °C for sewage sludge and river sediment, and 900 °C for fly ash. As a result, materials such as metakaolin and fly ash are more advantageous due to the energy savings at the lowest sintering temperature required to manufacture lightweight aggregate. The sintering method will also be able to produce lightweight aggregate in a shorter time, at which it is suitable to be used to replace natural aggregate. Nevertheless, the sintering method will require high energy during the production, and this will increase the price of the production. The usage of sintered lightweight aggregate in the construction field will increase the overall cost of construction. As a result, new approaches, such as cold bonding, are being studied to address the problems that the sintering method encountered.

2.2. Cold Bonding

Cold bonding is a process of enhancing fine particles, either by pressure or non-pressure agglomeration methods, forming larger particles. In the cold bonding process, cement or alkaline activator will be chosen as the binder. The cold bonding method has been noted as a cost-effective method as it agglomerates at room temperature [29]. Furthermore, the cold bonding method tends to minimize energy usage when compared to other production processes [6]. For cold bonding, the pellets will be dried at room temperature for 24 h once the shape of the pellets is formed. The pellets are then sealed in the bag until the testing day [7][19][25][29][35][36]. According to Jiang et al. [37], normal curing at room temperature was required for cold-bonded artificial aggregate to achieve the strength. However, aggregates produced using the cold bonding method required curing at room temperature or in an enclosed chamber with steam until the required strength was attained [38]. The major challenge for cold-bonded aggregate is the requirement for a longer hardening period, as it is normally required to cure for 28 days before being discharged and used as construction materials [23].

From both economic and environmental viewpoints, the cold bonding process is fulfilling, as it involves low energy consumption. Wastewater treatment sludge, ground granulated blast furnace slag, rice husk ash, and fly ash are some of the common materials used to produce cold bonding lightweight aggregate. In addition, lightweight aggregate produced by using cold bonding instead of sintering is considered to have a strong effect on customer acceptance, as it reduces the environmental impact [7].

Meanwhile, the addition of nano SiO₂ from 0.5% to 1.5% during the production of artificial lightweight aggregate leads to increasing water absorption from 12.5% to 30.1% [39]. In addition, the utilization of foaming agents in lightweight aggregate causes more pores and makes the aggregate lighter than cold-bonded artificial lightweight aggregate. This was supported by the high water absorption ranging from 28.7% to 33.5% when compared to cold-bonded artificial lightweight aggregate, which had a water absorption ranging from 15.1% to 18.9% [40].

In a nutshell, the cold bonding method is considered a low-cost method, as it can be hardened at room temperature. Cold bonding has been recognized as a major step forward in the production of lightweight aggregate. Moreover, the cold bonding method is more likely to be adopted by society, as it does not require additional energy during the process. However, in order to improve the properties of the cold-bonded lightweight aggregate, it needs considerable treatment, particularly the use of a foaming agent during the manufacturing process. Another challenge is the curing day for cold bonding lightweight aggregate, which should be reduced to achieve acceptance in the construction industry.

2.3. Autoclaving

Autoclaving is a process that involves the addition of chemicals, such as lime or gypsum, in the agglomeration stage. In addition, autoclaving produced aggregates with little binding material and low curing time [6]. For autoclaving, the pellets will be hardened by the autoclave pressure and temperature to gain strength. By Wan et al. [41] reported autoclaving for the production of aggregates. The quartz tailing aggregate was cured at room temperature for 24 h, followed by curing at a temperature of up to 195 °C for 3 h with an autoclaved pressure of 1.38 MPa. The aggregates were further cured at 195 °C for another 10 h without autoclaved pressure before

cooling at room temperature. The cured aggregate was then dried in order to achieve the desired weight of less than 1100 kg/m^3 . The autoclaving method produced aggregates very quickly and it required little binding material and curing time [6]. Moreover, lightweight aggregate can be made with a considerable number of industrial solid wastes utilizing autoclave technology, which not only reduces the curing time (to only 4 h) to maximize space utilization, but also meets commercial environmental and economic requirements [42].

However, there are still limited studies available on autoclaving. This is because the autoclaving method requires an autoclaved machine with the required temperature and pressure to harden the aggregate. In addition, the autoclaved machine is very expensive and requires high power consumption and large production facilities to complete the process.

