Arch. Metall. Mater. **69** (2024), 4, 1407-1412

DOI: https://doi.org/10.24425/amm.2024.151407

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PROPERTIES OF ARTIFICIAL LIGHTWEIGHT AGGREGATES FROM VARIOUS POZZOLAN MATERIALS – A REVIEW

The use of lightweight aggregate can bring advantages to the construction field. Lightweight aggregate has been used due to its lower density and can reduce the dead load applied to the structural elements. Due to the number of natural resources, such as natural aggregate having decreased, producing lightweight aggregate from industrial waste materials can overcome the problem. Different methods produce lightweight aggregates, such as sintering, cold bonding, and autoclaving. From earlier studies, spherical sintered lightweight aggregate can manufacture structural concrete. Using artificial lightweight aggregate in concrete can achieve the minimum strength requirement of structural concrete and has been applied in the construction field. The properties of lightweight aggregate, such as specific gravity, water absorption, crushing strength, and impact value, are reviewed. Besides that, the mechanical and thermal properties review is also important for using lightweight aggregate in concrete. The review also indicates that aggregate produced using the cold bonding method and autoclaving method potential can be used in the concrete.

Keywords: Lightweight aggregate; geopolymer; crushing strength; impact value; thermal properties

1. Introduction

Aggregates are materials that are widely used in the field of construction. In addition, aggregates are one of the materials that should be used to manufacture concrete. Most of the aggregates used are obtained through natural resources, including rock. The concrete industry impacts the global environmental problem because it uses large amounts of natural resources [1]. Developing lightweight material, such as lightweight aggregate, will help minimize the use of natural resources.

In the field of construction, lightweight aggregate used in concrete is a type of material that is very environmentally friendly. Lightweight aggregate is dramatically different from conventional aggregate, the modifications bring advantages for the designers for several reasons other than weight reduction, such as decreased early cracking, reduced permeability, and longer lifespan [2]. Lightweight aggregates can be grouped into the following categories [3]:

1. Materials that naturally occur and require further processing such as expanded-clay, shale and slate, vermiculite,
2. Industrial waste by-products such as sintered pulverized fuel ash (fly ash) foamed or expanded-blast-furnace slag, hemalite and
3. Materials that naturally occur such as pumice, foamed lava, volcanic tuff and porous limestone.

According to Nadesan and Dinakar [4], sintered fly ash aggregate used in concrete can produce high strength concrete. The most significant value of compressive strength, split tensile strength, and flexural strength of concrete is on 50% substitution of coarse aggregate with pumice aggregate [5]. From the study conducted by Özkan et al. (2022) [6], concrete strength decreased by up to 16% when the sintered aggregate replacement was increased by 45%. Still, the compressive strength can achieve more than 45MPa at 28 days which is suitable for the high-strength application. The surface roughness of aggregates also can affect how well they adhere to cementitious materials. The artificial lightweight aggregates with rough surface texture have more excellent adhesion capabilities [7]. The artificial lightweight aggregate with a size range from 4 mm to 20 mm had been used in the application of concrete [1,8,9]. Then, the con-

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crete incorporate with lightweight aggregate had lower thermal conductivity [10]. This paper aims to review the manufacturing method of lightweight aggregate for producing lightweight concrete. A review was conducted on the physical properties of specific gravity, water absorption, and mechanical properties of crushing strength and aggregate impact value. In addition, the mechanical and thermal properties of lightweight aggregate concrete are also reviewed.

2. Manufacturing of lightweight aggregate

The manufacturing process of artificial aggregate consists of three stages: mixing raw materials, pelletization, and hardening. First, well-proportioned ingredients were mixed during mixing until the consistency was obtained. In a disc-based pelletizer machine, the mixed raw materials started the palletization process by agglomerating the fine particles using the suitable binder [6]. Some previous research used pozzolanic materials such as metakaolin and bentonite [4,7,8] as a binder. Alkaline activators can also be used as binders to produce geopolymer aggregate [8-12]. Depending on the disc's angle, the pelletizer's speed, and the moisture content, the formation of the appropriate size of pellets will be collected in the disc. The hardening of the fresh pellet can be carried out by using sintering, cold bonding, or autoclaving to gain the aggregate's strength. Fig. 1 shows the flow chart of producing lightweight aggregate. TABLE 1 shows the recent research on producing lightweight aggregate.

In summary, recent research showed that fly ash is the common material to produce lightweight aggregate. Besides that, cold bonding has been used widely due to the low energy consumption and showed good compressive strength when applied in the concrete. Therefore, the artificial lightweight aggregate applied in the concrete can benefit the construction field.

