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Development of a geopolymer made from bagasse ash for use as a cementitious material

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Abstract

This research aimed to improve the properties of geopolymer made from bagasse ash. Bagasse ash, directly collected from disposed landfills, was burnt and ground to a higher fineness. Both original and re-burned bagasse ash were used as source materials, which were mixed with an alkaline solution to influence the geopolymer properties. Ordinary Portland cement (OPC) was applied to replace the bagasse ash between 5-15% by weight of the binder, and two methods of curing were observed. It was found that the re-burned bagasse ash tended to exhibit better compressive strength compared to original ash, and was compatible with both curing methods. The geopolymer from original bagasse ash, only with heat curing at 75 ℃, exhibited useable compressive strength. The strength of geopolymer increased with an escalating amount of the OPC, whilst the workability was reduced. Geopolymer, which was made with OPC cured under moist conditions at room temperature, had an initial compressive strength that was lower than that with heat curing. However, this compressive strength was developed and became higher at a later age. From this study, the highest compressive strength of geopolymer produced from re-burned bagasse ash and blended with 15% of OPC was 49.9 Megapascal (MPa) at 90 days. In addition, geopolymer concrete displayed better abrasion resistance compared to the OPC concrete.

Keywords: Geopolymer, Bagasse ash, Cement, Waste materials, Compressive strength

1. Introduction

Geopolymer might conceivably be an alternative construction material in lieu of the concrete made from ordinary Portland cement (OPC). Geopolymer concrete could be produced from aluminosilicate material, which is used to replace OPC to improve concrete properties and enable enhanced cost-benefit. Well-known pozzolan, such as fly ash, rice husk ash, and bagasse ash (BA), is a waste or by-product from the agricultural processing and mill industries. These materials are mainly composed of silica and alumina, or only silica. The polymerization reaction occurs when mixing silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3) with an alkaline solution to get a good binder [1]. Most geopolymer concrete is produced from fly ash; various properties have been researched and reported [2]. Geopolymer concrete and fly ash are produced as commercial products and have begun to be used prevalently. Fly ash is used as a supplementary material, together with ordinary concrete and geopolymer concrete. Consequently, the value of fly ash has grown increasingly. In order to eliminate and make the maximum use of excessive waste products, the researchers in the current study focused on other pozzolanic materials that are of minimal value and widely available. This provides a chance to utilize by-product materials and reduce the cost-benefit of waste management.

In carrying out the research, the current study primarily aims at using BA, which has been considered an outgrowth from the sugar mill industry. Every year, more than a million tons is generated. Regarding BA properties, it has high silica content, while its alumina is generally low. However, it has uncertain characteristics and high loss on ignition (LOI) [3]. Due to its advantage, it has been further reported that BA can be used to partially replace cement in OPC concrete [4-6]. Even though BA has little effect on compressive strength, it contains other usable properties such as sulfate resistance, but also a reduced water penetration rate [7,8]. Additionally, BA is also introduced to make geopolymer concrete. The disadvantage of the polymerization reaction when using BA or other pozzolan materials, except fly ash, is that BA could gain high compressive strength providing that it is conducted at a curing high temperature for 1-2 days [9]. At this point, this is considered to be wasteful and difficult to apply for construction work.

The development of BA geopolymer should place focus on the ambient curing temperature and gaining satisfactory compressive strength. In this research, a small amount of OPC was applied to the BA geopolymer mortar mixture. The OPC will increase the higher compressive strength of geopolymer while generating heat during the hydration reaction [10,11]. This material is called hybrid geopolymer concrete. The results obtained from this study should be of use for cost-effectiveness and possibility, as well as providing some beneficial data for those who use BA geopolymer concrete in construction processes. In addition, the results could lead to the utilization of waste materials and reduced use of OPC, which in turn will help to protect the global environment.

