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Effect of ground fly ash and ground bagasse ash on the durability of recycled aggregate concrete

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ABSTRACT

This research aims to study the effect of ground fly ash (GFA) and ground bagasse ash (GBA) on the durability of recycled aggregate concrete. Recycled aggregate concrete was produced with recycled aggregate to fully replace crushed limestone in the mix proportion of conventional concrete (CON) and GFA and GBA were used to partially replace Portland cement type I at the rate of 20%, 35%, and 50% by weight of binder. Compressive strength, water permeability, chloride penetration depth, and expansion by sulfate attack on concretes were investigated.

The results reveal that the use of GFA and GBA to partially replace cement in recycled aggregate concrete was highly effective in improving the durability of recycled aggregate concrete. The suitable replacement of GFA or GBA in recycled aggregate concrete to obtain the suitable compressive strength, low water permeability, high chloride penetration resistance, and high sulfate resistance is 20% by weight of binder.

1. Introduction

Recycled aggregate is used as coarse aggregate in concrete production in order to conserve the original aggregate sources, reduce waste from demolition, and reduce disposal landfills. Although, recovery waste from demolition is beneficial to the environment, it is important to study the properties of recycled aggregates before using them as coarse aggregate in concrete.

Recycled aggregates have been found to have low density, low specific gravity, high water absorption, and high porosity [1–3]. The mortar attached to the original aggregate results in lower density, higher water absorption, and higher porosity than those of natural aggregate [4–7]. Many researchers [1,8–11] have found that use of recycled aggregate to partially and fully replace natural aggregate in concrete not only decreases the density, compressive strength, and modulus of elasticity of the concrete but also decreases the durability of concrete, including chloride resistance [12,13].

The properties of recycled aggregate concrete could be improved by mixing methods, such as the double mixing method and the two-stage mix approach method [14–16]. Both methods have similar concepts, dividing mixing water into two parts in order to improve the interfacial zone around recycled aggregate by filling up some pores and cracks of cement slurry leading to denser recycled aggregate concrete and enhancing the strength and durability of the concrete. Use of pozzolanic materials has been found to improve strength and durability of recycled aggregate concrete. For instance, the compressive strength of recycled aggregate concrete could be improved by using ground fly ash and ground rice-husk bark ash [10,11]. Additionally, use of fly ash, ground granulated blast furnace slag, and metakaolin to partially replace cement could increase chloride penetration resistance of recycled aggregate concrete [13,17,18].

However, the use of fly ash to improve the strength and durability of the recycled aggregate concrete is discussed in only few reports and studies on the use of bagasse ash in recycled aggregate concrete can be rarely found. Therefore, this research aimed to use ground fly ash and ground bagasse ash as pozzolanic materials to improve the durability of recycled aggregate concrete, i.e., water permeability, chloride penetration resistance, and expansion due to sulfate attack.

2. Materials and experimental program

2.1. Cement Portland type I

Ordinary Portland cement type I (OPC) was used to cast all concretes in this study. Table 1 shows the physical properties of cementitious materials. OPC had specific gravity and median particle size (d_{50}) of 3.14 and 14.7 μm, respectively. Chemical compositions of OPC are shown in Table 2.

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Table 1
Physical properties of cementitious materials.

Cementitious materials	Specific gravity	Retained on a 45-μm sieve (%)	Median particle size, d_{50} (μm)
OPC	3.14	–	14.7
OFA	2.34	48.6	28.6
GFA	2.42	0.58	4.5
OBA	1.89	66.85	–
GBA	2.27	0.42	5.6

Table 2
Chemical composition and strength activity index of cementitious materials.

Chemical composition (%)	Type I cement	GFA	GBA
Silicon dioxide (SiO_2)	20.9	45.5	59.9
Aluminum oxide (Al_2O_3)	4.8	16.8	4.7
Ferric oxide (Fe_2O_3)	3.4	6.0	3.1
Calcium oxide (CaO)	65.4	20.9	10.5
Magnesium oxide (MgO)	1.3	1.2	1.3
Phosphorous oxide (P_2O_5)	–	0.3	0.91
Sulfur trioxide (SO_3)	2.7	4.0	0.04
Loss on ignition (LOI)	1	5.3	19.6
Strength activity index at 7 days (%)	–	100.9	87.4
Strength activity index at 28 days (%)	–	113.6	112.7