2.1. Sintering

Sintering is a process that consumes high energy to produce artificial aggregate. When the pellets in the disc pelletizer are shaped, the pellets will dry for a day before undergoing the

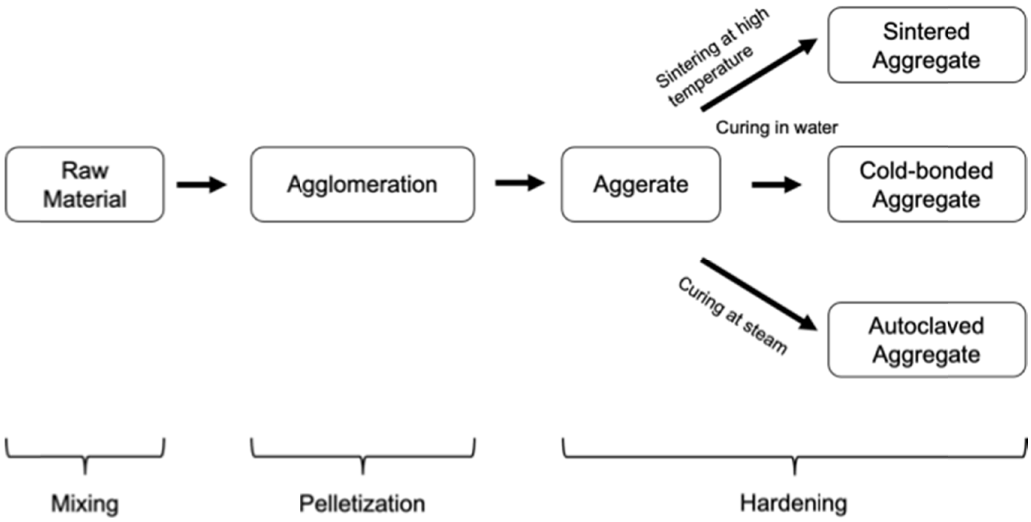

Fig. 1. Flow chart of producing lightweight aggregate [17]

TABLE 1

Recent search on producing lightweight aggregate

Ref.	Method	Material	Additives	Significane
[11]	Sintering	Sewage sludge	Waste glass powder	– The addition of waste glass powder help in reduction of water absorption
[9]	Sintering	Fly ash	Synthetic fibres	– Synthetic fibre increase the compressive strength of the concrete
[14]	Cold bonding	Fly ash	Sodium hydroxide (NaOH) solution	– 6M of NaOH brought a positive impact to aggregate strength – The highest compressive strength at 8M of NaOH
[15]	Cold bonding	Fly ash	Cement (Cement based) & Alkaline activator (Geopolymer based)	– Lightweight aggregate produced from cement based is strongest – Aggregate with hot water curing shows good properties as it can withstand half of the compressive load as compared to normal aggregate.
[18]	Cold bonding	Fly ash	Styrene-butadiene rubber	– Compressive strength increase compared to normal lightweight aggregate concrete
[8]	Autoclaved	Quartz tailings, fly ash	Quicklime	– The compressive strength is high – Higher structure efficiency for quartz tailing aggregate concrete

sintering process at temperatures between 1180°C and 1200°C [17,18]. In previous research, the sintering process will occur after the pellets are dried at room temperature for a day and oven-dried again at 105°C [8,19]. Based on the study by Chen et al. [22], the pellets will undergo the drying stage first, then pre-heating at 500°C and finally expanding temperature at a temperature between 1100°C and 1150°C for the sintering process. Based on a study by Griego and Pranevich [23], the aggregate produced through the sintering process is strong, lightweight, and high strength material. Lytag, Pollytag, LECA, and labor are some of the commercially sintered lightweight aggregates worldwide. However, the sintering process requires high energy consumption, producing a large number of pollutants that will cause environmental issues [24].

2.2. Cold bonding

Cold bonding is a process of enhancing fines particle by pressure or non-pressure agglomeration into larger particles. In cold bonding, cement or an alkaline activator will be chosen as the binder. For cold bonding, the pellets will be dried at room temperature for 24 hours once the shape of the pellets is formed. The pellets are then sealed in the bag until the testing day [10,15,18,20,23,24]. Some of the research [11,25] will undergo another hot curing before sealing the pellets in the bag until the testing day. 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 common materials that produce cold bonding lightweight aggregate.

