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Performance of Autoclaved Aerated Concrete (AAC) Containing Recycled Ceramic and Gypsum Waste for Partition Walls Application

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ABSTRACT

The normal growth population and development in big cities have caused many problems such as municipal solid waste (MSW) and noise pollution. To solve these problems, two type of eco-friendly autoclaved aerated concrete (AAC) containing recycled ceramic and gypsum waste (CGW) with different ratio (0, 5%, 10%, 15%, 20%, 25% and 30% wt) have been prepared according to American Society for Testing Materials (ASTM) C1693-09. Type one (I) is AAC containing recycled CGW as a partial replacement for sand. Type two (II) is AAC containing recycled CGW as additional material. The compressive strength of samples has been tested according to ASTM D695 by using Universal Testing Machine (UTM). The sound absorption coefficient (SAC) has been carried out by using Impedance Tube Model No: AED1000 according to ASTM E1050 at low frequency 75Hz to 500Hz. All samples showed free crack and normal colour behaviour such as grey. The compressive strength of AAC samples in the range of 6.10% to 29.88% for AAC Type I and in range of 29.27% to 45.73% for AAC type II. The maximum compressive strength was 2.13 MPa and 2.39 MPa for AAC type I and II at 15% wt and 5%wt of CGW, respectively. The maximum sound absorption coefficient was around 0.75 to 0.768 for AAC type I at frequency 500Hz. Generally, AAC type I has higher SAC compared to AAC type II and was categorized as class B absorbers at frequency 500Hz. Our results showed that CGW has succeeded in improving the performance of AAC such as work density, compressive strength and SAC. Especially for AAC type I, the samples are suitable for wall application such as partition walls, party walls and sound insulation material.

1. Introduction

Municipal solid waste (MSW) and noise pollution are two effects of the normal growth population and development in big cities. For instance, approximately 0.81 million metric tons (50.6%) of MSW from industries are also disposed to landfill in Malaysia including ceramic and gypsum waste [1]. The

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MSW that increases each year in landfill does not only result from the building life cycle but also from the construction industry such as ceramic and gypsum factories. According to Samadi *et al.,* [2], the ceramic production in Malaysia was increasing each year at a constant rate 2.3% and almost 30% of total ceramic production goes as waste in landfill. Meanwhile, gypsum production in world was around 150 million tons in 2022 [3]. Based on reference, only 6% of gypsum waste as hazardous waste was recovered or recycled with the remaining 94% has been sent for disposal in landfills in 2012 [4]. According to Ayilara *et al.,* [5], improper landfill management did not only have adverse effect on the ecological system such as water, soil and air pollution but also human health, deplete the ozone layer when burnt and increase the impact of climate change. MSW in landfill caused serious health problems if it comes in contact with groundwater [6]. For example, approximately 1400 people die daily in the world due to water and water-related problems [7]. Furthermore, MSW in landfill was suspected in giving the contribution to about 20% of the global GHG (methane and carbon dioxide) emission [8,9].

In other case, the average noise levels for urban residential areas along a busy street was over 50% of DOE standard in Batu Pahat Johor and Klang Valley Malaysia [10,11].

The autoclaved aerated concrete (AAC) is one of the lightweight concrete family members which is well known for its good sound insulation material [12-14]. Since the discovery in 1924 by Dr. Johan Eriksson, the AAC have attracted a lot of interest due to the advantages including eco-friendly environment [15], non-combustible building class A1 and non-emit smoke or toxic gases [16], a good earthquake resistance [17]. According to Iucolano *et al.,* [18], AAC has grown greatly in the building industry since the 1940s in Europe and the market related to AAC production is expected to reach 10.98 billion of dollars by 2023 due to the key factors of green building. AAC is the only one type of wall material that can save the building energy around 50% without adding other thermal insulation material and also can reduce carbon emission of building [19]. Usually, the main material of AAC is fly ash or sand as a primary siliceous material, cement and lime as primary calcareous materials, gypsum as the admixture material and aluminium powder was used as a foaming agent or aerating agent [20,21].