2.2. Ground fly ash

Original fly ash (OFA) is fluidized bed fly ash collected from a power plant in Prachinburi province in Thailand and its physical properties are shown in Table 1. The original fly ash had specific gravity of 2.34, particles retained on a 45-μm sieve of 48.6% by weight, and median particle size (d_{50}) of 28.6 μm. The percentage of particles retained on the 45-μm sieve was higher than that required by ASTM C 618, a maximum of 34% by weight. Therefore, the original fly ash was not suitable for using in concrete. Thus, it was ground to increase particle fineness. After grinding, ground fly ash (GFA) had the percentage of particles retained on a 45-μm sieve (No. 325) of 0.58% by weight, specific gravity of 2.42, and median particle size (d_{50}) of 4.5 μm.

The chemical compositions and strength activity index are shown in Table 2. GFA can be designated as class C fly ash according to ASTM C 618 because it had the total percentage of SiO_2 + Al_2O_3 + Fe_2O_3 of 68.3%. Moreover, it had SO_3 of 4.0%, LOI of 5.3%, and strength activity indices of 100.9% and 113.6% at 7 and 28 days, respectively.

2.3. Ground bagasse ash

Original bagasse ash (OBA), collected from the sugar industry in Lopburi province in Thailand, was ground to have high fineness. Before grinding, the percentage of particles retained on a 45-μm sieve (No. 325) was 66.85% while the limitation of ASTM C 618 for pozzolanic material is not exceeded 34%. After grinding, ground bagasse ash (GBA) had particles retained on a 45-μm sieve (No. 325) of 0.42% by weight, specific gravity of 2.27, and median particle size (d_{50}) of 5.6 μm. GBA had the total percentage of SiO_2 + Al_2O_3 + Fe_2O_3 of 67.7%, SO_3 of 0.04%, and the loss on ignition (LOI) of 19.6%. Use of ground bagasse ash with high LOI (20.36%) which was higher than the limitation of ASTM C 618 (10%) to partially replace cement resulted in increasing the setting time of paste [19]. However, the strength activity indices at 7 and 28 days of GBA in this research were 87.4% and 112.7%, respectively, which are higher than the requirement of ASTM C 618 which is 75% at 7 days or 28 days and the results of Chusilp et al. [20] confirmed that the use of GBA with high LOI (up to 20% by weight) slightly affected the compressive strength of mortar after the age of 28 days. Physical properties and chemical compositions and strength activity index of GBA are shown in Tables 1 and 2, respectively.

2.4. Natural fine and coarse aggregates

Natural fine aggregate was local river sand which had fineness modulus of 3.07, specific gravity of 2.62, water absorption of 0.91%, and dry-rodded weight of 1725 kg/m^3.

Natural coarse aggregate was crushed limestone. It had a maximum size of 19 mm, fineness modulus of 6.89, specific gravity of 2.73, water absorption of 0.45%, dry-rodded weight of 1650 kg/m^3, and Los Angeles abrasion loss of 23%.

2.5. Recycled aggregate

Recycled aggregate used in this study was obtained by crushing 150 × 300 mm concrete cylinder samples after being tested for compressive strength (25–40 MPa). These concrete cylinder samples were sent to the concrete laboratory in the Department of Civil Engineering, King Mongkut's University of Technology Thonburi by the construction companies in Thailand to determine the compressive strength. After crushing by swing hammer, it had the maximum size of 19 mm, fineness modulus of 6.47, and the specific gravity of 2.49. Moreover, dry-rodded weight, water absorption, and Los Angeles abrasion loss were 1480 kg/m^3, 4.81%, and 37%, respectively. The water absorption and the Los Angeles abrasion of the recycled coarse aggregate were higher than those of the crushed limestone while its specific gravity was lower than that of crushed limestone. Since the recycled aggregate used in this study was not scalped to remove attached mortar before using, it contained attached mortar higher than that of the commercial recycled aggregate, resulting in higher water absorption, greater weakness and higher porosity compared to the natural aggregate (crushed limestone) [6,21].

2.6. Mix proportions and mixing

The mixture proportion of conventional concrete (concrete mixed with natural fine and coarse aggregates), recycled aggregate concretes (*R*), and recycled aggregate concretes using GFA and GBA to replace cement at rates of 20%, 35%, and 50% by weight of binder (F20, F35, and F50 and B20, B35, and B50, respectively) are summarized in Table 4.