2.3. Autoclaving

Autoclaving is a process that involves the addition of chemicals such as lime or gypsum in the agglomeration stage. For autoclaving, the pellets will be hardened with the help of autoclaved pressure and temperature to gain the strength. Based on the research [8], the quartz tailing aggregate is curing at the room temperature for 24 hours. Then, it will be cured at a temperature of up to 195°C for 3 hours with an autoclaved pressure of 1.38 MPa. The aggregate will be cured at 195°C for another 10 hours without autoclaved pressure before cooling at room temperature. Finally, the aggregate will gain its required weight, less than 1100 kg/m^3, using oven-dried.

The sintering method has been used widely worldwide with some popular commercial products such as LECA and Lytag. Due to the requirement of high sintering temperature for the production of sintered aggregate, some researchers found an alternative way to produce lightweight aggregate, which is through the cold bonding method. They figured out that the cold bonding method could also be used in the concrete due to its properties. Besides that, the autoclaving method is also another method that can be used to produce artificial lightweight aggregate. The disadvantages of using cold bonding and autoclaving methods are that they require a longer time to acquire the required strength of the aggregate.

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 molarity of alkaline activator had specific gravity between 1.8 to 1.85, which 8M having the highest specific gravity [14]. Besides that, mixing 90% of fly ash with 10% cement by using cold bonding gives a specific gravity of 1.76 [28]. The artificial aggregate made up of fly ash using the cold bonding method had a specific gravity of 1.63 compared to normal coarse aggregate at 2.71 [26]. The specific gravity increased from 1.84 to 1.91 when the styrene-butadiene rubber (SBR) was added from 1% to 3% to the lightweight aggregate [18]. In addition, the aggregate produced by mixing bentonite and metakaolin with fly ash will have a specific gravity of 1.8 to 1.93 and 1.95 to 1.99 [27].

The sintered fly ash aggregate had a specific gravity between 1.41 to 1.44, with the size varying from 2 mm to 12 mm [4]. The specific gravity of aggregate made from water treatment residual increased from 1.21 to 1.78 when the increasing of sintering temperature from 1000°C to 1100°C [19]. The sintered dredged sludge lightweight aggregate had a specific gravity from 1.00 to 1.38 for the particle size from 4.75 mm to 12.5 mm [22]. The sintered fly aggregate with bentonite added a specific gravity of 1.57, while the sintered fly ash aggregate with glass powder added a specific gravity of 1.60 at the temperature of 1200°C [26]. The lightweight coarse aggregate is manufactured from bentonite and water glass with a specific gravity of 1.63 at the temperature of 800°C [12].

3.2. Water absorption

Water absorption indicates the internal aggregate structure. Higher water absorption of aggregates means it is more porous in nature and is usually considered unacceptable. The alkaline activator act as a binder for producing lightweight aggregate that will have 22% to 23% of water absorption [14]. Due to the high porosity of expanded perlite powder (EPP), the water absorption increases from 33% to 52% when the fly ash replacement increases to 30% [25]. When the sintering temperature is increased, the water absorption of all aggregates is decreased as temperature increase the fusion of material which lead to less water surface permeability [21]. The lightweight aggregate manufactured using sewage sludge and palm oil fuel ash called Posslite LWA had a water absorption of 4.11% [29]. The lightweight aggregate, with the addition of the waste glass powder, help to reduce water absorption from 7.73% to 0.5% [11]. Due to the porosity of the hydrated calcium silicate, the quartz tailing aggregate (QTA) had a high water absorption which varies from 13.77% to 21.93% [8]. 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, as voids were minimized during the SBR increase in the pellets [18]. The lightweight aggregate produced from different ratios of palm oil fuel ash and silt shows high water absorption of 32.2% when 90% clay is used [30]. This is due to the high pozzolanic reaction rate within the mixture and the high water absorption capillary of silt. The presence of a vitrified shell around the artificial lightweight aggregate will reduce water absorption [13].

3.3. Mechanical properties

When the replacement of fly ash with expanded perlite powder (EPP) increases, the artificial aggregate will have higher crushing strength as the pozzolanic activity is higher [25]. Sintered sediment lightweight aggregate with 859 kg/m^3 had the highest crushing strength at 13.4 MPa, which means the aggregate strength will increase with the bulk density [22]. The crushing strength decreased as the silt content increased because of the binding failure of palm oil fuel ash (POFA) with the silt content [30]. The fly-ash metakaolin binder aggregate showed high crushing strength when curing under high temperatures [27].