Because of the abundance of MSW in Malaysia especially ceramic and gypsum waste (CGW) and its purpose to solve noise pollution, it is very interesting to study the performance of AAC containing recycled CGW. To our knowledge, there is no report yet on the application of ceramic waste as well as gypsum waste to enhance mechanical and acoustic properties of AAC. The main objective of this work was to investigate the performance of two types of AAC containing recycled CGW such as physical, mechanical and acoustic properties. Two types of AAC containing recycled CGW with different ratio (5%, 10%, 15%, 20%, 25% and 30% wt) have been prepared according to ASTM C1693-09. Type one (I) is AAC containing recycled CGW as a partial replacement for sand and type two (II) is AAC containing recycled CGW as additional materials. The Universal Testing Machine (UTM) was used to test the compressive strength of sample. Meanwhile, Impedance Tube Model No: AED1000 was used to test the sound absorption coefficient of sample. All results are compared to previous research and both types of AAC. This work will offer many advantages such as reducing the landfill areas and the cost of recycling for CGW as well as reducing the sand import in Malaysia due to the Malaysia was a net importer of sand from 2008 to 2023, except in 2013 [22]. Additionally, the work is also to support the Paris Agreement (2015) and Malaysia commitment in reducing GHG emissions by roughly 50% by 2030.

2. Methodology

2.1 Raw Materials and Preparation

In this study, the sand and Portland cement used for preparing AAC samples were purchased from Pekan Pagoh, Johor. The lime and Aluminium powder used for preparing AAC samples were purchased from chemical industry of Malaysia. Water from the laboratory of Kim Hoe Thye Industries, Johor, Malaysia was used to make AAC slurry (pre-preparation).

Whereas, the ceramic as partial replacement for sand and additional was obtained from Prudent Deals Sdn Bhd 18 Lorong SS 1/11A, Petaling Jaya, 47301, Petaling Jaya, Selangor, Malaysia. The ceramic waste was sorted manually to remove other materials such as soil, stone, bitumen (asphalt), plasterboard, concrete, AAC, bricks, tiles, plastic, rubber, textile, glass, iron, aluminium, styrofoam, cable, nail, screw, anchors, wood, carpet, films, wallpaper remains, paper and gypsum. Then, ceramic waste was washed by using water to remove the dust, soil or sand and dried by using the hairdryer. After that, it was ground by using Ball Mill Machine to get the ceramic waste powder (CWP) particle size around 0.5-1mm.

Meanwhile, the gypsum as a partial replacement for sand was also obtained from Prudent Deals Sdn Bhd 18 Lorong SS 1/11A, Petaling Jaya, 47301, Petaling Jaya, Selangor, Malaysia. The gypsum waste was also sorted manually to remove other materials such as soil, stone, bitumen (asphalt), plasterboard, concrete, AAC, bricks, tiles, plastic, rubber, textile, glass, iron, aluminium, styrofoam, cable, nail, screw, anchors, wood, carpet, films, wallpaper remains, paper, ceramic, etc. Then, gypsum waste was ground by using a Ball Mill Machine manually to get the gypsum waste powder (GWP). Target particle size of GWP is 0.5-1mm. To get the target size of the particle, the GWP has sieved manually.

2.2 Methods used for AAC Samples Preparation

Two types of AAC containing recycled CGW with different ratio (5%, 10%, 15%, 20%, 25% and 30% wt) have been prepared according to ASTM C1693-09. Type one (I) is AAC containing recycled CGW as a partial replacement for sand. And type two (II) is AAC containing recycled CGW as additional material. The control sample of AAC contained 100% sand without gypsum and ceramic waste (CGW) powder. Two types of AAC based on CGW were designed with similar gypsum and different ceramic waste ratio.

Table 1 showed the mixture proportion for AAC type 1. The error in powder material and water has been controlled in ±0.1g and aluminium (Al) powder was controlled in ±0.01g. For instance, F30R sample, the amounts of sand (40%), cement (17%), lime (11.52%) and water (0.58%) have been mixed by using Allefix's 2100W Electric Mixer around 10 min and added gypsum waste (2%), ceramic waste (28%) and stirred for 5 min then add some Al paste (0.9%) and stirred for 30 seconds to produce slurry. The mixed slurry has been poured into a 2/3 box mould and shaken slowly until the air bubbles rise to the top. The reaction takes around 30 minutes to expand the mixed slurry into the full mould. This step has been repeated for samples with codes CS to E. Slurry has been cut at the cutting line and cured under hydrothermal conditions for 12 hours at 200℃ by using saturated steam at a pressure of 12bar.

