Jurnal Teknologi

Full paper

Effect of Silica Fume and Wood Ash Additions on Flexural and Splitting Tensile Strength of Lightweight Foamed Concrete

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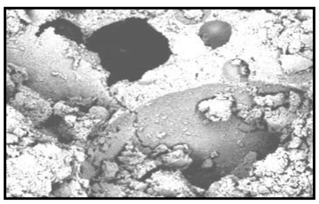
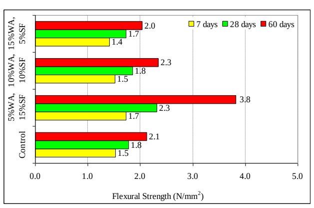
Article history

Received :7 November 2014
Received in revised form :
11 December 2014
Accepted :15 March 2015

Graphical abstract





Abstract

Reducing building material costs by identifying sustainable and green construction materials is desirable for economic reasons and environmental responsibility. This study examines ways to enhance strength of foamed concrete by adding wood ash (WA) and silica fume (SF). The effect of different percentage combinations is investigated, to understand the effect on the flexural and splitting tensile strengths. The supplementary binders replace a percentage by weight of the cement and are blended with foamed concrete. The WA–SF mixes at 5%–15%, 10%–10%, and 15%–5%, were compared to standard foamed concrete. The microstructures show evidence of novel densification and there was an improvement in the flexural and tensile strengths. The 5% WA–15% SF mix has the most significant effect on the foamed concrete compared to the control. The binder matrix also prolonged the setting time of the cement paste.

Keywords: Foamed concrete; sustainable; wood ash; silica fume; flexural; building material

Abstrak

Mengurangkan kos bahan mentah untuk bahan binaan dengan cara mengenal pasti bahan binaan yang lestari dan hijau adalah amat diperlukan bagi tujuan ekonomi dan kebertanggugjawaban alam sekitar. Kajian ini dijalankan untuk mengkaji kaedah untuk meningkatkan kekuatan konkrit ringan berbusa dengan kaedah menggunakan abu kayu (WA) dan wasap silica (SF) di dalam campuran konkrit ringan berbusa. Kesan penggunakan peratusan kombinasi abu kayu dan wasap silika yang berbeza telah dikaji bagi tujuan memahami kesannya ke atas kekuatan lenturan dan tengangan. Bahan pengikat tersebut (abu kayu dan wasap silika) menggantikan peratusan berat simen dan dicampur ke dalam campuran konkrit ringan berbusa. WA-SF bercampur pada kadar 5% -15%, 10% -10%, dan 15% -5%, dan dibandingkan dengan konkrit ringan berbusa kawalan (tanpa bahan tambah). Struktur mikrostuktur menunjukkan bukti densifikasi novel dan terdapat peningkatan dalam kekuatan lenturan dan tegangan. 5% WA dab 15% SF mempunyai kesan yang paling besar ke atas konkrit berbusa berbanding dengan kokrit ringan kawalan. Matriks pengikat juga telah melambatkan proses hidrasi simen.

Kata kunci: konkrit berbusa; kelestarian; abu kayu; wasap silika; lenturan, bahan binaan

1.0 INTRODUCTION

Recently, the Malaysian construction industry has shown remarkable interest in utilizing lightweight foamed concrete as a building material due to its numerous excellent characteristics such as lighter in total weight, easiness in fabricating process, durability and cost efficient thus providing flexibility for application such as for structural elements, partitions, insulating materials and filling grades [4, 5]. Foamed concrete has so far been applied primarily as a filler material in civil engineering works [6]. However, its good thermal and acoustic performance indicates its strong potential as a material in building construction [7]. Figure 1-3 show some examples of the utilization of lightweight foamed concrete in construction projects.

Foamed concrete is traditionally a cement-based matrix with a minimum 20% air volume. A multi-purpose material, it can be based on a range of dry densities, normally 500–1600 kg/m^3 , and 1–18 MPa compressive strengths [1]. It has a low aggregate content and self-weight, and high flow and thermal insulation properties [2]. Several studies have been carried out to identify new cement materials. This has included interest in the viability of wood ash and silica fume as supplementary binders [3]. No particular studies have been conducted in conjunction with foamed concrete [4]. Their ability to replace cement in standard concrete has been investigated [5].

Results showed that the high calcium wood ash and densified silica fume have good cementation properties [6]. Experimental WA–SF mortar mixes with 2–6% and 7.5% binder weights respectively, have shown to have compressive and flexural strengths at 2.4–31.2% higher than ordinary Portland cement mortar. The static and dynamic modulus of Portland cement mortar was shown to increase 1.9–24.7% by replacing some cement with 2–12% WA and 7.5% SF. Micrographs taken during this study showed notable microstructure densification of the cement paste matrix, which led to improvement in mechanical properties resulting from the use of the WA–SF binders [7].