The cold bonding fly ash aggregate is classified as the strongest aggregate as the impact value is 9.56%. In comparison, sintered fly ash aggregate and autoclaved aggregate can also be classified as strong aggregate as the impact value is 10.2% and 11.46% [31]. Adding styrene-butadiene rubber (SBR) to lightweight aggregate lowered the impact value, making the aggregate stronger [18]. The cement content enhanced the impact resistance of cement-based fly ash aggregate due to increased hydration reaction. Besides that, the curing temperature will also increase the impact resistance of artificial aggregate [15].

4. Lightweight aggregate concrete

4.1. Mechanical properties

The mechanical properties of lightweight aggregate concrete determine the suitability of artificial lightweight aggregate used in the concrete. The interfacial zone (ITZ) between the coarse aggregate and paste is a critical factor that will affect the mechanical properties of concrete [13].

Compressive strength is the ability of the structure to resist compression, which is the primary design variable for engineers. The compressive strength of mortar that contains fly ash aggregate will increase slowly at the beginning of the hardening stage, but it will increase rapidly after 14 days. In addition, the heavier the mortar, the highest the compressive strength, as mortar with fly ash 8M shows the heaviest bulk density with the highest compressive strength [14]. The compressive strength of quartz tailings aggregate (QTA) concrete reaches 74 MPa, which is considered as high strength concrete. considered high strength concrete. This is because the cements binders are readily penetrated to form a layer of mechanical interlocking structure around the aggregates to strengthen the bonding between aggregate and cement paste since the shell of QTA is a porous, fibrous, and needle-flake tobermorite structure [8]. The increasing amount of styrene-butadiene rubber (SBR) in pellets will cause an increase in compressive strength for SBR-modified lightweight aggregate (SLWA) concrete. This is due to the microstructure of the SLWA, which generates a strong bond

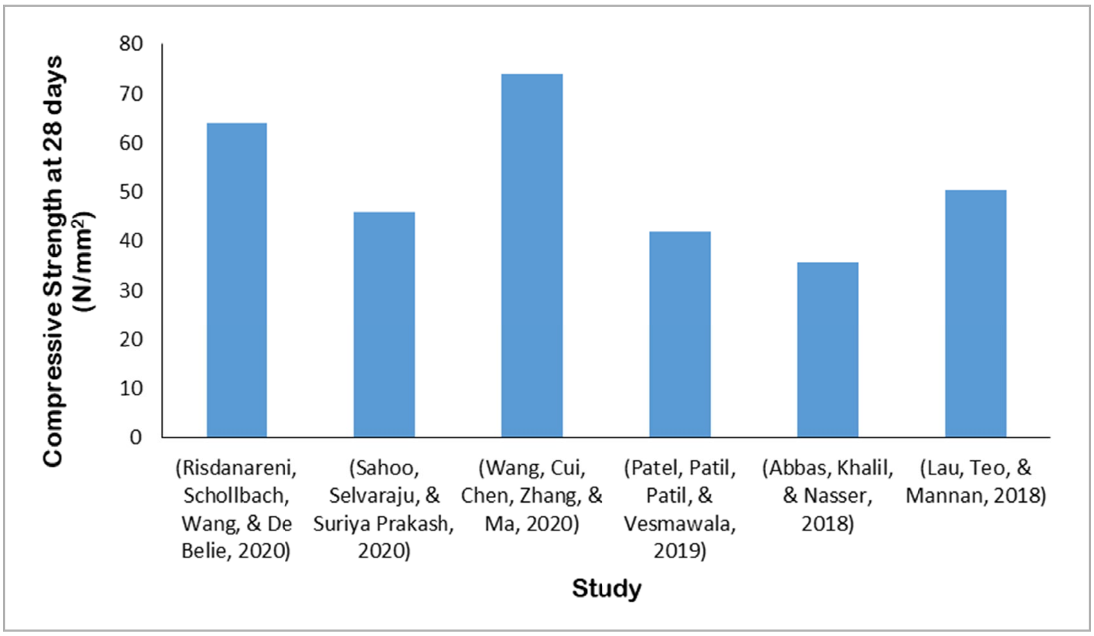

Fig. 2. The compressive strength of lightweight aggregate concrete based on previous study

between the aggregate and the cement paste [18]. Due to the impact on the restriction of the spread of cracking, the beneficial effect of adding fibers to the lightweight aggregate cement mix gives higher compressive strength over 40 MPa. It can be used as a structural application in construction [9]. Fig. 2 shows the compressive strength of lightweight aggregate concrete based on a previous study. According to Fig. 2, it can have concluded that the artificial lightweight aggregate concrete had achieved the compressive strength for structural concrete, which is 17 MPa based on ACI 318M-14.