Table 1
The AAC type I which CGW as a partial replacement for sand

Raw mix	Sand, %	Gypsum Waste, %	Ceramic Waste, %	Lime, %	Cement, %	Aluminium, %	Water, %
CS	70.00	0.00	0.00	18	12	0.1	0.58
A05R	65.00	2.00	3.00	18	12	0.1	0.58
B10R	60.00	2.00	8.00	18	12	0.1	0.58
C15R	55.00	2.00	13.00	18	12	0.1	0.58
D20R	50.00	2.00	18.00	18	12	0.1	0.58
E25R	45.00	2.00	23.00	18	12	0.1	0.58
F30R	40.00	2.00	28.00	18	12	0.1	0.58

Whereas, Table 2 showed the mixture proportion for AAC type II. The error in powder material and water has been controlled in ±0.1g and aluminium (Al) powder was controlled in ±0.01g. For instance, sample A, the amount of sand (70%), cement (17%), lime (11.52%) and water (0.58%) has been mixed by using Allefix's 2100W Electric Mixer around 10 min and added gypsum waste (2%), ceramic waste (3%) and stirred for 5 min then add some Al paste (0.9%) and stirred for 30 seconds to produce slurry. The mixed slurry has been poured into a 2/3 box mould and shaken slowly until the air bubbles rise to the top. The reaction takes around 30 minutes to expand the mixed slurry into the full mould. This step has been repeated for samples with codes CS, B to F. Slurry has been cut at the cutting line and cured under hydrothermal conditions for 12 hours at 200°C by using saturated steam at the pressure of 12bar.

Table 2
The AAC type II which CGW as a raw material addition

Raw mix	Sand, %	Gypsum Waste, %	Ceramic Waste, %	Lime, %	Cement, %	Aluminium, %	Water, %
CS	70.00	0.00	0.00	18	12	0.1	0.58
A05%	70.00	2.00	3.00	18	12	0.1	0.58
B10%	70.00	2.00	8.00	18	12	0.1	0.58
C15%	70.00	2.00	13.00	18	12	0.1	0.58
D20%	70.00	2.00	18.00	18	12	0.1	0.58
E25%	70.00	2.00	23.00	18	12	0.1	0.58
F30%	70.00	2.00	28.00	18	12	0.1	0.58

2.3 Physical-Mechanical Properties Testing

The sample has been cut into size 100 x 100 x 100 mm for work density and compressive strength testing. Figure 1 showed specimen's dimension of AAC samples. The work density of the AAC samples has been weighed by using electrical balance AND GF-6100 at Concrete Lab UTHM Pagoh. The values of work density were calculated [23]. Formula for work density was defined as Eq. (1).

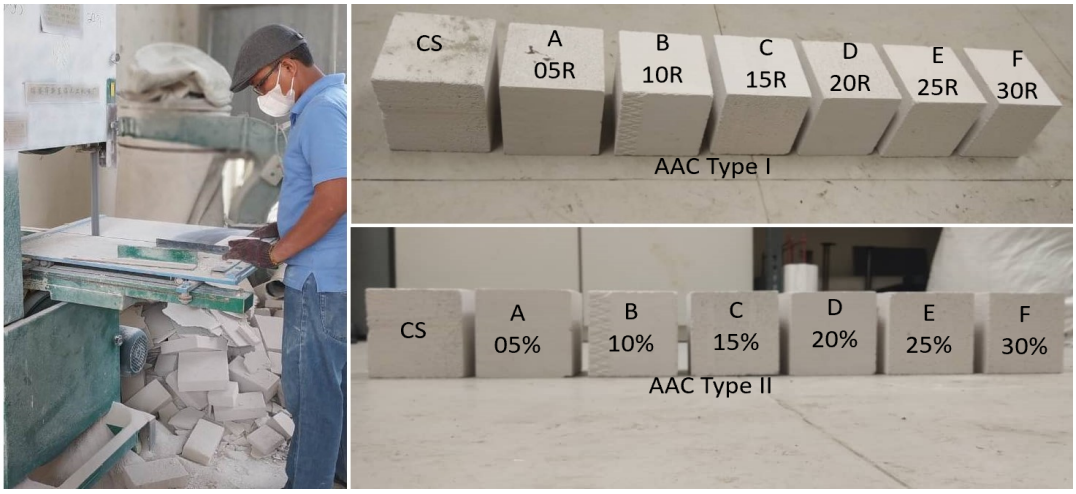
$$\rho_w = \frac{M(kg)}{V(m^3)} \tag{1}$$

where *M* is the weight of the AAC-CGW sample and *V* is the AAC-CGW sample volume.

