An Innovative Autoclaved Aerated Concrete (AAC) with Recycled AAC Powder for Low Carbon Construction

AR Rafiza¹, HY Chan¹*, A Thongtha², W Jettipattaranat³ and KL Lim⁴

1 Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
2 Department of Physics, Faculty of Science, Naresuan University, Phitsanulok, 65000, Thailand
3 INSEE Superblock Co., Ltd., 99 Moo 9 and 219 Moo 5, Mitrararb Road Km. 129-131 Tambon Tabkwang, Amphor Kangkoy, Saraburi Province 18260, Thailand
4 Fuel Cell Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
E-mail: hoyyen.chan@ukm.edu.my

Abstract. Recycling of materials, in particular concrete was not frequently practiced in construction and moreover no study has been carried out yet. Furthermore, the environmental impact of recycling in construction was not known and no study has been carried out, thus now it leads to give an abundance of wasted concrete at site. Autoclaved aerated concrete (AAC) is one of the lightweight concretes that commonly used in construction. AAC is relatively light in weight, having lower thermal conductivity, higher heat resistance, lower shrinkage, and faster in construction process when compared to the conventional concretes. AAC consist of silica sand, cement, lime, water and expansion agent. To reduce the construction waste, an innovative AAC block has been developed by using recycled AAC in powder form to replace sands in the manufacturing process. The new developed AAC was conducted by replacing sand with recycled AAC in ratio of 0%, 15%, 20%, 25%, 30%, 45%, 40% and 45%. Microstructure analysis were conducted using optical microscopic and scanning electron microscopic (SEM) while the chemical analyses were conducted using X-ray diffraction (XRD). Mechanical tests such as density, compressive strength, flexural strength and water absorption also have been carried out. It could be observed that by replacing the sand content with recycled AAC, AAC with fine recycling powder content of 30% by weight has a compressive strength that is approximately 16.1% greater than conventional AAC and is between 30-110% higher than any value obtained by utilizing industrial waste product.

1. Introduction

Constructions of high-rise commercial buildings and dwellings have been rapidly developed in developing countries, such as Malaysia. The climate of Malaysia is hot and humid [1] and thus heat and moisture are easily accumulated or trapped in the building wall. As a result, ventilating fans and air-conditioners have been used to remove heat in ensuring the indoor thermal comfort of the occupants.

Autoclaved aerated concrete (AAC) is one of the lightweight concretes that commonly used in construction. AAC is relatively light in weight, having lower thermal conductivity, higher heat resistance, lower shrinkage, and faster in construction process when compared to the conventional concretes [2]. AAC can be considered as a green or environmentally friendly material, which the
preparation process consumes lesser energy and is able to reduce the building energy consumption for about 50% without adding thermal insulation layers to the building wall, compared to the conventional concretes [3]. Its popularity is getting greater in Malaysia and Thailand, there are numbers of manufacture plants in Malaysia for AAC production and in Thailand, around 28,000,000 m² of AAC was used in 2012 [6].

Nonetheless, AAC wastes are generated in the production process; the finished products, which are cracked will be rejected. Therefore, AAC wastes are available in abundance. Every year in Malaysia and Thailand approximately 140,000,000kg of recycling AAC waste are produced. Also, AAC wastes are disposed at the construction and demolition sites. Recycling the AAC wastes will be a good approach to minimize the final disposal in landfill. Using this abundant and free raw material for the AAC production has not been reported in the literature. There are abundance of AAC wastes were collected at the construction and landfill sites, which the total amount was nearly 140 kilo tones in 2012 [6].

Apart from that, previous studies show a lot of researchers used the industrial by-product wastes for concrete productions, in order to reuse the wastes, which can reduce the raw material costs, and hence the production costs. Studies have been carried out to use the industrial waste such as efflorescent sand and phosphorescent slag, iron ore tailings, air-cooled slag, siliceous crushed stone, lead–zinc tailings, coal bottom ash copper tailings and blast furnace slag and calcium fly ash and natural zeolite as well as sugar sediments to replace the conventional raw materials in AAC production [4-9].