Figure 1 Lightweight foamed concrete been poured in sections to prevent loss in density and reduce shrinkage problems in slabs for UEM building project in Kuala Lumpur, Malaysia

Figure 2 Lightweight foamed concrete insulation screed was utilized to offer thermal protection for a multi storey building in Mauritius

Figure 3 Utilization of lightweight foamed concrete as sewer fill in United Kingdom

2.0 MATERIALS

The Portland cement in the foamed concrete had a 1043.2 m^2/kg specific surface area, a specific gravity of 3.02, and a 3.9 μm median particle size. The fine aggregates used in the mortar mixes in this study were uncrushed and had a specific gravity of 2.83 and a maximum size of 5 mm. They were graded according to British Standard BS 812: Part 102 [8] and the fineness modulus measured 3.26. Table 1 shows the cement quality that was used in this study. Potable fresh water was used in the mixing and curing process and the water had no harmful oil, acid, alkaline, salt or sugar levels [9]

Table 1 Properties of cement

Item	Clinker %	Cement %
Oxide composition		
SiO_2	21.04	19.98
Al_2O_3	5.24	5.17
Fe_2O_3	3.41	3.27
CaO	63.31	63.17
MgO	0.85	0.79
SO_3	0.41	2.38
Total Alkalis	0.9	0.9
Insoluble residue	0	0.2
LOI	0.5	2.5
Modulus		
Lime saturation factor	0.93	0.96
Silica modulus	2.39	2.37
Iron modulus	1.9	1.58
Mineral composition (%)		
C_3S	55.4	59.9
C_2S	18.53	12.71
C_3A	8.59	8.18
C_4AF	10.36	9.94
Free CaO (lime)	1.9	0

The wood ash and silica fume binders were low-density and acted as surfactants. They were added directly into sand-rich, low cement content concrete to produce 15–25% air. The foamed concrete was produced in a generator and the raw foam had no significant density. Blending it 50% by volume to a 2200 kg/m^3 density mortar, produced 1100 kg/m^3 of foamed concrete.

Silica fume is ultrafine and consists of spherical particles measuring <1 μm in diameter, with an approximate average size of 0.15 μm. Its size is about 100 times smaller than average cement particles. The bulk density is 130–600 kg/m^3, depending on the degree of densification in the silo.

The composition of wood ash is affected by the combustion conditions. About 0.43–1.82% of burned wood will typically turn to ash. Less ash will result from burning wood at higher temperatures.

The protein based foaming agent was used (Noraite PA-1). This foaming agent was diluted in water with a ratio of 1:33 by water volume. The foam density needed to be between 75 to 80 g/L before being mixed with other materials. Flow ability times were also calculated as the time will be used as a reference to add the required amount of foam into the mix. The flow ability, known as flow rate, usually valued between 2.3 to 2.7 litres per second to achieve 75 to 80 g/L density of the foam depended on the foam machine used.

3.0 MIX PROPORTIONS & EXPERIMENTAL SETUP

Table 2 shows the mix proportions of 1350 kg/m^3 density foamed concrete. To determine the flexural strength, 500 mm × 100 mm × 100 mm prism specimens were prepared and tests were carried out at 7, 28 and 60 days. In addition, 300 ×100 mm cylinder specimens were prepared, to test the splitting strength at the same intervals [10]. Figure 4 shows the equipments (GOTECH) used for the flexural and splitting tensile strength tests. In addition, a scanning electron microscope (SEM) was used to observe the formation of foamed concrete microstructures. The observation from this microscope was best viewed using 4.0 magnifications. For samples preparation, it needed to be cut, shaped into a cube and dried before being viewed in the microscope. Scanning electron microscopy (SEM) was used to give a detailed view on each of the particles produced by the reaction of additives in the hydration process. A detailed view of each particle, with some other objects, can be seen clearly from many types of magnification.

Table 2 Mix proportion of mortar specimens

Mix	Cement (kg)	Wood Ash (%)	Silica Fume (%)	Fine Aggregates (kg)	w/c ratio
Control	54.2	-	-	81.3	0.45
5% WA, 15% SF	43.4	5	15	81.3	0.45
10% WA, 10% SF	43.4	10	10	81.3	0.45
15% WA, 5% SF	43.4	15	5	81.3	0.45

Figure 4 GOTECH equipments used for the flexural and splitting tensile strength tests

4.0 RESULTS AND DISCUSSION

Three samples with different WA–SF percentages by weight were combined in foamed concrete and compared to a control foamed concrete mortar. The results of the flexural strength tests carried out are shown in Figure 5. Similar trends in the compressive strength of foamed concrete with WA–SF mixes were observed. Testing at 7, 28, and 60 days of curing consistently showed that overall, the mixes resulted in better flexural strength and splitting tensile strength compared to the control. At day 7, the 5% WA–15% SF mix exhibited significantly higher flexural strength compared to all the other mortars. The flexural strength of the 10% WA–10% SF mix was identical to the control at 1.5 N/mm². However, the 15% WA–5% SF mix had the lowest flexural strength overall at 7 days curing. The reason for this could be a more dense cement paste matrix with higher bond strength with the aggregate. The presence of the silica fume may have caused more resistance to tensile rupture [11].