Whereas, the compressive strength of all samples has been carried out by using a compressive strength test (ASTM D695) machine with brand Universal Testing Machine (UTM) Model No: VEW 2308, UTHM, Pagoh. The specific strength of AAC samples has been calculated to obtain compressive comparison among samples at different working densities [24,25]. Formula for specific strength was defined as Eq. (2).

$$S = \frac{f_c(\text{MPa})}{\rho_w(kg)} \quad (2)$$

where f_c is compressive strength of AAC sample and ρ_w is work density of AAC sample.



(a) (b)

Fig. 1. (a) The cutting process (b) Specimen's dimension of AAC samples

2.4 Sound Absorption Coefficient Testing

The sound absorption coefficient (SAC) versus frequency has been carried out by using Impedance Tube Model No: AED1000 according to ASTM E1050 at low frequency. The specimen's dimension of SAC was 100 mm in radius with a thickness was 100 mm for low frequency (Figure 2).

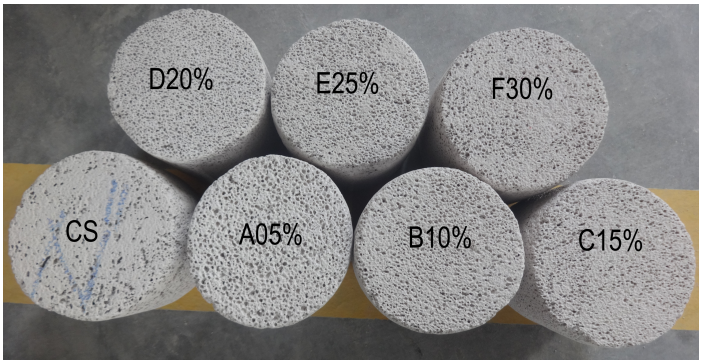


Fig. 2. The specimen's dimension of AAC samples for sound absorption coefficient testing

3. Results

3.1 Work Density of AAC Type I and II

All samples showed normal colour behaviour i.e. grey. The physical surface of the samples had free crack which can be seen by the naked eye. Table 3 shows the work density of AAC type I and II respectively. For AAC type I, the work density of the sample increased with the increasing of CGW ratios. The work densities of the sample slowly increase by around 0.61% at 5% wt of CGW. The maximum work density was 1.95% at 15% wt replacement of natural sand when compared to the control sample (CS). Except for 30% wt of CGW, all of work densities of samples were higher than CS. Similar trend has been observed in another study by Luo and friends in 2023 [26]. According to Ali *et*

al., [27], the pozzolanic material reduced the porosity and width of the interfacial zone in a way that increased the density. The work density of AAC type I is presented in Figure 3. Meanwhile, according to Lam [28], the work densities slowly increased may be due to the fineness of natural sand and CGW, as well as the density of these materials almost similar and did not significantly change the work density of samples and it was almost negligible.

Table 3
The work density of AAC type I and II

Samples	Work Density, kg/m^3		Enhance work density, %	
	AAC Type I	AAC Type II	AAC Type I	AAC Type II
CS	593.71	593.71	-	-
A-05	597.35	609.32	0.61	2.63
B-10	601.33	627.05	1.28	5.62
C-15	605.29	632.70	1.95	6.57
D-20	603.49	639.51	1.65	7.71
E-25	600.06	649.57	1.07	9.41
F-30	592.65	672.70	-0.18	13.30

Meanwhile, the work densities of the AAC type II also increase around 2.62% to 13.30% for CGW addition from 5% to 30% wt. The maximum work density was 13.30% at 39% wt addition compared to the control sample (CS). The result showed that the addition of CGW have a significant effect on the work density of AAC. All of work densities of samples are higher than CS. The densities increase due to the sample's composition increases with the addition of CGW. Figure 3 shows the work density of AAC type I and II.