Huang et al., [4] investigated the lime replacement by copper tailings and blast furnace slag in autoclaved aerated concrete, which exhibited a dry density of 0.61 g/cm³ and compressive strength of 4.0 N/mm². Furthermore, Jitchaiyaphum et al. [7] found that 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. Wang et al. [6] applied the tailings from Chengchao Iron Ore Mine to the mixture in aerocrete that investigated the optimal proportion of cement and lime, dosage of the additional silicon-materials, calcium-silicon proportion, dosage of aluminium powder and other parameters. Their findings opened a new way for the exploitation of low-silicon iron ore tailings. Mostafa [5] studied lime and sand replacement up to 50% by air-cooled slag in AAC to enhance the compressive strength. This optimum condition showed compressive strength of around 3.8 N/mm². Wang et al. [6] further used clayish crushed stone for making aerated concrete and indicated that the hydration products were poorly crystalline C-S-H, tobermorite and hydrogarnet.

Another researcher has developed AAC by using the waste sugar sediment as a sand and lime replacement to investigate the possible improvements in three major properties of concrete, i.e. compressive strength, weight and thermal resistance. In this work, it was found that the compressive strength was increased significantly with an associated decrease in weight and gave compatible resistance that can be used as building blocks without insulation layer needed [7].

Based on previous studies, it has been reported a lots of research progress aiming in improving AAC thermal conductivity and other structure properties. Most researched innovation that has been carried out proved that either the replacement of cement or fine aggregate proven that it might increase its properties such as strength, lower the density as well as thermal conductivity. In such innovation, none of recycled AAC has been used to replace fine sands in order to improve its properties even though there are abundance of recycled AAC could be found. Therefore, recycling of wasted AAC concrete become important in order to reduce the environmental impact of wastes and reduce the production cost of using fine sands. Furthermore, the mixtures from recycled AAC will enhance the tobermorite phase thus increase its strength, lower the density as well as its thermal conductivity.

This research aims to use the recycled AAC waste powder to replace the fine sands contents as raw materials for AAC. The new developed AAC will be prepared with different ratios of recycled AAC waste powder to fine sands. By replacing fine sands with the recycled AAC wastes powder will enhance the tobermorite crystalline contents and hence increase the strength of AAC. This is not only reducing the environmental impact for landfilling, but also reducing the energy consumption and simplifying the production process. Therefore, the new AAC product is a low cost AAC material, and because it was
made by the AAC wastes, it carries the same advantages of AAC. This will make the product lifecycle more ecological soundness.

In this paper, the new developed AAC samples were prepared by using the recycled AAC waste powder to partially replace the fine sand contents in AAC production. These samples were characterized in terms of microstructure, physical and mechanical properties. Physical and mechanical tests were such as density, water absorption, humidity, compressive strength and flexural strength. The objective of these analyses is to assess the compatibility of the developed AAC to the commercial AAC and the Thai Industrial Standard TIS 1505-2541 [12], which is a compulsory standard in Thailand was used as a reference.

2. Materials and Methods
In this present study, the new developed AAC samples were prepared by replacing sand contents with the recycled AAC powder (R-AAC) in ratios of 0%, 15%, 20%, 25%, 30%, 45%, 40% and 45% by weight. These samples were fabricated by an AAC manufacturer.

Microstructure analysis were conducted using optical microscopic and scanning electron microscopic (SEM) while the chemical analyses were conducted using X-ray diffraction (XRD). The samples were also tested for physical and mechanical properties at the laboratories of the Universiti Kebangsaan Malaysia and also Naresuan University. The mechanical properties assessment was included density, compressive strength, flexural strength and water absorption tests. As the sample were prepared at Naresuan University and as it’s to assess the compatibility to the commercial AAC, the analyses of the developed AAC were compared to TIS 1505-2451 [12] and for mechanical strength the results were compared to ASTM C 1555-3a Standard [13].

3. Results and Discussion
In general, by replacing the sand content with the recycled AAC waste powder will improve the tobermorite crystalline contents and hence increase the strength of the AAC. From the microstructure of the AAC composition and mixtures with the different compositions using the scanning electron microscopy (SEM), and the X-ray diffraction (XRD) tests, the formation and quality of the tobermorite phase were identified and analysed.