2. Materials and methods

2.1 Materials

BA was collected from Mitr Phol Kuchinarai sugar mill factory, located in Kalasin Province in the northeast of Thailand. To start, BA was cleaned by removing impurities and then re-burning at 600 ℃ for 2 h. Original and re-burned BA was then ground by a ball mill until their particle sizes were retained on the sieve No.325 at less than 5%. OPC was used to replace the BA between 0-15% by weight of binder (B). 10 molars of sodium hydroxide (NH) and sodium silicate (NS) with 28.65% SiO_2, and 9.77% Na_2O_3 were used as the alkaline solution. Fine aggregate was river sand with a fineness modulus of 2.73.

2.2 Test methods

The mixture proportions of geopolymer mortar are shown in Table 1. The ratio of NH: NS was 1.0, while the ratio of alkaline solution to binder (AL/B) ratios was 0.55, and the sand to binder ratio was 2.75. The concentrate of NH was fixed at 10 molars. The mixing process was carried out by mixing the BA with NH, followed by sand, NS, and finally adding OPC to the mixture. In accordance with ASTM C1437, the workability of mixtures, in terms of flow testing [12], was observed. Two curing processes were performed and studied: the moist curing at room temperature and the heat curing in an oven. For the moist curing process, geopolymer samples were cast and placed in a controlled 25 ℃ room for 24 h as a delay time. Then, the samples were demolded and brought to store in a closed cabinet under moist conditions until the testing stage. For the heat curing process, geopolymer samples were placed in the same controlled room for 60 min after mixing. In the final step, samples were removed to cure in an electric oven at 75 ± 5 ℃ for 48 h. After that, the samples were demolded and stored at an ambient temperature until the testing stage.

For durability observation, the abrasion resistance of the sample was performed. The abrasion resistance of concrete and geopolymer concrete was maintained according to ASTM C1138 (Underwater method). Samples of 300 mm in diameter and 100 mm in thickness were cast and cured under moist conditions. At 28 days of curing, samples were taken to install in the chamber or abrasion apparatus, as shown in Figure 1. Then, 3 different sizes of 70 steel balls were placed on the concrete upper surface. Fresh water was filled in the chamber up to the specified level and stirred with a blade at 1200 ± 100 r/min for 12 h. This procedure was repeated 2 times. The abrasion of concrete was calculated from the weight loss of the samples.

Figure 1 (A) Abrasion resistance apparatus (B) Sample of abrasion resistance testing.

Table 1 Mix proportion of geopolymer mortar (kg/m^3).

No.	Mixture	OBA	RBA	OPC	NH	NS	Fine aggregate
1	O00	700	-	-	192.5	192.5	1925
2	O05	665	-	35	192.5	192.5	1925
3	O10	630	-	70	192.5	192.5	1925
4	O15	595	-	105	192.5	192.5	1925
5	R00	-	700	-	192.5	192.5	1925
6	R05	-	665	35	192.5	192.5	1925
7	R10	-	630	70	192.5	192.5	1925
8	R15	-	595	105	192.5	192.5	1925

O = OBA (Original bagasse ash), R = RBA (Re-burned bagasse ash), OPC = Ordinary Portland cement, NH = Sodium Hydroxide, NS = Sodium Silicate, 00, 05, 10 and 15 = Replacement of OPC at 0, 5, 10 and 15% by weight

3. Results and discussion

3.1 Characterization of raw materials

For the chemical composition of bagasse ash in Table 2, the original bagasse ash (OBA) consists of SiO_2 60.7% Fe_2O_3 21.6% compared to the re-burned bagasse ash (RBA) with SiO_2 66.9% Fe_2O_3 14.8%. It was found that the repeated burning of bagasse ash resulted in a slight change of oxide content. The amount of SiO_2 was modestly higher, while the content of Fe_2O_3 was reduced, and LOI was lower. The combination of SiO_2+Al_2O_3 + Fe_2O_3 of OBA and RBA was 82.3% and 81.7%, respectively. The content of the main oxide in bagasse ash exceeded 70%. Therefore, it could be classified in class N pozzolan, as described by ASTM C618 [13].

Table 2 The chemical compositions of original bagasse ash (OBA) and re-burned bagasse ash (RBA).