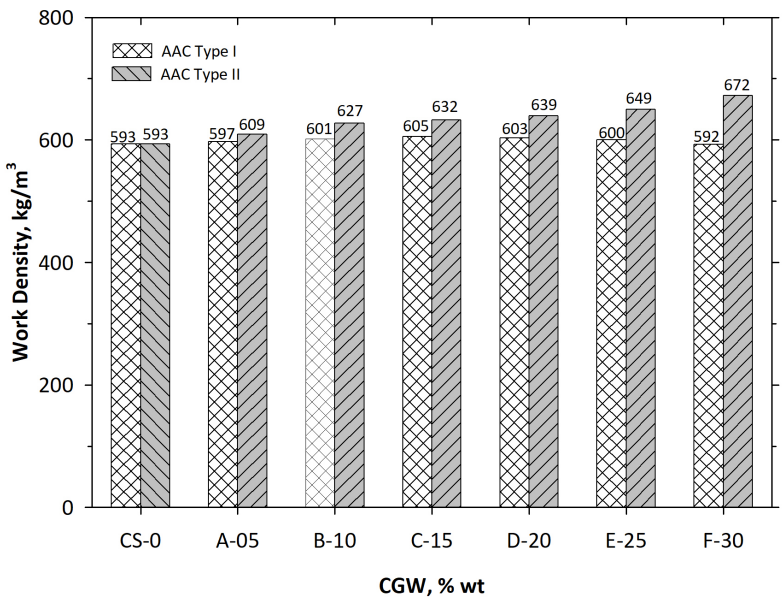


Fig. 3. The work density of fresh AAC type I and II

3.2 Compressive Strength of AAC Type I and II

Figure 4 shows the compressive strength of AAC type I and II. Especially for AAC type I, the compressive strength increased with the increment of CGW ratio for not more than 15% wt. The compressive strength of AAC increased with the increase of CGW ratio from 1.92 MPa to 2.13 MPa or from 5% to 15% wt.

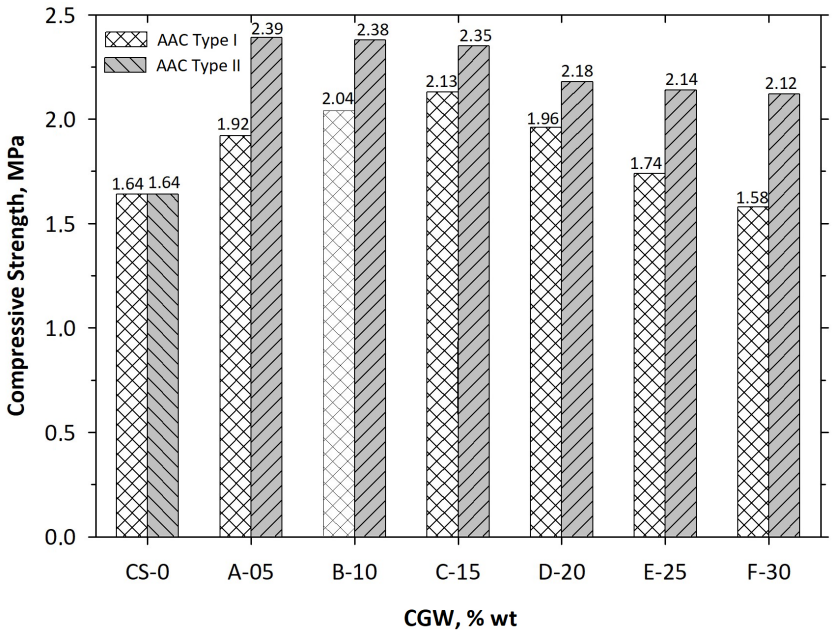


Fig. 4. The compressive strength of fresh AAC type I and II

The maximum value of compressive strength was 2.13 MPa at 15% wt of CGW or around 29.88% as shown in Table 4.