The compressive strength of CON concrete obtained by the ACI method was approximately 30 MPa at 28 days. For recycled aggregate concrete, the recycled aggregate was used to fully replace crushed limestone in the mix proportion of CON concrete. This study used the two-stage mixing approach (TSMA) method recommended by Tam et al. [15] for mixing the recycled aggregate concretes as well as the conventional concrete. This method could reduce the porosity of recycled aggregate by providing cement or binder gel to fill in the crack and void on recycled aggregate, resulting in denser recycled aggregate concrete. The slump of all

Table 3
Physical properties of aggregates.

Properties	River sand	Crushed limestone	Recycled coarse aggregate
Fineness modulus	3.07	6.89	6.47
Bulk specific gravity (SSD)	2.62	2.73	2.49
Absorption (%)	0.91	0.45	4.81
Dry-rodded weight (kg/m^3)	1725	1650	1480
Void (%)	33.9	39.3	40.4
Los Angeles abrasion (%)	–	23	37
Moisture content (%)	0.27	0.20	0.85

Table 4
Concrete mix proportions.

Mix	Mix proportion (kg/m^3)										W/B	Slump (mm)
	Cement	GFA	GBA	Crushed limestone[a]	RCA[b]	Sand	SP[c]	Absorp. water	Mixing water	Eff. water		
CON	295	–	–	1036	–	809	–	12	200	192	0.65	80
R	295	–	–	–	953	772	–	52	234	192	0.65	90
F20	236	59	–	–	946	765	–	52	234	192	0.65	75
F35	192	103	–	–	938	762	0.3	52	234	192	0.65	70
F50	147.5	147.5	–	–	934	756	0.6	51	233	192	0.65	90
B20	236	–	59	–	944	763	0.4	52	234	192	0.65	75
B35	192	–	103	–	934	759	0.9	52	233	192	0.65	75
B50	147.5	–	147.5	–	928	751	1.8	51	233	192	0.65	70

[a] Crushed limestone in the air dry state.
[b] Recycled coarse aggregate in air dry state.
[c] Superplasticizer was assumed to have water 50% by weight.

concretes was controlled between 50 and 100 mm by varying the amount of superplasticizer.

2.7. Compressive strength

The compressive strength was investigated at 7, 28, 90, and 180 days by using concrete cylinder of 100-mm in diameter and 200-mm in height as the samples for testing.

2.8. Water permeability

The water permeability of concretes was determined at the ages of 28 and 90 days. To prepare a concrete specimen, a 100 × 200 mm cylindrical concrete was cut at the top and bottom of concrete to obtain a 100 mm diameter and 80 mm length. The concrete was cut again at mid-height to obtain two pieces of concrete having 100-mm diameter and 40-mm length. The 25 mm thick non-shrinkage epoxy resin was cast around the perimeter of the 100 × 40 mm cylindrical concrete sample approximately 24 h before testing to prevent water leakage during testing. A water pressure (P) of 0.5 MPa or 5 bars recommended by the concrete society [22] was used in this study. The water permeability was determined and calculated by Eq. (1) which was used by many researchers [23–27].

$$K = \frac{\rho LgQ}{PA} \tag{1}$$

where K is the water permeability coefficient (m/s), ρ is the density of water (kg/m^3), g is the acceleration due to gravity (m/s^2), Q is the flow rate (m^3/s), L is the length of concrete sample (m), P is the absolute water pressure (kg m/m^2/s^2), A is the cross sectional area of concrete sample (m^2)

2.9. Chloride penetration depth

The concrete samples for the chloride penetration test were obtained by cutting a 100 × 200 mm cylindrical concrete at mid-height after curing in water for 28 days. Around the perimeter, the concrete sample surface was coated by the non-shrinkage epoxy resin in order to control chloride ion penetration into the concrete along one dimension. The chloride penetration depth was tested using a procedure similar to the description in RTA T362 [28], except for the dimension of concrete specimen. The concrete samples were immersed in 3% sodium chloride solution for periods of 6, 12, and 18 months.

After being immersed in sodium chloride solution for a specified period, the concrete samples were split into two pieces and then sprayed with 0.1 N silver nitrate ($AgNO_3$) solution as a suitable concentration for measurement of chloride penetration of the low and normal strength concretes [29,30]. This concentration was also used for testing chloride penetration depth by many researchers [30–32]. The chloride penetration depth was measured and the average value was obtained from five measurements after the white color of AgCl appeared on concrete at the depth where free chloride could penetrate.

