CHAPTER 4 RESULTS AND DISCUSSION

This chapter consists of results and discussion of physical and chemical properties of materials, compressive strength, modulus of elasticity, water permeability, chloride resistance, and expansion due to sulfate attack of concretes.

4.1 Physical Properties of Materials

Physical properties of materials in this research consist of particle morphologies, specific gravity, percentage of particle retained on a sieve No. 325, median particle size, and particle size distribution.

The particle morphologies of Portland cement type I (OPC) are shown in Figure 4.1. It was found that the cement particles had irregular and angular shape. Its specific gravity and median particle size (d_{50}) were 3.14 and 14.7 micron, respectively as shown in Table 4.1.

Fly ash from the fluidized bed combustion is different from that obtained from pulverized coal combustion due to the different combustion processes involved. The irregular shape and rough surface of both original fluidized bed fly ash (OFA) and ground fluidized bed fly ash (GFA) are shown in Figures 4.2(a) and (b). GFA has specific gravity of 2.42, particles retained on a 45-μm sieve of 0.58% by weight, and median particle size (d_{50}) is 4.5 micron (as shown in Table 4.1). Moreover, GFA has strength activity index at 7 and 28 days of 100.9 and 113.6%, respectively as shown in Table 4.2. With the above results, GFA is suitable to be used as a pozzolanic material.

Original bagasse ash (OBA) and ground bagasse ash (GBA) particle morphologies are shown in Figures 4.3(a) and (b), respectively. OBA had large particle, irregular shape, rough surface, and high porosity. Ground bagasse ash (GBA) still had irregular shape and rough surface but it had smaller particles and lower porosity than those of OBA. GBA had specific gravity of 2.27, amount of retained particles on a 45-μm sieve of 0.42% by weight, median particle size (d_{50}) of 5.6 micron, and the strength activity indices at 7 and 28 days of 87.4 and 112.7%, respectively (see in Tables 4.1 and 4.2). The particle size distributions of GFA and GBA are shown in Figure 4.4.

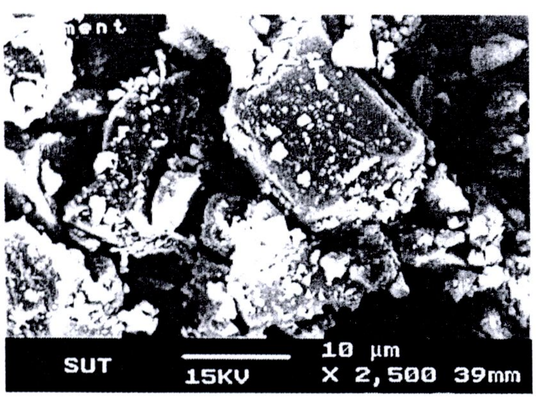
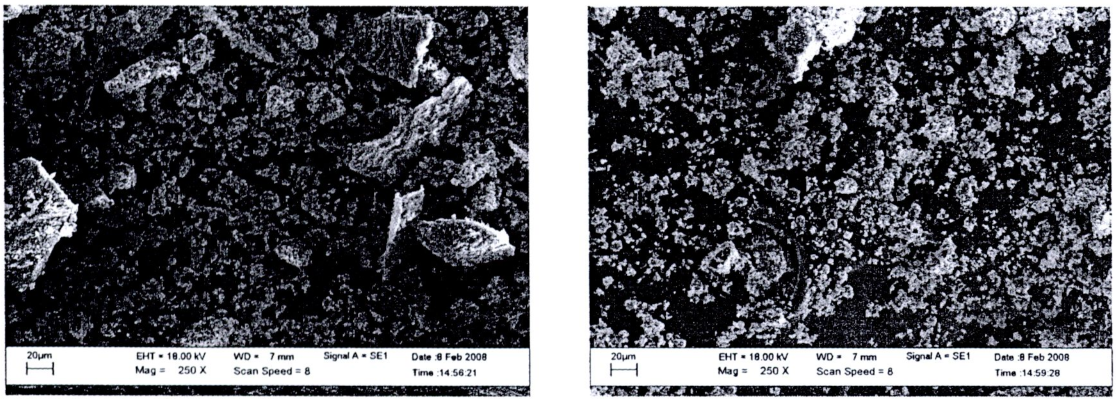
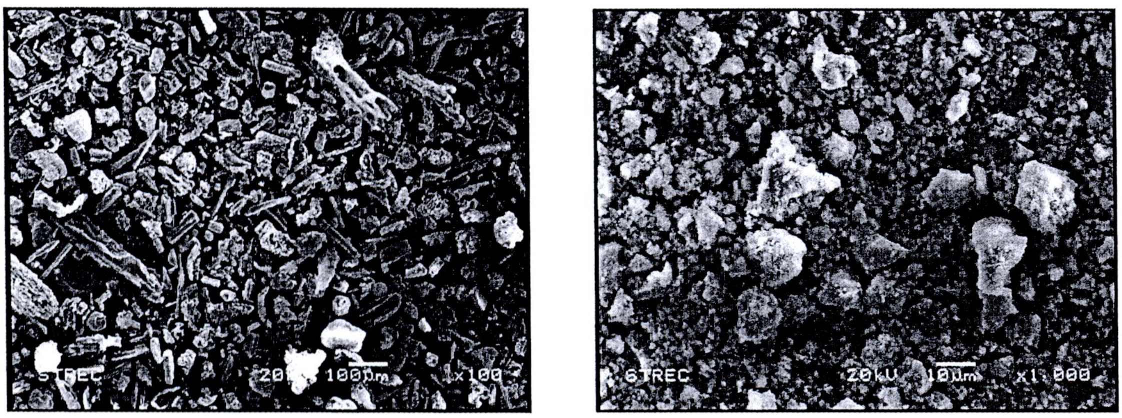