Materials	Chemical composition (%)								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	TiO_2	MnO_2	Other	LOI
OBA	60.7	-	21.6	6.0	7.1	1.5	1.7	1.4	13.2
RBA	66.9	-	14.8	6.2	7.3	1.6	1.7	1.5	6.4

Table 3 shows the physical properties of OBA and RBA. The specific surface area of materials was measured by Blaine air-permeability fineness testing. The original bagasse ash (OBA) and re-burned bagasse ash (RBA) were ground until the particles retained on sieve No. 325 were less than 5%, and the specific surface area was 9,000 and 12,000 cm^2/g, respectively. It was found that the specific surface areas of OBA and RBA were much higher than that of the OPC (the standard OPC = 3,500-3,600 cm^2/g), while the average median particle size of all materials had the same range of 12.1-14.6 µm. This was because the particles of OBA and RBA were spongy and rough on the surface, as seen in Figure 2. This phenomenon was likely to increase the water requirement of the mixture and tended to reduce workability.

Table 3 Results of testing the basic properties of materials.

Materials	Specific gravity	Specific surface area (cm^2/g)	Retained on No.325 (%)	d50 (µm)
OBA	2.34	9,000	4.0	12.3
RBA	2.52	12,000	2.0	9.1

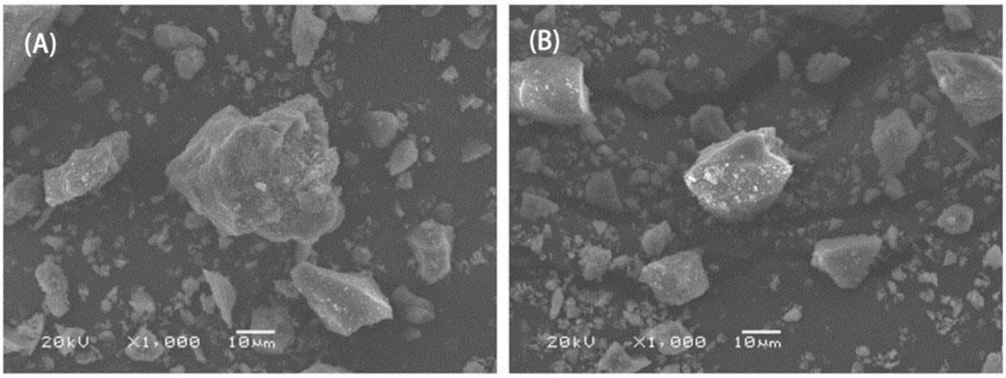

Figure 2 Morphology of (A) Original bagasse ash (OBA) and (B) Re-burned bagasse ash (RBA).

3.2 Workability

The workability was investigated by using a flow table in conformity with ASTM C1437. Figure 3 shows the percentage of the flow of geopolymer mortar which was made from OBA or RBA. These two bagasse ashes had the same trend of workability in both the increase and decrease of the OPC mixture. This resulted from the hydration reaction between cement and water. It has long been known that the least water to cement ratio (w/c) between 0.18-0.20 [14,15] is required to complete the hydration reaction. The amount of water will be drawn from the alkaline solution accordingly. While mixing the mixture, the RBA geopolymer was found to have more fluid than the OBA mixture. When adding no cement, the flow of RBA with none of the OPC mixture (R00) was 27%, while the mixture of OBA (O00) was 23%. The RBA had more fineness than the OBA, which needed additional water or had a lower percentage of flow; the opposite result was noticed. This is possibly because the re-burned bagasse ash reduced in the loss on ignition (LOI); it demanded less water, a trend to increasing workability [16,17].

3.3 Compressive strength

The compressive strength testing of bagasse ash geopolymer mortar in congruence with ASTM C109 [18] is shown in Table 4, Figure 4, and Figure 5. The strength development trend of the samples was similar to ordinary concrete, which increased with age. The maximum compressive strength was obtained from re-burned bagasse ash by replacing it with Portland cement of 15% (R15) and performing wet curing at 49.9 MPa for 90 days. There were 2 mixtures with compressive strength at an early age that was unobserved because the geopolymer mortar setting was not properly completed. As seen in Table 4, O00 and R00 were geopolymer mixtures produced from both bagasse ashes without cement content and had to cure in a moist condition. The compressive strength testing could be carried out since the age of the sample was 28 days. Consequently, the strength of both mixtures for O00 and R00 was developed to 15.1 and 15.6 MPa at 90 days, respectively.