2.10. Expansion due to sulfate attack

The prism of 75-mm square cross-section and 285 mm in length was used as concrete samples to study expansion due to sulfate attack. After casting for 24 h, the concrete samples were removed from the molds and separated into two groups. The first group was immersed in 5% of sodium sulfate solution. The second was immersed in 5% of magnesium sulfate solution. The percentage of expansion was investigated by using length change comparator to measure the length of concrete for up to 24 months. The percentage of concrete expansion due to sulfate attack was calculated according to ASTM C 490.

3. Results and discussion

3.1. Compressive strength

Fig. 1 shows the compressive strengths of concretes. The results show that R concrete had compressive strength lower than that of CON concrete at the same tested ages. For instance, at 28 days, R concrete had compressive strength of 24.8 MPa or 81.6% of CON concrete which was 30.4 MPa. When the age increased up to 180 days, the compressive strength of R concrete was 36.4 MPa or 89.5% of CON concrete. The low compressive strength of R concrete was similar to the results reported by many researchers who used recycled aggregate to fully replace natural coarse aggregate to produce concrete [3,10,18,33]. This is due to the attached cement

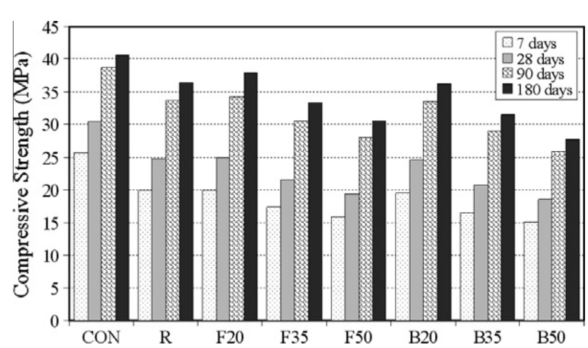

Fig. 1. Compressive strength of concretes.

mortar in the recycled aggregate had higher porosity and was weaker than the crushed limestone [34] (see its abrasion loss value in Table 3).

When GFA and GBA were used to partially replace cement in recycled aggregate concrete, the results of the compressive strength show a similar trend. The compressive strengths for both recycled aggregate concretes using GFA and GBA were lower than that of CON concrete, especially at early age. Although reduction in the quantity of cement caused reduction in compressive strength and use of recycled aggregate causes further reduction in compressive strength, the use of GFA and GBA to partially replace cement in recycled aggregate concrete at 20% by weight of binder could improve the compressive strength of recycled aggregate concrete at 28 days to be as high as that of *R* concrete. Calcium silicate hydrate from the pozzolanic reaction between GFA or GBA and calcium hydroxide filled in the voids of concrete and produced the compressive strength. In addition, the products could reduce the average pore diameter and pore size distribution in the concrete, resulting in a denser recycled aggregate concrete [35].

Moreover, it was found that use of GFA and GBA to replace cement at the rate of 35% and 50% by weight of binder could not develop compressive strength of recycled aggregate concrete to be as high as recycled aggregate concrete that does not use any GFA or GBA (*R* concrete) and to be much lower than that of CON concrete. Use of the high volume of the ashes to replace cement resulted in low cement content in concrete leading to the low compressive strength and low quantity of $Ca(OH)_2$ from the hydration reaction of concrete. Thus, the quantity of $Ca(OH)_2$ was not enough for the pozzolanic reaction [36] resulting in much lower compressive strength of recycled aggregate concrete with 35% and 50% of GFA and GBA.

Although the compressive strength of recycled aggregate concrete with GFA and GBA at 20% by weight of binder was lower than that of CON concrete by approximately 10%, it was as high as the compressive strength of recycled aggregate concrete without GFA and GBA.

3.2. Water permeability

Relationship between water permeability coefficient and replacement of GFA or GBA is shown in Fig. 2. *R* concrete had the water permeability coefficient at 28 and 90 days higher than that of CON concrete. The water permeability coefficient of *R* concretes at 28 and 90 days were approximately 80×10^{-13} and 21×10^{-13} m/s, respectively, while those of CON concrete were approximately 16×10^{-13} and 9×10^{-13} m/s, respectively. This is due to the higher porosity in recycled aggregate compared to crushed limestone [37].