Generally, the sintering method has been widely used around the world with some popular commercial products, such as LECA and Lytag. LECA is one of the most popular artificial lightweight aggregates that has been commercialized in the market used to replace natural aggregate. The production rate can be up to $200,000 \text{ m}^3$ per year, depending on local LECA requirements and capital available. LECA is a new revolutionary material, and its manufacturing rate compared to standard aggregate is still dependent on customer demand. However, due to the requirement of high sintering temperature to produce sintered aggregate, the cold bonding method has been introduced as an initiative towards saving energy. The lightweight aggregate produced through the cold bonding method has the potential to be applied in concrete production due to its comparable properties to other methods. Moreover, cold bonding also showed promising properties, such as high compressive strength when applied to the concrete. Cold bonding also contributes to low pollutant production and low operating expenses. In addition, the autoclaving method is also another method that can be used to produce artificial lightweight aggregate. However, an autoclaved pressure machine is required for this method, which is very costly. The autoclaving method also required longer curing time to achieve the strength of the aggregate. Therefore, among all of the commonly reported methods, the cold bonding method with proper optimization of mix design is noted to be advantageous to the construction field. Furthermore, variations in manufacturing methods, as well as mix designation, were known to have a significant impact on the properties of lightweight aggregate, particularly on physical and mechanical properties.

3. Physical and Mechanical Properties of Lightweight Aggregate

3.1. Specific Gravity

The specific gravity of the aggregate varies depending on the type of raw material used. The cold-bonded fly ash aggregate that used different molarities of alkaline activator had a specific gravity of between 1.8 and 1.85 [7]. In addition, mixing 90% of fly ash with 10% of cement by using cold bonding gives a specific gravity of 1.76 [38]. The artificial aggregate that was made up of fly ash by using the cold bonding method had a specific gravity of 1.63 as compared to normal coarse aggregate at 2.71 [36]. The specific gravity was found to be increased from 1.84 to 1.91 when the styrene–butadiene rubber (SBR) was added from 1% to 3% to the lightweight aggregate [19]. In addition,

the aggregate produced by mixing bentonite and metakaolin together with fly ash has a specific gravity of 1.8 to 1.93 and 1.95 to 1.99 [43].

The sintered fly ash aggregate had a specific gravity between 1.41 and 1.44, with a size that varied from 2 mm to 12 mm [15]. The specific gravity of aggregate that was made from water treatment residual increased from 1.21 to 1.78 when the sintering temperature was increased from 1000 °C to 1100 °C [24]. The sintered dredged sludge lightweight aggregate had a specific gravity of 1.00 to 1.38 for the particle size of 4.75 mm to 12.5 mm [29]. The sintered fly ash aggregate with bentonite added had a specific gravity of 1.57, while the sintered fly ash aggregate with glass powder added had a specific gravity of 1.60 at the temperature at 1200 °C [36]. Meanwhile, coarse aggregate manufactured from bentonite and water glass has a specific gravity of 1.63 at a temperature of 800 °C [28].

In comparison to natural aggregates, the specific gravity of artificial geopolymer aggregates formed by sintering is quite low [6]. For instance, Kamal and Mishra (2020) [44] reported on the specific gravity of the fly ash aggregates as well as raw materials, including fly ash and binder, and the amount of void space in the aggregate. In addition, whenever cold-bonded aggregate was combined with other pozzolanic binding materials, such as GGBS, the specific gravity was found to be as high as 2.42, in which the hydrated lime acts as a primary binder [45].

3.2. Water Absorption

Water absorption provides an indication of the internal aggregate structure. Higher water absorption of aggregates indicates the large number of pores in nature and usually gives drawbacks to the aggregates. For instance, expanded perlite powder (EPP) was noted as being high in porosity, thus causing the water absorption to increase from 33% to 52% when the replacement of fly ash increased to 30% [35]. Meanwhile, when sintering is applied, increasing the sintering temperature was found to decrease water absorption of all aggregates due to the increment in the fusion of material, which led to less water surface permeability [30]. By Sun et al. (2021) [46], it was found that the sintered aggregate made up of red mud and municipal solid waste incineration bottom ash with the temperature increased from 1010 °C to 1090 °C caused the porosity of the aggregate to increase and the water absorption to decrease significantly until 1070 °C. Furthermore, Liu et al. (2018) [47] also found that lower water absorption can be obtained when the lightweight aggregate was sintered at a temperature of around 1100 °C. Lightweight aggregate made up of drill cuttings containing synthetic-based mud, when sintered at 1180 °C, had water absorption of 3.6% [9]. In addition, the water absorption of metakaolin artificial lightweight aggregate increases at the sintering temperature over 900 °C. The pores formed during the sintering process were found to be closed pores, thus causing a reduction in permeability to water [48].

In addition, the addition of the waste glass powder to lightweight aggregates was found to significantly reduce water absorption from 7.73% to 0.5% [20]. Meanwhile, due to the porosity of the hydrated calcium silicate, the quartz tailing aggregate (QTA) also possessed high water absorption, which varies from 13.77% to 21.93% [41]. In another, the water absorption was reduced from 12.1% to 8.58% when styrene–butadiene rubber (SBR) was added from 1% to 3% to the lightweight aggregate, which proved the minimizing of voids when the SBR increased

in the pellets [19]. Furthermore, it was found that the lightweight aggregate produced from different ratio palm oil fuel ash and silt causes high water absorption of 32.2% when 90% of clay is used [49]. This is due to the high pozzolanic reaction rate within the mixture, thus causing higher water absorption through the capillary of silt. Moreover, water absorption for aggregates incorporated with 10% cement was lowered by 13.97% due to a stronger hydration reaction and a denser microstructure with more C-S-H and CH products, thus leading to an increase in the strength of the aggregate [50].