From the FESEM investigation on the surface of new developed AAC blocks, it could be clearly observed that new develop AAC with lowest recycled contents consisted of large pores while new develop AAC with highest recycled contents is smoother in surface with much smaller pores as in Figure 1 (a) to 1(i).

![Figure 1. FESEM micrographs of (a) 0% R-AAC (b) 15% R-AAC (c) 20% R-AAC (d) 25% R-AAC (e) 30% R-AAC (f) 35% R-AAC (g) 40% R-AAC (h) 45% R-AAC (i) 50% R-AAC](image)

From Figure 1, no cracks were observed on all samples which it could be clearly stated that these samples having good mechanical strength and the surface looks smoother and finer. For further investigation of their crystallinity of all samples, FESEM micrographs with higher enlargement also

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have been performed at 5000 times for further investigations. Figure 2(a) to 2(i) shows the AAC sample crystallization image resulting from the characterization of FESEM with higher crystallization. All AAC samples showed the presence of tobermorite crystals. The visible particulate matrix is constructed from thin platelets from tobermorite. Platelets have more uniform thickness which will not exceed tens of several nanometers while the width is about 5 to 10 microns. Tobermorite crystals also appear to be interspersed with one another so that the pore structure looks like a sharp angled corner cell network [5].

**Figure 2.** Comparison of crystalline structure of specimen for (a) 0% R-AAC (b) 15% R-AAC (c) 20% R-AAC (d) 35% R-AAC (e) 30% R-AAC (f) 35% R-AAC (g) 40% R-AAC (h) 45% R-AAC (i) 50% R-AAC

Based on crystalline structure, it can be clearly seen that 35% R-AAC has more crystal than others while at 50% R-AAC shows more finer pores, tremendous amount of finer porosity within the matrix of fine particulate would also result in much lower specific density in AAC. In order to confirm the crystal structure of the samples, XRD analysis was also carried out. XRD patterns which compared 30% and 50% samples reveals that 50% samples mainly consist of calcite and quartz with less tobermorite. Meanwhile in 30% samples main product is crystalline in as much as tobermorite and quartz are present. By replacing more recycling powder with sands content, it could increase more tobermorite phase which could lead in increasing the mechanical strength. The existence of tobermorite phase in AAC plays an important role in providing various outstanding properties. From this experiment, it shows that new developed AAC could enhance phase transformation of calcite to tobermorite phase and control formation of microporosity in the cement matrix. The existence of crystalline tobermorite phase could enhance AAC mechanical properties which are justified by microscopic analysis. This result shows that samples with more tobermorite phase will contribute in mechanical properties such as higher compressive strength as shown in Table 1.

**Figure 3.** XRD patterns of (a) 30% R-AAC (b) 50% R-AAC

### 3.1. Physical Properties
While reducing the cost of its production, partial replacement using waste materials in AAC also contributes to its property’s enhancement [2-9]. AAC physical properties represents by its microstructure and density. Most AAC properties such as compressive strength, thermal performance and drying shrinkage depend on the density of AAC itself.

3.1.1. Density. AAC density values are usually between 300 - 1800 kg / m³ [8]. The new develop AAC blocks density ranges from 0.53 – 0.61 g/cm³ which is group in quality class 4 (510-800 g/cm³), based on TIS 1505-2451 [12]. AAC humidity also needs to be identified in order to identify the density values of AAC. From Table 1, the higher the density value, less of humidity were recorded which is good and it is resulting in possibility to prevent mold growth in such construction materials. Additionally, materials from autoclaved process can be 15% to 25% heavier than materials that using dry ovens [9] and longer process of autoclaved (> 8h) could increase the density because this process contributed to the formation of more hydration [10]. 3 samples with higher density recorded in sample 20%, 25% and 30% where from FESEM analyses which shows that the structure with less finer porosity.