Table 4
The compressive strength of AAC type I and II

Samples	Compressive Strength, MPa		Compressive Strength, %	
	AAC Type I	AAC Type II	AAC Type I	AAC Type II
CS-0	1.64	1.64	-	-
A-5	1.92	2.39	17.07	45.73
B-10	2.04	2.38	24.39	45.12
C-15	2.13	2.35	29.88	43.29
D-20	1.96	2.18	19.51	32.93
E-25	1.74	2.14	6.10	30.49
F-30	1.58	2.12	-3.66	29.27

The increment in the compressive strength of samples may be due to the pozzolanic effect or reaction of ceramic waste which had a positive effect on the formation of crystalline phases such as tobermorite and C-S-H phase. The chemical reaction between reactive silica and portlandite formed during the cement hydration in the presence of water at ambient temperature was defined as pozzolanic reaction [29]. According to Zafar *et al.,* [30], the material containing a cumulative concentration of silica, alumina and iron of 87.41% (>70%) was categorized as pozzolanic material. The ceramics was a type of pozzolanic material [31]. The positive effects of pozzolanic on the compressive strength of AAC were also investigated [32]. Based on results, gypsum waste is also suspected to play a role in increasing the compressive strength of the sample. In addition, the sulphate carriers in the form of anhydrite or gypsum are added which provide both enough green stability during the production process and improved hardened properties, such as compressive strength and shrinkage [33]. The Sulphate carriers provide green stability by increasing the pH and increasing the SiO2 solubility, which result in faster CSH growth. Then, the sulphate regulates CSH recrystallization which was originally formed into tobermorite through the solution phase [34,35].

However, with the increment of CGW from 15% to 25% wt, the compressive strength slowly reduced from 2.13 MPa to 1.74 MPa, but the value is still higher than CS at 19.51% and 6.09% for 20% and 25 % wt of CGW, respectively. For more partial replacement of sand with CGW for 30% wt, the compressive strength of the sample has been very lower than CS at 3.65%. The derivation of compressive strength can be explained that the quantity of calcium hydroxide formed after cement hydration, which was the most expected insufficient, react with the high volume of silica and some silica stayed without reaction [36]. This is may be due to the increasing of CGW composition would lead to the increase in the Ca/Si which played a major role in the formation of hydration products such as tobermorite crystals phase. According to Kunchariyakun *et al.,* [37], the optimum range of Ca/Si ratio for the formation of tobermorite crystals lies between 0.8 and 1.0. Further studies are needed to evaluate precisely the effect of CGW on the tobermorite phase formation and Ca/Si ratios to get the correlation with compressive strength. In addition, the decrease of compressive strength can be attributed to the reduction of work density of AAC which compressive strength has a linear correlation with density.

Meanwhile, the compressive strength of AAC type II also increased with the increment of CGW addition, not more than 5% wt. The addition of CGW on the AAC enhanced the compressive strength of samples in the range of 29.27% to 45.73%. The maximum value of compressive strength was 2.39MPa for 5% wt in CGW addition. All of compressive strength of samples was also higher than CS. The results showed that the CGW was more effective in enhancing the compressive strength of AAC compare to previous studies [38,39]. Furthermore, the percentage increase in sample strength was also higher than AAC reinforced by dopamine-modified polyethylene terephthalate waste fibres [40] and bamboo cellulose nanofibers [41]. The increment of compressive strength may be due to the pozzolanic effect of ceramic waste which has a higher percentage of silica and alumina [42]. According to Li *et al.,* [43] and Rashid *et al.,* [44], a higher percentage of silica, alumina and calcium oxide are responsible to pozzolanic reactivity and cementitious property. The pozzolanic effect of material always support the formation of C-S-H and tobermorite as the major phase of AAC enhanced the compressive strength of samples [45]. In addition, the pozzolanic material can improve the long-term strength of Poland cement binder by pozzolanic reaction among Ca(OH)2 remaining from cement hydration [46]. The positive effect of pozzolanic material on the compressive strength of AAC and aerated concrete has also been investigated [47-49].

The gypsum waste is also suspected to play a role in increasing the compressive strength of sample. According to Hansen and Sadeghian in 2020 [50], a proper content of gypsum waste could enhance the strength of concrete. In addition, the gypsum also participated in the recrystallization process from C-S-H (I) to tobermorite [51].

With the increasing of CGW addition from 10% to 25% of sand weight, the compressive strength slowly reduced from 2.39 MPa to 2.14 MPa, but the value is still higher than CS, around 31.01%. The derivation of compressive strength can be explained that the quantity of calcium hydroxide formed after cement hydration, it was the most expected insufficient, react with the high volume of silica and some silica stayed without reaction.