In addition, the utilization of alkaline activator as a binder for the production of lightweight aggregate was found to increase the water absorption from 22% to 23% [7]. Meanwhile, the geopolymer lightweight aggregate sintered using microwave radiation had water absorption of 18.98%, as it was affected by the high density of the aggregate [14]. In another study, it was found that the pores in the fly ash geopolymer aggregate were reduced after the geopolymerization process, thus giving a denser microstructure, which resulted in lower water absorption at 10.05% [51]. Meanwhile, increasing the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio from 1.5 to 4.0 caused the water absorption values for geopolymer lightweight aggregate to steadily increase from 15.2% to 19% due to the foaming activity of Na_2SiO_3 [40]. Furthermore, the metakaolin geopolymer aggregate sintered at 600 °C will have lower water absorption as the greater the sintering temperature, the more voids created, and, hence, the higher the water absorption of lightweight aggregate [52]. Moreover, the fly ash geopolymer aggregates had higher water absorption when curing at 80 °C due to the water in the aggregates participating in the geopolymerization process, which improves the strength of the pellets [53].

3.3. Mechanical Properties

In terms of mechanical properties, fly ash with expanded perlite powder (EPP) has a higher crushing strength due to increasing pozzolanic activity [35]. Sintered sediment lightweight aggregate with a bulk density of 859 kg/m³ had the highest crushing strength of 13.4 MPa. This occurrence proves that the aggregate strength increases with increasing bulk density [29]. The crushing strength decreased as the silt content increased due to the binding failure of palm oil fuel ash (POFA) with the silt content [49]. Meanwhile, the fly-ash metakaolin binder aggregate showed high crushing strength when curing under high temperatures [43]. For instance, when the sintering temperature exceeds 900 °C, the sintered aggregate made up of metakaolin and alkaline activator has high aggregate impact value, which cause decreasing aggregate strength due to the increasing amounts of pore space in the aggregate [48]. Moreover, combination of fly ash and clay with 10% of sodium carbonate and sintering temperature of 1220 °C leads to a higher pellet strength of 4.25 MPa [18].

In addition, regardless of methods applied, the cold-bonded fly ash aggregate, sintered fly ash aggregate, as well as autoclaved aggregates were found to have a high impact value of 9.56%, 10.2%, and 11.46%, respectively [54]. According to research of Kamal and Mishra (2020) [44], the addition of binder is noted as effective due to the binder's role, which is to wrap the pellets, therefore causing the voids to have better resistance to compression. Meanwhile, the addition of styrene–butadiene rubber (SBR) to lightweight aggregate leads to a lower impact value, which makes the aggregate stronger [19]. The impact resistance of cement-based fly ash aggregate was enhanced by the cement content because of the increased hydration reaction. In addition, the curing temperature will also

increase the impact resistance of artificial aggregate [22]. The high porosity of phosphogypsum-based cold-bonded aggregates with 90% of phosphogypsum accounts for high water absorption with 13.6%, as it holds fewer binders and allows it to absorb more water [55]. The inclusion of cement enhanced the pellet strength from 1 MPa to 2.3 MPa when compared to the pellet strength of the cold-bonded lightweight aggregate made with only concrete slurry waste and fine incinerator bottom ash [56].

In addition, the lightweight aggregate with the lowest water absorption has better sustainability towards the impact of the load. In a previous study, it was discovered that increasing the maximum amount of fly ash replacement with 10% cement or 5% calcium hydroxide increased cold-bonded aggregate strength with decreasing water absorption [57]. On the other hand, curing at higher temperatures causes the impact value of artificial lightweight aggregate to improve by 12.5% to 14.75% and the crushing strength by 28.2% to 39.7% [53]. By Rehman et al. (2020) [50], the aggregate with the lowest water absorption of 12.5% had the lowest aggregate impact value of 22.12%, thus proving the stronger microstructure and lower porosity had led to high resistance to crack penetration and increasing strength. Meanwhile, according to Ghosh (2018) [58], the autoclaved aggregate made by using fly ash and cement can be used to replace the gravel as the crushing value and impact value due to the similar value.

3.4. Morphology

The morphology of lightweight aggregate can be observed through scanning electron microscopy (SEM). In addition, alkaline activators such as sodium hydroxide and sodium silicate have been used previously as liquid precursors and mixed with aluminosilicate materials such as fly ash and rice husk ash to create a cold bonded lightweight aggregate known as geopolymer aggregate.

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