**Table 1** Average density, humidity, water absorption, compressive strength and flexural strength of AAC with the variation sand and fine recycled AAC wastes.

| Characteristic properties of tested sample | Content of the fine recycling powder (Weight %) |
|-------------------------------------------|-----------------------------------------------|
| Density (g/cm³)                           | 0.53 0.57 0.61 0.60 0.59 0.53 0.55 0.56 0.55 |
| Water absorption (g/cm³)                  | 0.39 0.41 0.40 0.36 0.39 0.42 0.43 0.45 0.47 |
| Humidity (%)                              | 32.7 25.8 20.3 20.6 24.8 28.2 29.2 30.1 23.5 |
| Compressive strength (N/m²)               | 5.04 5.19 5.32 5.37 5.85 5.27 4.97 4.45 4.21 |
| Flexural strength (N/m²)                  | 2.04 2.52 2.71 2.28 2.75 3.14 3.10 2.55 2.37 |

3.1.2. Water Absorption The high absorption of water by AAC is due to its high porosity and a large drainage channel [10]. The amount of water absorption has two parts i.e in capillary hole (pore diameter <1μm) and in large ventilation port. All the capillaries in the matrix are basically saturated with water, but the role of ventilation pores is only to create winding paths for extending water [11]. In this finding, the maximum water absorption of the AAC was around 0.45 g/cm³ at 50% recycling powder content. All water absorption lies under 0.5 g/cm³ which could classify in quality class 4 based on TIS 1505-2451 [12]. Highest water absorption is recorded at 50% samples which shows that the more recycled content in AAC contributes to higher water absorption but with lowest compressive strength.

3.2. Mechanical Properties

3.2.1. Compressive and Flexural Strength Generally, compressive strength increases linearly with density. Porosity of the AAC also being affected by the compressive strength. Based on FESEM and Table 1, sample with higher density and strength such as 30% and 35% shows less of porosity. The compressive strength increased and reached its highest at 30% sample and then dropped when the sample is higher than 30%. The maximum compressive strength was around 5.85 N/mm² obtained from the sample of 30 %. This value is higher than lightweight concrete with the component of coal bottom ash (2.78 N/mm²) [4], copper tailings and blast furnace slag (4.00 N/mm²) [5] and high-calcium fly ash and natural zeolite (4.51 N/mm²) [6]. The compressive strength of traditional autoclaved aerated concrete has a value of around 5.04 N/mm² and based on ASTM C 1555-3a the compressive strength is around 5.00 N/mm²[13]. New develop AAC of 30% sample has a compressive strength that is approximately 16.1% greater than conventional AAC and is between 30-110% higher than any value
obtained by utilizing industrial waste product [4-6]. The maximum compressive strength was claimed in quality class of 4 (≥ 5 N/mm² and < 6 N/mm²), which also based on the TIS 1505-2451 [12]. While for the flexural strength obtained its highest at 35% sample and then dropped at sample higher than 30%. The maximum flexural strength was around 3.14 N/mm² of 35% sample. This value was claimed in quality class of 4 (≥ 30% of the compressive strength), which also based on the TIS 1505-2451 [13].

Conclusions
By replacing more recycling powder with sands content, it could increase more tobermorite phase which could lead in increasing the mechanical strength. The existence of tobermorite phase in AAC plays an important role in providing various outstanding properties. Through experiments, results show that new developed AAC could enhance phase transformation of calcite to tobermorite phase and control formation of microporosity in the cement matrix. The existence of crystalline tobermorite phase could enhance AAC mechanical properties which are justified by microscopic analysis. Also, through this finding, by comparing the percentage of recycled powder and sand content, the higher recycle content could increase the water absorption while it is reducing the mechanical properties of existing AAC. By comparing all samples, 30% sample consist of higher tobermorite phase and thus results in higher compressive strength. It could be observed that by replacing the sand content with recycled AAC, AAC with fine recycling powder content of 30% by weight has a compressive strength that is approximately 16.1% greater than conventional AAC and is between 30-110% higher than any value obtained by utilizing industrial waste product. All samples of this new develop AAC blocks is claimed as class 4 which is could be commercial and with a series of experiments it could be confirmed that this new develop AAC could be employed as a promising concrete building material.

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