Utilization of waste material for aerated autoclaved concrete production: A preliminary review

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Abstract. Autoclaved aerated concrete (AAC) has become more attractive in construction due to its excellent environmentally friendly in building construction. Due to its increasing applications, the AAC wastes become abundance in construction site. Apparently, recycling the concrete waste powder to a wall concrete, particularly an autoclaved aerated concrete (AAC) was not frequently practiced in construction and moreover no study has been carried out yet. AAC is relatively lightweight, having lower thermal conductivity, higher heat resistance, lower shrinkage, and faster in construction process compared to normal concrete. AAC concrete is a combination of silica sand, cement, lime, water and an expansion agent. To improve its physical and mechanical properties and to reduce its production cost, tremendous innovation which used waste materials as partial replacement of AAC materials have been done. From these innovations, the use of recycled AAC as a partial replacement for wall concrete has not been carried out yet. This paper is intended to classify the literatures on the innovations that have been done on replacement in AAC materials to enhance its physical and mechanical properties and thermal performance. The physical properties in terms of its microstructure and the mechanical properties such as density, compressive strength, water absorption are presented to classify the investigation that has been done in such innovations. Apart of that, the discussion on innovations to improve its thermal performance also presented. To conclude, up to now, there is no attempt on using the recycled AAC waste powder as a partial replacement in AAC as a wall concrete is reported.

Keywords: Autoclaved aerated concrete; Microstructure; Waste material; Compressive strength

1. Introduction

Autoclaved Aerated Concrete (AAC) is a quite popular concrete that has been used in construction building due to its environmentally friendly characteristics and has an excellent thermal insulation. Apart of that, AAC is relatively lightweight, having lower thermal conductivity, higher heat resistance, lower shrinkage, and faster in construction process when compared to normal concrete [1–6]. AAC can be considered as a green or environmentally friendly due to its ability to reduce building energy consumption for about 50% without adding thermal insulation layers on the building wall [7].

Most researched innovations that have been carried out proved that the replacement of either fine sands or cement may improve its strength, lower the density as well as thermal conductivity and other properties [8,9]. Apart of its properties’ enhancement, research in AAC also includes partial materials
replacement using waste materials that contribute to lower production cost, thus reduce the cost in AAC construction [7–14]. In such innovation, none of researcher use recycled AAC as a material to improve its physical and mechanical properties.

2. AAC Manufacturing Process

Aerated concrete can be classified as autoclaved aerated concrete (AAC) and non-autoclaved aerated concrete (NAAC) based on the method of pore-formation, the type of binder and method of curing [15]. The compressive strength, drying shrinkage, absorption properties, etc. directly depend on the method and duration of curing. Figure 1 shows the process difference in preparation of aerated concrete between the foamed concrete (NAAC) and AAC.

Autoclaved aerated concrete that has been used in current construction materials, having an entrapped air voids product manufactured by combining silica sand, cement, lime, water and the expansion agent [16] and pouring it into a mould. In the mixture, the aluminium powder that serves as an expansion agent will react with the silica thus resulting in the formation of millions of microscopic hydrogen bubbles [17]. The hydrogen then subsequently evaporates and leaving a highly closed-cell aerated concrete. The partially dried aerated concrete is cut into blocks or panels which are then steamed and pressure-cured in an autoclave [17].

![Figure 1. Process flow of the preparation of aerated concrete between the foamed concrete (NAAC) and AAC](image)