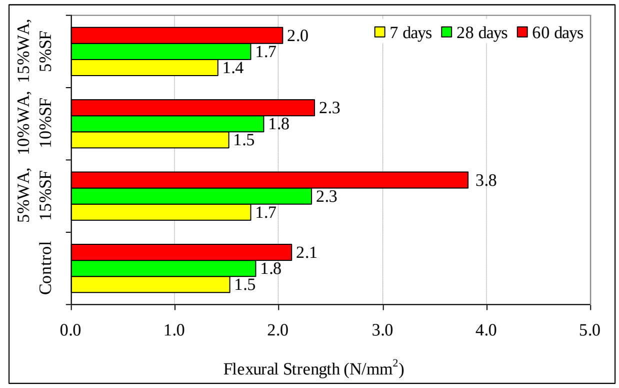


Figure 5 Flexural strength by mortar mix

Tests at day 28 showed that the highest flexural strength was in the 5% WA–15% SF foamed concrete, whilst the 10% WA–10% SF sample and the control, recorded the same result. However, once again the 15% WA–5% SF foamed concrete showed the lowest flexural strength. The findings showed the WA–SF binders enhance the flexural strength in the early stages (days 3 and 7) and at day 60 the 5% WA–15% SF cement replacement achieved significantly higher levels. The foamed concrete with 10% WA–10% SF recorded a higher strength than the control. The 15% WA–5% SF sample continued to display lower flexural strength compared to the control. Tests at day 60 showed the flexural strengths of the 5% WA–15% SF and 10% WA–10% SF foamed concretes were 37.8% and 4.4% higher respectively, than the control.

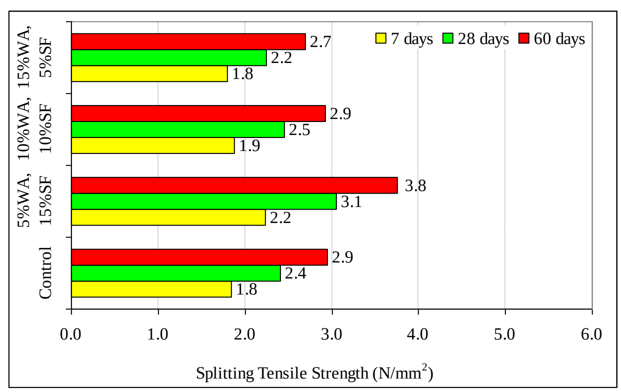
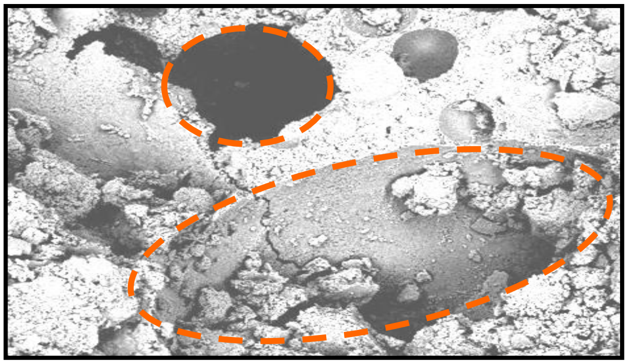
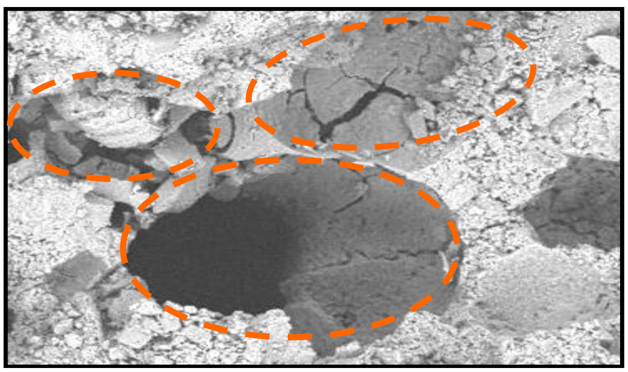