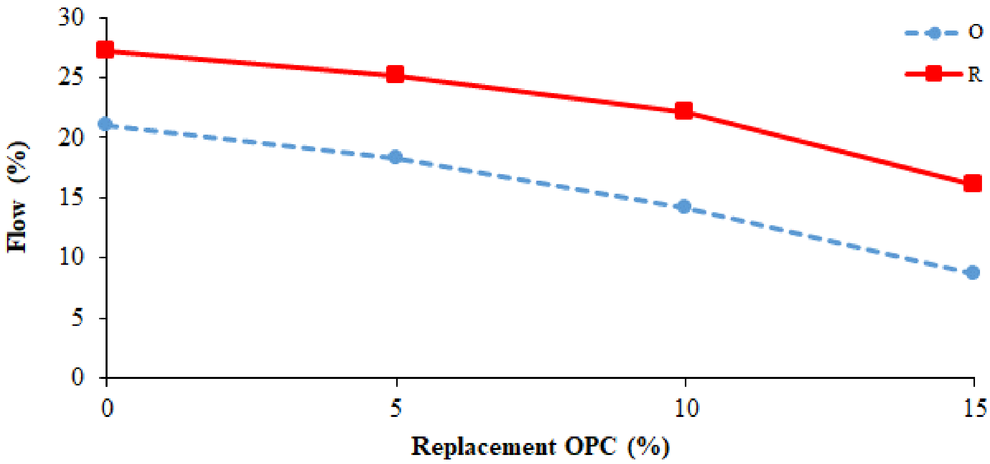

Figure 3 The flow of geopolymer mortar made with O (OBA) and R (RBA).

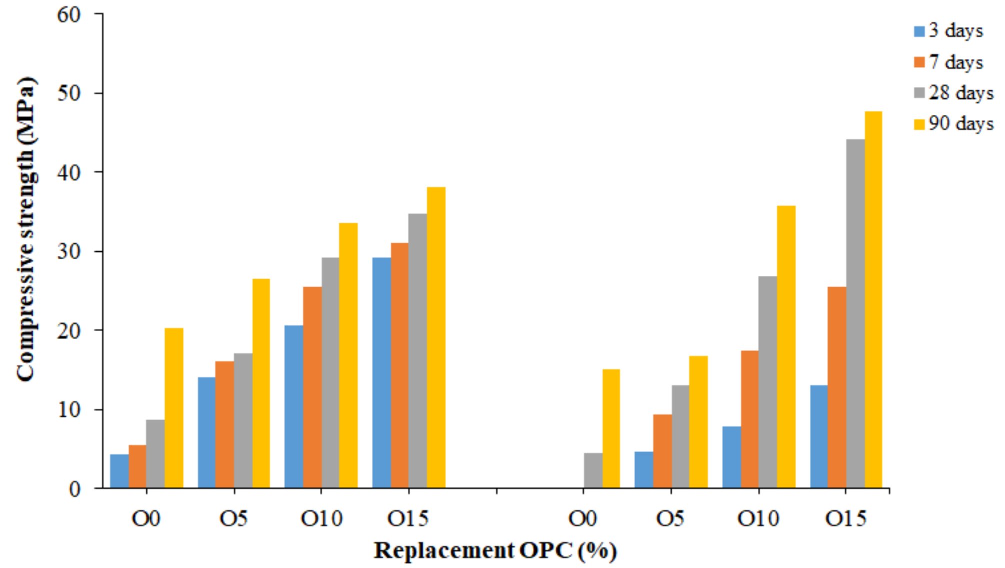

Figure 4 The compressive strength of geopolymer mortar made with original bagasse ash (OBA). O00-O15 = original BA with Replacement OPC 0.15%.