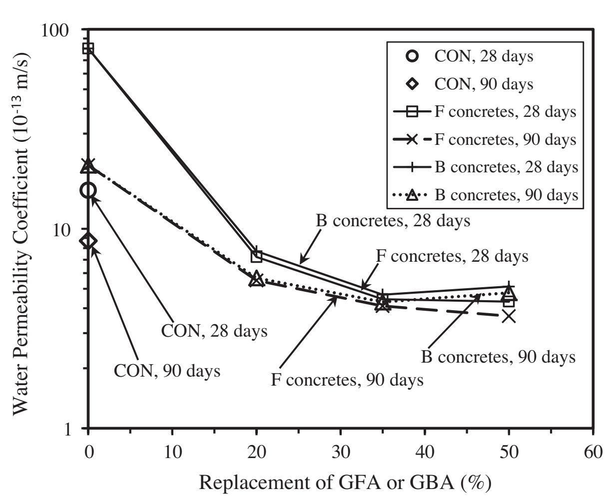

Fig. 2. Relationship between water permeability coefficient and replacement of GFA or GBA.

When GFA and GBA were used to partially replace cement in recycled aggregate concrete, the water permeability coefficient of the recycled aggregate concrete were greatly reduced and lower than that of CON concrete at the same age. However, the water permeability of recycled aggregate concrete containing GFA or GBA tended to increase when the replacement increased up to 50% by weight of binder. Although the increasing of curing time could help to reduce the water permeability coefficient of recycled aggregate concrete, the use of GFA and GBA had more effect on the reduction of water permeability coefficient of recycled aggregate concrete.

The high reduction of water permeability coefficient of recycled aggregate concrete occurred when GFA and GBA were used to partially replace cement because fine particles of GFA and GBA filled the voids in the concrete matrix resulting in a denser recycled aggregate concrete. This is similar to results of other researchers who used fine pozzolanic materials in concrete [25,26].

Therefore, to obtain recycled aggregate concrete with the low water permeability coefficient, the use of GFA and GBA to partially replace cement is recommended. The suitable replacement ratio of GFA and GBA in recycled aggregate concrete to obtain the low water permeability coefficient and high compressive strength is 20% by weight of binder.

3.3. Chloride penetration depth

Fig. 3 shows the results of chloride penetration depths of concretes immersed in 3% sodium chloride solution at 6, 12, and 18 months. Chloride penetration depths of CON concrete at 6, 12, and 18 months were 32, 52, and 60 mm, respectively while those of *R* concrete were 45, 70, and 75 mm, respectively. The results indicated that the chloride penetration depth of *R* concrete was higher than that of CON concrete, similar to what has been reported by other studies [13,18]. The use of recycled aggregate as coarse aggregate to fully replace crushed limestone contributed to increase in porosity and cracks in recycled aggregate causing chloride ions to penetrate easier into *R* concrete [37,38].

The chloride penetration depths of F20, F35, and F50 concretes at 6-month immersed time were 18, 15, and 14 mm, respectively. When the immersed time increased up to 18 months, the chloride penetration depths of F20, F35, and F50 concretes were 33, 19, and 16 mm, respectively. These results indicated that the use of GFA to partially replace cement could significantly improve the resistance of chloride penetration of recycled aggregate concrete to be better than that of CON and *R* concretes.

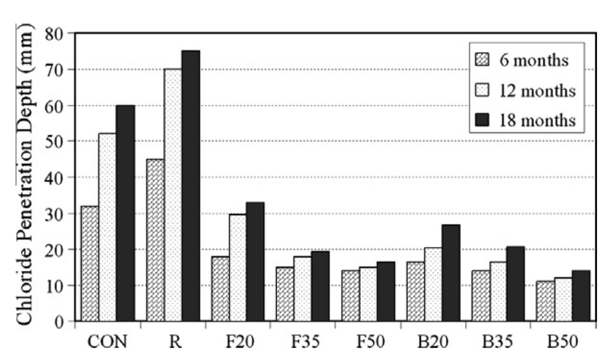

Fig. 3. Chloride penetration depth of concrete immersed in 3% sodium chloride solution at 6, 12, and 18 months.

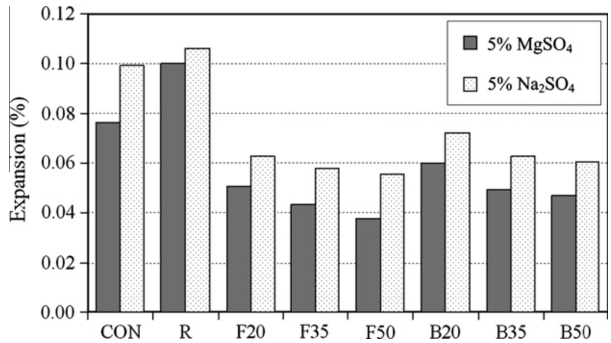

Fig. 4. Expansion of concretes immersed in 5% magnesium sulfate solution and in 5% sodium sulfate solution at 24 months.