4.2. Thermal properties

Lightweight concrete normally had lower thermal conductivity than normal concrete [3]. The thermal conductivity for lightweight concrete is 0.9567 W/ (m.K) while the normal weight aggregate is 1.98-2.94 W/ (m.K) [12]. The low thermal conductivity of lightweight concrete can be due to the material used to produce lightweight aggregate. According to the study of Tajra et al. [25], the low conductivity of lightweight concrete is because of the expanded perlite used as the core structure, which has a low thermal conductivity of about 0.05 W/ (m.K) and the use of expanded perlite powder in the shell structure which enhanced its thermal properties. Concrete with lightweight coarse and fine aggregate shows the lowest thermal properties, which are 0.0703 W/ (m.K), as compared to normal concrete with thermal properties at 1.736 W/ (m.K) [32]. Fig. 3 compares lightweight aggregate concrete with normal concrete based on a previous study. Based on Fig. 3, the lightweight aggregate concrete had decreased by 95.95% and 67.46% compared to normal aggregate concrete. Therefore, it can conclude that lightweight aggregate concrete is more suitable to be used as thermal insulation.

5. Conclusion

Based on the review, the cold bonding and autoclaving methods can be considered an alternative way to produce the lightweight aggregate as they show the same properties as the sintering method. The lightweight aggregate with a density which is below 2.0 and can be widely used in concrete. Besides that, the artificial lightweight aggregate showed low water absorption. The curing temperature will cause affect the crushing strength and impact resistance of lightweight aggregate. The compressive strength of lightweight aggregate concrete can be increased by adding additives such as synthetic fibres. The low thermal conductivity of lightweight aggregate concrete can be applied in the construction field as thermal insulation material. Therefore, the production of lightweight aggregate can minimize the usage of natural aggregate and bring benefits to the environment.

Acknowledgment

This research was funded by Ministry of Higher Education Malaysia, Fundamental Research Grant Scheme (FRGS), and grant number of 9003-00747 FRGS/1/2019/TK06/UNIMAP/02/1.

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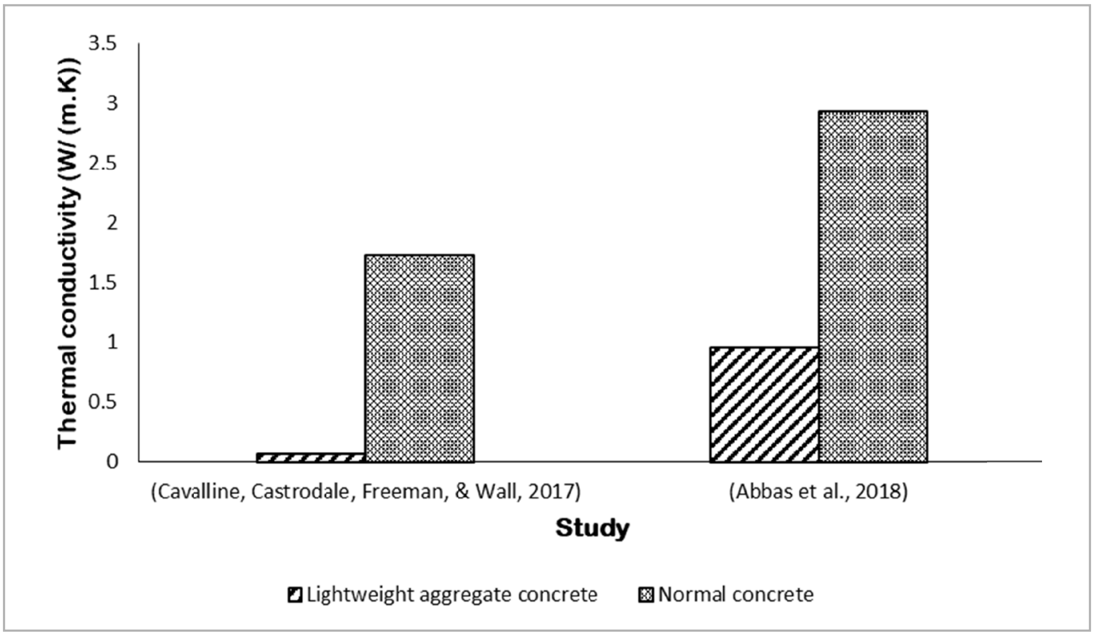

Fig. 3. The comparison between lightweight aggregate concrete with normal concrete based on previous study

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