3.3 Specific Strength of AAC Type I and II

Figure 5 shows the correlation between the specific strength with compressive strength and work density of AAC type I. However, with increasing of CGW from 0% to 15% wt, the specific strength has also increased from 2757.2 N.m/kg to 3514.0 N.m/kg and generally decreased linearly with increasing the ratio of CGW from 20% to 30% wt.

It could be seen the correlation between specific strength with compressive strength and work densities. The specific strength of AAC samples increase as the compressive strength's increment and decrease as the compressive strength decreased. Similar results about the correlation between specific strength with compressive strength and bulk density were also studied by Tang *et al.,* [52]. The maximum specific strength was 3514.0 N.m/kg for 15% wt of CGW. This work showed that CGW had a significant influence on the specific strength.

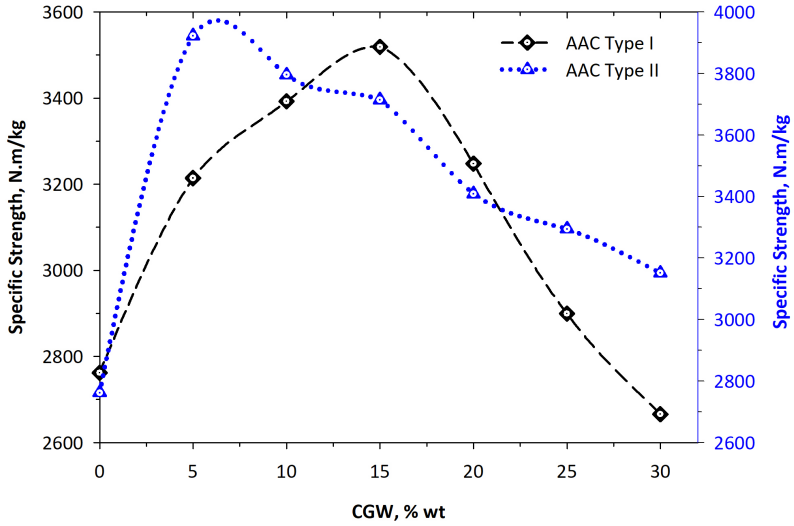


Fig. 5. The correlation between the specific strength with compressive strength and work density of AAC type I and II

Especially for AAC type II, by increasing of CGW addition from 0% to 5% wt, the specific strength has also increased from 2757.2 N.m/kg to 3918.58 N.m/kg and generally decreased linearly with increasing the percentage of CGW addition from 10% to 25% of the sand weight. It could be seen the correlation between specific strength and compressive strength. But the results do not show the linear correlation of specific strength and compressive strength with work density. The similar results about the inverse correlation between works densities with compressive strength were also studied by Peng *et al.,* [53] and also Shams *et al.,* [54]. The maximum specific strength was 3918.58 N.m/kg for 5% wt of CGW. This work showed that the CGW addition has a significant influence on the specific strength.

3.4 Sound Absorption Coefficient of AAC Type I and II

Figure 6 and Figure 7 shows the sound absorption coefficient (SAC) of fresh AAC type I and II. The SAC has been carried out in low frequency. The SAC was around 0.13 to 0.89 at frequency range of 100Hz to 500Hz. The SAC for CS was around 0.65 at a frequency of 500Hz. The SAC increased with increasing of the CGW ratio but not more than 15% wt in 500Hz frequency. The SAC of all samples were higher than the reference sample at a frequency of 500Hz. The highest SAC was showed for the AAC sample with CGW content of 15% wt i.e 0.89 at a frequency 500Hz.