The results of chloride penetration depth of the recycled aggregate concretes containing GBA were similar to those of the recycled aggregate concrete containing GFA. Chloride penetration depths of all of the recycled aggregate concretes highly decreased and were lower than those of CON and *R* concretes when GBA was used to partially replace cement and was similar to the result obtained by Ganesan et al. [39]. For example, the depths of chloride penetration of B20, B35, and B50 concretes at 12-month immersed time were 20, 16, and 12 mm, respectively. Thus, the use of GBA or GFA to increase the chloride resistance of recycled aggregate concrete was effective.

The above results obviously show that both GFA and GBA are good pozzolanic materials for increasing the chloride penetration resistance of recycled aggregate concrete. The fine particles of GFA and GBA not only reduced the porosity and average pore size of the paste [35] but also filled up the voids and cracks in the recycled aggregate. Moreover, chloride ions were also blocked to penetrate into the concretes by calcium silicate hydrate (CSH) obtained from the hydration and pozzolanic reactions [40].

Although the chloride resistance of recycled aggregate concrete increased with increasing the replacement of GFA and GBA, the compressive strength of recycled aggregate concrete decreased. Therefore, the suitable percentage of the replacement of GFA and GBA to obtain adequate compressive strength and adequate chloride resistance was 20% by weight of binder.

3.4. Expansion due to sulfate attack

Fig. 4 shows the results of the expansion of concretes immersed in 5% $MgSO_4$ and in 5% Na_2SO_4 solutions at 24 months. The expansions of CON concretes in 5% $MgSO_4$ and in 5% Na_2SO_4 solutions were 0.076% and 0.099%, respectively. The results suggested that CON concrete was more expansive in 5% Na_2SO_4 solution than in 5% $MgSO_4$ solution and this result was similar to the expansion behavior of Portland cement mortars immersed in sodium and magnesium solutions observed by Santhanam et al. [41].

The highest expansion in sulfate solutions occurred in *R* concrete. The expansions of *R* concrete in 5% $MgSO_4$ and in 5% Na_2SO_4 solutions were 0.100% and 0.106%, respectively. The voids and cracks in recycled aggregate made it easier for the sulfate ions to penetrate into the recycled aggregate concrete and react with the hydration products to form gypsum and ettringite which are expansive in nature resulting in higher expansion.

When GFA was used to partially replace cement in recycled aggregate concrete, the expansions of the F20, F35, and F50 concretes immersed in 5% $MgSO_4$ solution were 0.051%, 0.043%, and 0.038%, respectively, while the expansions of F20, F35, and F50 concretes immersed in 5% Na_2SO_4 solution were 0.063%, 0.058%, and 0.056%, respectively.

In the same manner, the expansion of recycled aggregate concrete containing GBA immersed in 5% $MgSO_4$ and in 5% Na_2SO_4 was lower than that of CON concrete. For instance, the expansions of B20, B35, and B50 concretes immersed in 5% Na_2SO_4 were 0.072%, 0.063%, and 0.060%, respectively.

The results indicated that the use of GFA and GBA to replace cement could decrease the expansion of recycled aggregate concrete in the sulfate solutions to be lower than that of CON concretes. The use of GFA and GBA to partially replace cement could reduce tricalcium aluminate (C_3A) and calcium hydroxide ($Ca(OH)_2$) which could react with sulfate to form gypsum and ettringite [42,43]. Moreover, the fine particles of GFA and GBA could improve recycled aggregate concrete to be denser resulting in less sulfate ion penetration into the recycled aggregate concrete. This was confirmed in previous sections by the results of water permeability and chloride penetration depth of recycled aggregate concrete with GFA and GBA.

Although the use of 35% and 50% of GFA and GBA by weight of binder in recycled aggregate concrete reduced expansion due to sulfate attack, the specimens still showed significant surface damage. This is due to low compressive strength of the concrete and the surfaces of concretes using 35% and 50% of GFA or GBA were subjected to a high level of sulfate ions which could react with calcium aluminate hydrate and calcium hydroxide in the matrix resulting in gypsum and ettringite formations. This caused expansion and internal stresses, which weakened and destroyed the bonding of paste, especially in concretes immersed in 5% $MgSO_4$. Finally, the concrete surface swelled, cracked, and spalled, especially that of recycled aggregate concretes containing 50% of GFA and GBA. The surface damage and cracks of concrete samples are shown in Figs. 5 and 6.