3.3.1 Effects of Portland cement replacement

The results from Figure 4 and Figure 5 show that adding OPC increased the compressive strength of hybrid geopolymer [19]. In this regard, the increase of compressive strength should be from two effects. First, it is derived from the hydration reaction of the cement system. Therefore, some water in the mixture was drawn to use for the cement hydrate. The water was from the solution in the geopolymer system. For the second effect, increasing the concentration of an alkaline solution brought about a higher compressive strength in the geopolymer [20]. The SiO_2 and $Ca(OH)_2$ continued to react in the later stage and resulted in higher compressive strength. A similar result was also found in fly ash geopolymer concrete [21]. The rate of compressive strength increase was directly proportional to the increase of cement content. Observed at 28 days, most of the OPC or the pure bagasse ash geopolymer generated a low level of compressive strength. There was merely the R00 mixture, which was cured with heating that obtained approximately 18.8 MPa. This was suitable to use as lean concrete. When applying the amount of OPC at 5%, the R05 mixture gained the compressive strength of 22.3 and 24.4 MPa for heat curing and moist curing. This compressive strength had the same level as normal concrete for simple-structure construction, as found in 1-2 story buildings.

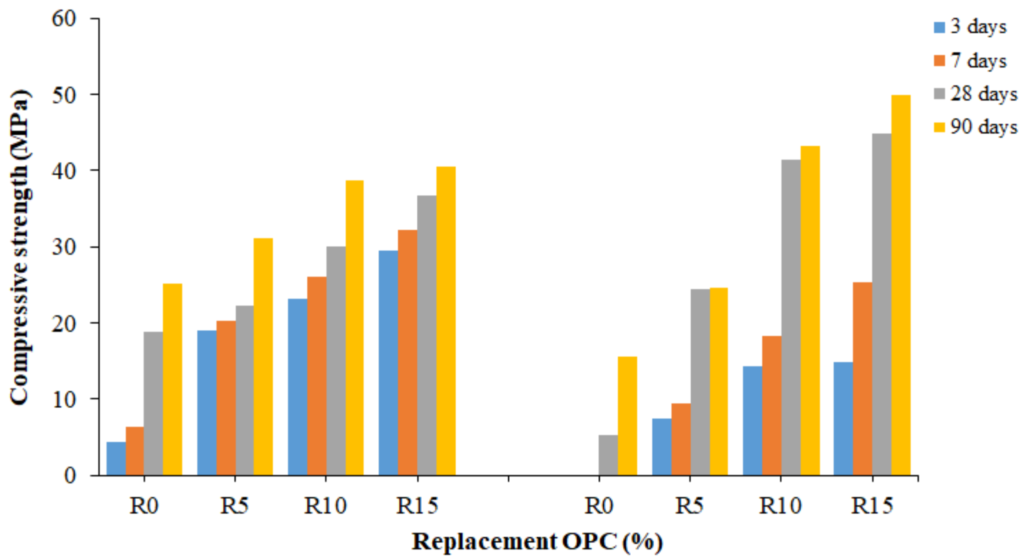

Figure 5 The compressive strength of geopolymer mortar made with re-burned bagasse ash (RBA). R00-R15 = Re-burned BA with Replacement OPC 0.15%.

Table 4 The compressive strength of geopolymer mortar.

Curing process	Mixture	Compressive strength (MPa)			
		3 days	7 days	28 days	90 days
Heat curing	O-00	4.3	5.5	8.7	20.2
	O-05	14.0	16.0	17.0	26.4
	O-10	20.6	25.5	29.2	33.5
	O-15	29.2	31.0	34.7	38.1
	R-00	4.4	6.3	18.8	25.1
	R-05	19.0	20.2	22.3	31.2
	R-10	23.1	26.1	30.0	38.8
	R-15	29.5	32.2	36.8	40.5
Moist curing	O-00	0	0	4.4	15.1
	O-05	4.6	9.4	13.0	16.8
	O-10	7.8	17.4	26.8	35.7
	O-15	13.1	25.4	44.2	47.7
	R-00	0	0	5.3	15.6
	R-05	7.4	9.5	24.4	24.6
	R-10	14.4	18.3	41.4	43.2
	R-15	14.8	25.4	44.9	49.9