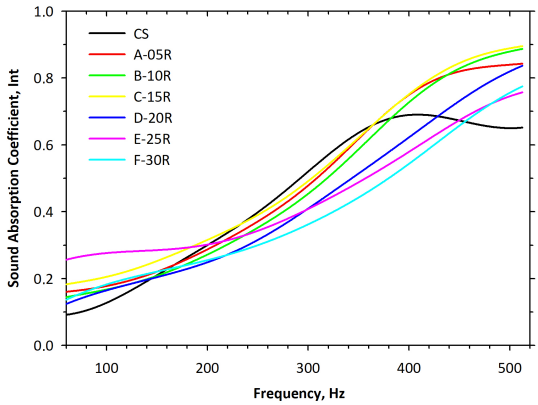


Fig. 6. The sound absorption coefficient of fresh AAC type I

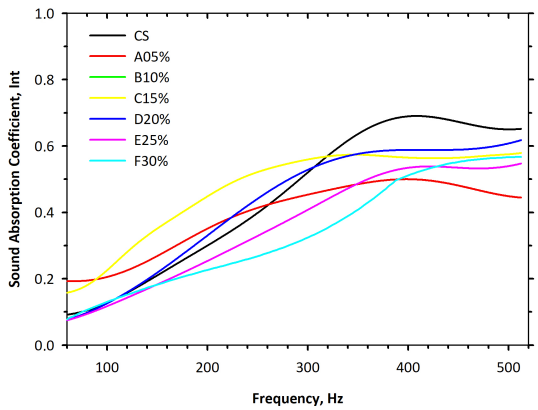


Fig. 7. The sound absorption coefficient of fresh AAC type II

According to BS EN ISO 11654:1997, the CS sample was categorized as a class C absorber as shown in Table 5 at a low frequency (500Hz). Meanwhile, AAC samples with CGW content of 5 to 20% wt were also categorized as class B absorbers. However, AAC with CGW content of 25% and 30% wt, the samples were categorized as a class C absorber at frequency 500Hz. According to BS EN ISO 11654:1997, a class C absorber refers to a material that absorbs more than 60% of sound while a class B absorber is able to absorb between 80% – 85 % of sound [55,56].

Table 5
The SAC of fresh AAC type I

Frequency, Hz	Sound absorption coefficient (SAC)						
	CS	A05R	B10R	C15R	D20R	E25R	F30R
100	0.13	0.18	0.17	0.21	0.16	0.28	0.18
125	0.17	0.20	0.19	0.23	0.19	0.28	0.20
160	0.23	0.23	0.22	0.26	0.21	0.29	0.23
200	0.30	0.29	0.27	0.32	0.25	0.30	0.26
250	0.40	0.37	0.35	0.39	0.32	0.34	0.30
315	0.56	0.52	0.49	0.53	0.44	0.43	0.39
400	0.69	0.75	0.73	0.75	0.62	0.58	0.54
500	0.65	0.84	0.88	0.89	0.82	0.75	0.76
Class absorber	C	B	B	B	B	C	C

Meanwhile, SAC of AAC-CGW type II was around 0.12 to 0.65 at 100 – 500Hz. The sound absorption coefficient increased with increasing of the CGW ratio from 5 to 20% wt in 500Hz frequency but still low then CS. The highest sound absorption coefficient was showed for the AAC sample without CGW content i.e 0.65 at a frequency 500Hz. The AAC samples with CGW content of 5% – 30% wt were categorized as class D absorbers.

Generally, it is clear from the result that the SAC of AAC has been affected by CGW contents but the negative effects. The result showed that the value of SAC decreased with increasing compressive strength. In general, AAC-CGW samples have still higher SAC at low frequency (500Hz) compared to previous studies [57-59].

4. Conclusions

Two types of AAC containing recycled CGW with different ratio (5%, 10%, 15%, 20%, 25% and 30% wt) have been prepared according to ASTM C1963-09 and the physical, mechanical and acoustic properties of samples have been investigated. All samples showed normal colour and free crack. Both

samples, the CGW succeeded in enhancing the compressive strength of AAC samples in the range of 6.10% to 29.88% for AAC type I and in the range of 29.27% to 45.73% for AAC type II. The AAC type II has the best value of compressive strength compared to AAC type I. However, the SAC of AAC type II were categorized as class D absorbers and did not suitable for partition walls application. Except for 25% and 30% wt of CGW, AAC type I was categorized as material class B and suitable for partition walls application. Our results show that CGW as partial replacement for sand has positive effect to enhance the strength and SAC of AAC samples. Meanwhile, CGW as additional material has also positive effect to AAC performance but only for the strength of samples. Furthermore, chemical properties such as phase formation, crystallite size, open and closed pore of AAC based on CGW are still in progress.

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