Figure 6 Splitting tensile strength by mortar mix

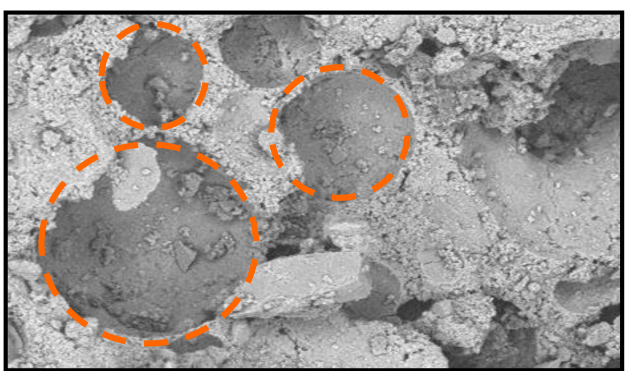
Turning to tensile strength, Figure 6 provides an overview of the measurements at days 7, 28, and 60. The 5% WA–15% SF foamed concrete at day 7 recorded the highest tensile strength of all the samples, the 10% WA–10% SF mix was lower, but still higher than the control. The tensile strength of the 5% WA–15% SF mix was significantly higher than all the other mortars. The lowest tensile strength were exhibited by the 15% WA 5% SF mix and the control. At day 28 the tensile strength of the 5% WA–15% SF foamed concrete continued to record a higher level compared to the remaining mortars. The tensile strength of the 10% WA–10% SF mix was lower, but still above the control. At day 60, the tensile strength of the 15% WA–5% SF mortar was the lowest, and the 5% WA–15% SF was the highest by a considerable margin. The results showed that the control and the 10% WA–10% SF mix recorded the same splitting tensile strengths. After prolonged curing for 60 days, the improvement in tensile strength of the 5% WA–15% SF foamed concrete was 20% higher compared to the control [12]. By replacing some cement with the WA–SF mix, stronger concrete resulted and the increase in overall tensile strength measured 3.9 N/mm² [13].



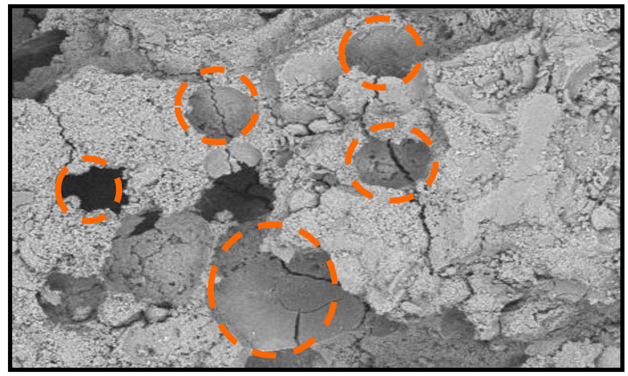
a) Control – Normal Foamed Concrete



(b) With 15% WA and 5% SF



(c) With 10% WA and 10% SF



(d) With 5% WA and 15% SF

Figure 4 Formation of pores in (a) control foamed concrete and (b-d) foamed concrete with different percentages of Wood Ash (WA) and Silica Fume (SF) at a density of 1350 kg/m^3

Figure 7 shows the comparison of the formation of pores in control sample (Figure 7a) and foamed concrete with different percentages of Wood Ash and Silica Fume (Figure 7b-7d) at a density of 1350 kg/m^3. It can be seen that the formation of pores in was extensively influenced by the amount of wood ash and silica fume placed into the foamed concrete mix. Indication of this comes from the formation of larger sized pores in the control lightweight foamed concrete mix as can be referred to Figure 7a [15]. On the other hand, the foamed concrete mixes with different percentages of wood ash and silica fume by replacing 20% of the cement quantity had reduced the size of pores and also the number of pores in each different mortar mix. The most effective foamed concrete was that with a composition of 5% wood ash and 15% silica fume as can be seen on Figure 7d. This happened owing to the nature of silica fume, which has great fineness and elevated silica content, whereas wood ash contains calcium carbonate as its main constituent.

■4.0 CONCLUSION

The experiments on mixing wood ash and silica fume in foamed concrete, has results in some conclusive findings. The most significant result is when concrete is substituted with a 5% WA–15% SF mix, as this proved to be the optimum percentage by weight. In general, there is enhancement in the flexural and splitting tensile strengths of foamed concrete when wood ash and silica fume are added, due to a higher pozzolanic reaction rate between the amorphous silica and the Portlandite mineral. Compared to standard concrete, smaller pores are formed and this alteration in the structure contributes to increased strength.

Acknowledgement

The authors would like to thank the funding bodies of this research: Universiti Sains Malaysia under USM Short Term Grant. No. 304/PPBGN/6312147.

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