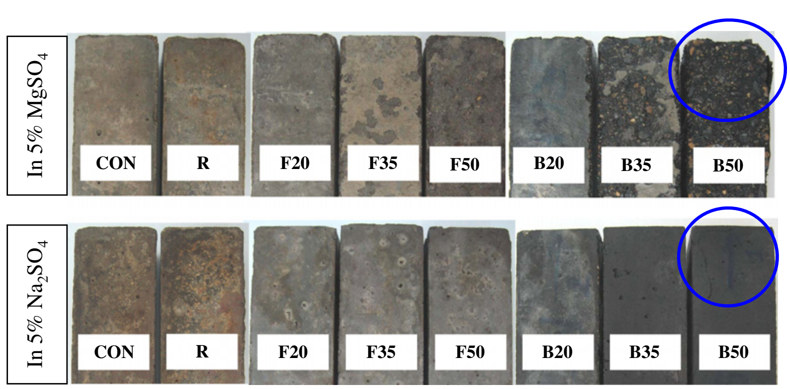

Fig. 5. Concrete samples after immersing in 5% magnesium sulfate solution and in 5% sodium sulfate solution for 24 months.

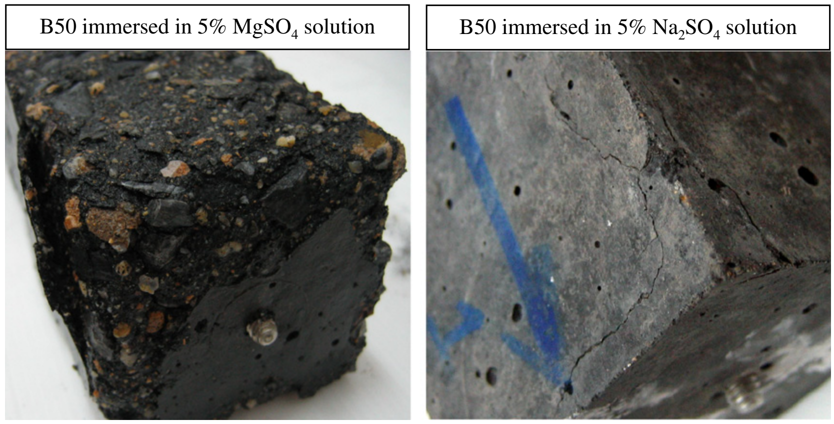

Fig. 6. The damage of B50 concrete immersed in 5% $MgSO_4$ and 5% Na_2SO_4 solutions for 24 months.

Use of both GFA and GBA to partially replace cement in recycled aggregate concrete was effective in reducing the expansion due to sulfate attack, but it should not be used at more than 20% by weight of binder to avoid the damage at the surface of the concrete.

4. Conclusions

Based on the experimental results, it can be concluded that:

1. Use of both ground fly ash (GFA) and ground bagasse ash (GBA) to partially replace cement at 20% by weight of binder in recycled aggregate concrete results in compressive strength similar to that of recycled aggregate concrete without GFA and GBA which is lower than that of conventional concrete (CON) by approximately 10%.
2. Both GFA and GBA could reduce the water permeability of recycled aggregate concrete to be lower than that of CON concrete although the compressive strengths of recycled aggregate concretes with both ashes were lower than that of CON concrete.
3. GFA and GBA have high potential to be used as pozzolanic materials to improve the chloride penetration resistance of recycled aggregate concrete to be higher than that of CON concrete. Moreover, the chloride penetration resistance of recycled aggregate concrete increased with increasing replacement percentage of GFA and GBA.
4. The expansion of recycled aggregate concrete by sulfate attack could be reduced to be lower than that of CON concrete by using GFA and GBA to partially replace cement; however the use of GFA and GBA in high volume resulted in damage to the surface of the concrete, especially the use of GBA at 35% and 50% in 5% $MgSO_4$ solution.
5. The optimum replacement of cement by GFA or GBA in recycled aggregate concrete to obtain high compressive strength, low water permeability, high chloride penetration resistance, and high sulfate resistance is 20% by weight of binder.

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