O = Original bagasse ash, R = Re-burned bagasse ash, 00, 05, 10, 15 = Percentage of replacement level by OPC

The original bagasse ash geopolymer began to provide usable strength when the OPC was replaced at 10%. The 28-day compressive strength of the O10 mixture exhibited 29.2 and 26.8 MPa from both curing methods. The geopolymer made with re-burned bagasse ash and 15% of OPC gave the maximum strength of 49.9 MPa at 90 days. The geopolymer with this level of compressive strength could be classified as similar to high-strength concrete [22]. It was seen that general concrete (OPC concrete) with this strength needed approximately 450-550 kg of OPC in the mixture for a cubic meter of concrete. As shown in Table 1, the amount of OPC in the R-15 geopolymer mixture was 105 kg, which was about 20% of the usage amount in general concrete. The results of this research could be a starting point for the production of hybrid geopolymer concrete from bagasse ash.

3.3.2 Effects of re-burned bagasse ash

The 90-day compressive strength of geopolymer mortar made from original and re-burned bagasse ash is shown in Figure 6. It was revealed that the re-burned bagasse ash had higher compressive strength than the original bagasse ash for all mixtures and in both curing methods [23]. The compressive strength of re-burned geopolymers was about 1.03-1.46 times that of the original bagasse ash. This means that the re-incineration of bagasse ash assists the strength of geopolymer. Two properties of RBA improved better than the OBA, namely the fineness of particles and the percentage of LOI [24]. The fineness, in terms of the specific area of OBA and RBA, was 9000 and 12000 cm^2/g, respectively. The alkaline solution was able to reach the silicon oxide and alumina oxide from the high fineness particles more easily than the coarser particle [25]. A similar result was echoed when fly ash or other pozzolanic materials was applied to replace OPC in ordinary concrete mixtures [26]. The use of higher fineness pozzolan resulted in increased compressive strength.

The LOI percentages of OBA and RBA were 13.2 and 6.4, respectively. Repeated burning at 600 ℃ turned the color of bagasse ash from black to gray within a few minutes. The second burning eliminated moisture and other elements (e.g., carbon remains in the ash from the first combustion). It is widely known that carbon is an element that dampens or reduces the compressive strength of concrete [17,27]. A similar result is resonated when replacing the bagasse ash in OPC concrete [28]. However, the level of LOI of re-burned bagasse ash is relatively high, which might be because the compressive strength becomes higher due to the use of bagasse ash with lower LOI. It is notable that grinding by ball mill of the re-burned bagasse ash will make the particle size reduction retain on sieve No.325 (less than 5%) more easily and faster than the original bagasse ash.

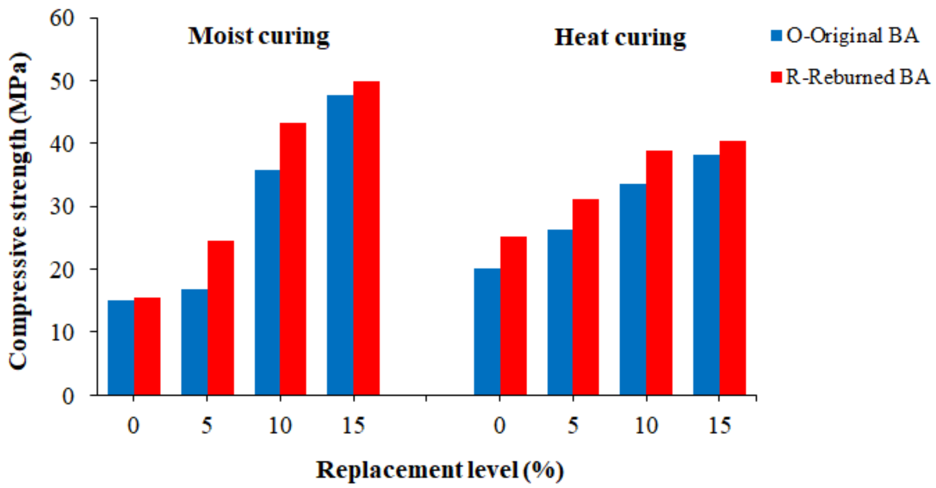

Figure 6 The 90-day compressive strength ratio of the re-burning ash versus original ash. OPC0-OPC15 = Replacement level OPC 0.15%.