3. Material Replacement in AAC Production

AAC can be classified into cement or lime based depending on its materials used. Previous research shown in Table 1 are the innovations that has been done by replacing its based materials. These innovations are either to improve AAC characteristics, properties and performance or the manufacturing cost while maintaining its properties at the acceptable ranges.
| Ref. | Materials | Replacement Method | Enhancement/Improvement |
|------|-----------|--------------------|-------------------------|
| [1]  | S/C/L/Natural Zeolite (NZ) | NZ to replace a portion of sand (optimum at 50%) | Decreases the unit weight of aerated concrete specimens hence decrease density |
| [2]  | S/C/L/Sugar Sediment waste (SSW) | SSW to replace portion of sand and lime (optimum at 30% of sand and 7.5% of lime) | Higher compressive strength, better thermal resistance and finer crystalline morphology |
| [3]  | S/C/L/Air-cooled Slag (AS) | AS to replace Lime and sand (optimum at 50 % low-lime mixes and 30% for high-lime mix) | Enhance the compressive strength and shorten the curing times |
| [4]  | FA/C/L/G/Incineration Bottom Ash (IBA) | IBA to replace aluminium powder as aerating agent and a portion of silica/fly ash | IBA-AAC has higher compressive strength compared to normal AAC at given density & aluminium dosage |
| [5]  | S/C/L/Rice Husk Ash (RHA) | RHA and aluminum containing waste as a partial aggregate and expansive agent replacement | Super fine particle size has positive effect on the transformation of CSH to tobermorite |
| [6]  | C/L/G/Coal Gangue (CG)/ Iron Ore Tailings (IOT) | Optimum composition: 20% CGC, 40% (IOT), 25% lime, 10% cement, 5%, 0.06% Al powder | Completely replace sand to achieve bulk density and compressive strength of 609 kg/m³ and 3.68 MPa, respectively |
| [7]  | C/Pulverized Fuel Ash (PFA)/ Palm Oil Fuel Ash (POFA) | PFA and POFA to completely replace cement. | Control heat of hydration |
| [8]  | S/C/L/Palm Oil Fuel Ash (POFA) | POFA to partially replace cement at 20% | Finer particle sizes and pozzolanic reaction favor for strength development |
| [9]  | S/C/L/G/Fly Ash (FA) | FA from cellulose industry that has high content of Al to replace lime-sulphate | Effect of waste element on the microproducts phase formation |
| [10] | C/L/G/Self-ignition Coal Gangue (SCG) | Optimal mix proportion is SGC: lime: cement: gypsum = 54: 23: 20: 3 with 1.3% aluminum powder | The products are mainly consisted by CSH gel and tobermorite phase. |
| [11] | S/C/G/Copper Tailing (CT)/Blast Furnace Slag (BFS) | Mixture composition SCT:BFS:Sand: Cement:Gypsum = 30:35:20:10:5 | The compressive strength was 4.0 MPa and the dry density was 610.2 kg/m³ |
| [12] | S/C/L/Coal Bottom Ash (CBA) | CBA to replace sand. Optimum replacement of CBA is 50% | Decreased the thermal conductivity values up to 39% and increased strengths up to 16% higher than reference AAC |
| [13] | S/C/L/G/Iron Tailing (IT) | IT to substitute sand at 40-60% | The bulk density can be between 490 - 525 kg/m³, compressive and specific strength >2.5 MPa and >4700 N/m², respectively |
| [14] | S/C/L/G/Perlite Waste (PW) | PW to replace sand | PW at 10% reduced the thermal conductivity about 15% without significant reduction of compressive strength |
| [15] | S/C/L/G/Waste Glass (WG) | Various types of WG are used to replace sand | AAC with cathode ray tube glass has similar characteristics to the reference sample |
| [16] | C/L/Fly Ash/Silica Fume (SF) | 5% SF addition | SF can be used as a functional additive to the fly ash/cement based AAC systems |
| [17] | S/L/G/Hematite Tailings (HT) | Optimum formulation was the mixtures of 70% hematite tailings, 15% lime and 15% sand | The compressive strength of HT autoclaved bricks and the mass loss of it with optimum process condition were 18.36 MPa and 0.72%, respectively |
4. Physical Properties

4.1. Density
AAC physical properties represents by its microstructure and density. The aluminum powder as an expansion agent reacts with other materials and water to form hydrogen that slightly adjust the density of AAC. The hydrogen gas foams and doubles the volume of the raw mix creating gas bubbles which then evaporates leaving air voids up to 3 mm in diameter [25]. The other AAC physical properties such as compressive strength, thermal performance and drying shrinkage depend on the density of AAC itself. AAC density values are usually between 300 - 1800kg / m³ [17].

4.2. Shrinkage
Drying shrinkage of concrete is defined as the contracting of hardened mixture due to loss of capillary water leading to the increase in tensile stress, which may cause crack formation [26]. AAC has lower drying shrinkage compared to the conventional concrete due to high porosity and specific pore surfaces [23]. The theory of Ziembicka interpreted that the tensile strength found in the microporous compresses the distance between the other particles or the walled pores during the autoclaved process [27]. Lam et al. suggested that drying shrinkage of AAC is a function of the specific surface area of fine pores of radii 2–20 nm [28]. Additionally, increased of crystalline content in the substance will also reduce drying shrinkage of the substance [29]. Drying shrinkage also depends on the amount of calcium silicate hydrate. In other words, the addition of alumina materials, such as high-grade sand blast furnace, bauxite, and high alumina cement, can reduce the dry shrinkage between 300- 100% due to the high tobermorite formation [30].

4.3. Water Absorption
AAC is known to have high water absorption due to its high porosity and a large drainage channel [23]. The amount of water absorption has two parts, i.e. in capillary hole (pore diameter <1μm) and in large ventilation port. Typically, there are two categories of pores, namely open pores which are connected with each other and the outside, and blind pores which are not connected. Apparently, driven by capillary force, the open pores have water absorption effect [31].