3.3.3 Effects of curing method

The effect of the curing method can be analyzed from Table 4 and Figure 7. It is revealed that both OBA and RBA geopolymer with none of the cement content (O00 and R00 mixture) could not develop the compressive strength with curing under moist conditions within 7 days. Although their compressive strength was developed, it was only 4.4 and 5.3 MPa at 28 days. On the other hand, the strength of both mixtures with heating curing at the same age was 8.7 and 18.8 MPa, respectively. It was noted that the pure bagasse ash geopolymer was probably suitable for heat curing to gain usable compressive strength.

When the cement was applied to the bagasse ash geopolymer, curing with water or moist conditions started to gain compressive strength. However, it was much lower than curing with heat at an early age (3 and 7 days). The compressive strength of both curing methods was similar when the age of the sample was 28 days. The trend of strength development appeared to be close to ordinary concrete. This was owing to the hydration reaction of cement in the mixture. When the heat curing of hybrid geopolymer gained high compressive strength at the initial age, the rate of strength increase then became slow at a later stage.

Figure 7 shows the 90-day compressive strength of OBA and RBA geopolymer with various cement replacement levels, which involved curing by two methods. Intriguingly, the sample with moist curing tended to develop higher compressive strength than the one with heat curing at 90 days. This phenomenon occurred with the replacement of OPC at 10 and 15% for both OBA and RBA geopolymer. Because the additional amount of cement would lead to more reactions of hydration, a further amount of water was required as well. The same result was also found in geopolymer made from fly ash and partially replaced by cement [29].

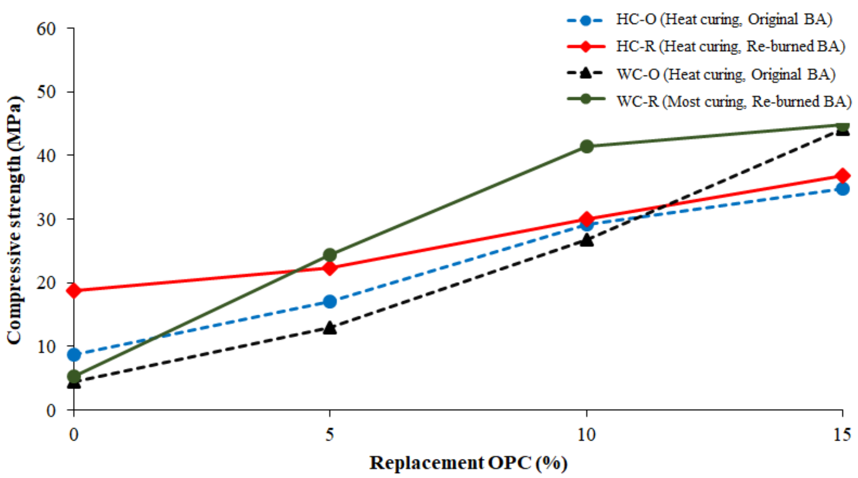

Figure 7 Compressive strength of bagasse ash geopolymer at 90 days. OPC0-OPC15 = Replacement level of OPC 0.15%

3.4 Abrasion resistance

The durability property was investigated in terms of abrasion resistance. Table 5 shows the weight loss and average depth of abrasion (ADA) at the end of the test increment at 12 and 24 h, which was calculated by following ASTM C1138. The ADA of OPC concrete, O00 and O05 bagasse ash geopolymer concrete are also shown in Figures 7 (A) (B), and (C), respectively. The OPC concrete had an ADA value of 0.92 mm at the end of the first interval of testing or 12 h, and the depth of abrasion increased to 2.23 mm at 24 h. The ADA values of O00 and O05 bagasse ash geopolymer concrete were 0.40 and 0.37 mm at 12 h, respectively, and they were 1.10 and 0.82 mm at the end of testing. The results show that the abrasion resistance of bagasse ash geopolymer concrete was better than the OPC concrete, although the surface of the bagasse ash geopolymer concrete sample had more holes or pores than that of conventional concrete samples. Similar results were also found in geopolymer concrete made from low calcium fly ash [30].

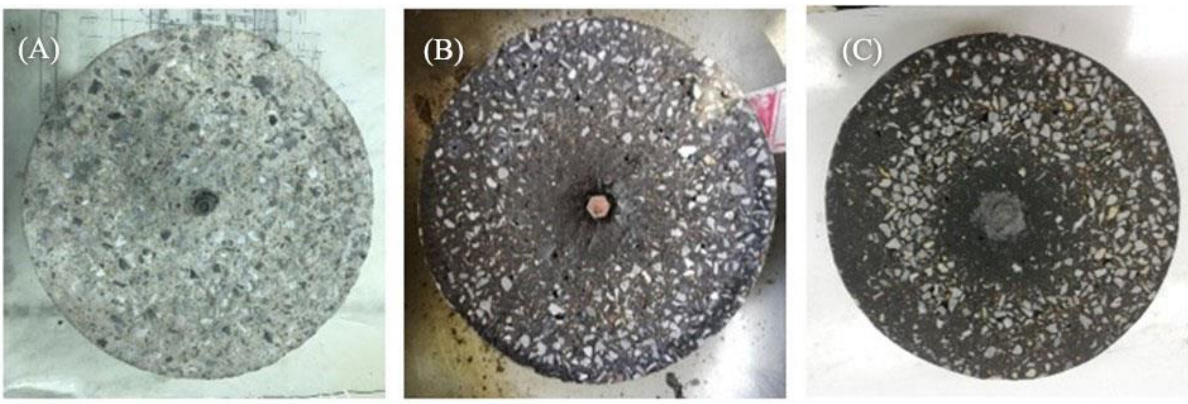

Figure 8 Abrasion specimens after testing, (A) OPC concrete, (B) O00 bagasse geopolymer concrete, (C) O05 bagasse geopolymer concrete.

Table 5 Test results of abrasion resistance.

Material	Initial weight in (kg)		Time (h)	Final weight in (kg)		ADA at time (mm)
	Air	Water		Air	Water	
OPC	15.18	8.43	12	15.11	8.42	0.92
			24	14.90	8.30	2.23
O00	16.52	9.53	12	16.45	9.50	0.40
			24	16.34	9.43	1.10
O05	16.67	9.64	12	16.60	9.60	0.37
			24	16.53	9.56	0.82

OPC = Ordinary Portland cement, O00 = Original bagasse ash with OPC 0%, O05 = Original bagasse ash replacement OPC 5%

4. Conclusion

Based on the information gained by the current study, it was found that the workability of geopolymer depended on the amount of OPC in the mixture, which decreased when increasing the percentage of OPC. The use of re-burned bagasse ash has a vital role in enhancing workability of geopolymer than original bagasse ash. In such a case, the replacement of bagasse ash by OPC directly governed the strength of bagasse ash geopolymer. The amount of cement in bagasse ash geopolymer was about 20% of conventional concrete mixture, which yielded the same level of compressive strength. It was possible to produce high-strength geopolymer concrete from bagasse ash with 15% of OPC. In addition, the improvement of bagasse ash by re-burning reduced the percentage of LOI, resulting in increasing the compressive strength of geopolymer. Furthermore, moist curing was suitable for bagasse ash geopolymer to be blended with cement and the compressive strength; it was higher than heat curing at a later stage. Nevertheless, heat curing enables higher compressive strength from the early stage of curing and is suitable for all mixtures of bagasse ash geopolymer. In addition, the geopolymer concrete revealed better abrasion resistance compared to the OPC concrete.

5. Acknowledgements

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