5. Mechanical Properties

5.1 Compressive Strength
Generally, compressive strength increases linearly with density [32]. Autoclaving increases the compressive strength significantly, as high temperature and pressure results in a stable form of tobermorite. Final strength is achieved in this case, depending on the pressure and duration of autoclaving [33]. The compressive strength will decrease by decreasing density and increase porosity as shown in Figure 2 below [34]. Furthermore, the mixtures from recycled AAC will enhance the tobermorite phase thus increase its strength.

Studies done by Jityachaipum in aerated concentrated to improve its strength shows by replacing the Portland cement content by fly ash and natural zeolite, each 10% by weight, resulted in a lightweight concrete that showed relatively good compressive strengths of 3.65 and 4.51 N/mm², respectively [35]. In aerated concrete itself, sand replacement has taken part in enhance its properties in terms of its physical strength, microstructure and thermal conductivity. Wang et al. improved the microstructure of AAC by using used clayish crushed stone for making aerated concrete and indicated that the hydration products were poorly crystalline C-S-H, tobermorite and hydrogamet [36]. Li, Chen and Long had produced aerated concrete using lead-zinc tailings which explained the effects of water-binder ratio, casting temperature and aluminum powder content on the gas forming behavior, and those of lead-zinc tailing content, cement content and conditioning agents on the compressive strength of the aerated concrete [12].
While in AAC itself, Mostafa conducted a study in lime and sand replacement up to 50% by air-cooled slag in autoclaved aerated concrete to enhance the compressive strength. This optimum condition showed compressive strength of around 3.8 N/mm$^2$ [4]. The use of coal bottom ash from Tuncbilek Thermal Power Plant as an aggregate to produce aerated concrete could increase its compressive strength gain to 2.78 N/mm$^2$ [19]. Density reduction by the formation of large macropores is found to cause a significant strength to drop [37]. Values of compressive strength for different densities tabulated in Table 2.

![Figure 2. The relationship between compressive strength and density [34].](image)

| Table 2: Properties of AAC [6] |
|--------------------------------|
| Dry density (kg/m$^3$) | Compressive Strength (MPa) | Static Modulus of Elasticity (kN/mm$^2$) | Thermal Conductivity (W/m$^3$°C) |
|------------------------|-----------------------------|--------------------------------------|-------------------------------|
| 400                    | 1.3 – 2.8                   | 0.18 – 1.17                          | 0.07 – 0.11                   |
| 500                    | 2.0 – 4.4                   | 1.24 – 1.84                          | 0.08 – 0.13                   |
| 600                    | 2.8 – 6.3                   | 1.76 – 2.64                          | 0.11 – 0.17                   |
| 700                    | 3.9 – 8.5                   | 2.42 – 3.58                          | 0.13 – 0.21                   |

5.2. Thermal Performance
AAC has good thermal insulation due to its cell structure. Thermal performance value (k) is in the range of 0.1 - 0.7 W/(mK) for dry density values between 400 - 1700 kg/m$^3$, which is about 2 to 20 times less than the conventional concrete where it is in the range of 1.6 - 2.0 W/(mK) [2,3,34]. Thermal performance is a function of dry density wherein if the density value decreases, the thermal performance will also decrease as shown in Figure 3 below. Based on the data obtained from the previous experimental studies, a decrease in density of 100 kg/m$^3$ causes a decrease in thermal performance at least 0.02 - 0.04 W/(mK). In addition, the pores and distribution counts are also important in testing the thermal performance.

6. Opportunity of Recycled AAC
Based on the previous study conducted, replacement of AAC materials such as using bottom ash, addition of lead-zinc tailings and blast furnace slag could enhance the AAC properties in terms of its physical and mechanical properties [38]. AAC itself has higher micropores, thus by applying recycled AAC wastes powder it is believed that it will enhance the tobermorite crystalline contents and hence increase the strength of AAC. In addition, in Malaysia the AAC wastes is in abundance and it is free, not only reduce in production cost but it could contribute to the environmental impact.
7. Summary
Summarizing the research pertaining innovations of replacement in AAC materials to enhance its properties and lower its production cost, the observations show the properties are influenced by the density and thus, they should be qualified with the density, strength of AAC is significantly higher due to its tobermorite which is more stable form of tobermorite on autoclaving and the drying shrinkage of AAC is lower. In such innovations, recycled AAC hasn’t taken part yet thus it is an opportunity to use recycled AAC as materials in order to enhance its properties and reduce its production cost.

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