Figure 4.1 Particle morphology of Portland cement type I



a) Original Fluidized Bed Fly Ash b) Ground Fluidized Bed Fly Ash

Figure 4.2 Particle morphologies of original and ground fluidized bed fly ashes



a) Original Bagasse Ash (OBA) b) Ground Bagasse Ash (GBA)

Figure 4.3 Particle morphologies of original and ground bagasse ashes

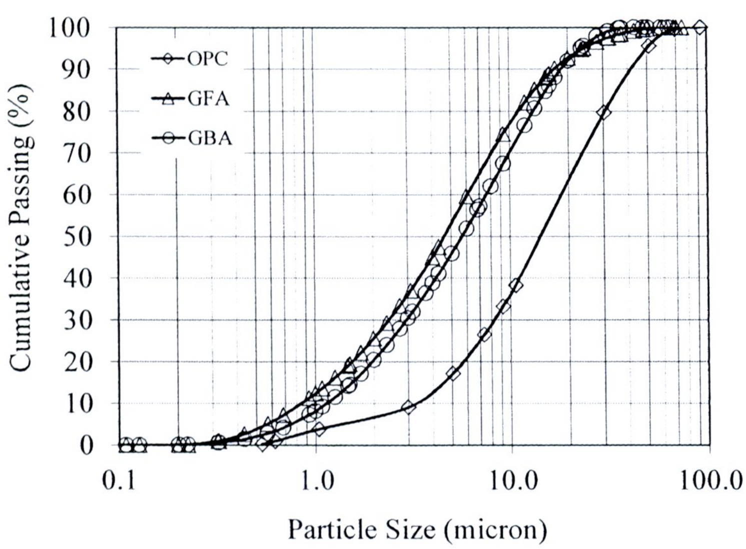


Figure 4.4 Particle size distributions of materials

Table 4.1 Physical properties of materials

Materials	Specific Gravity	Retained on a 45-μm Sieve (%)	Median Particle Size, d_{50} (micron)
OPC	3.14	-	14.7
GFA	2.42	0.58	4.5
GBA	2.27	0.42	5.6

4.2 Chemical Compositions

Table 4.2 shows the chemical compositions of Portland cement type I, ground fluidized bed fly ash, and ground bagasse ash. Portland cement type I had CaO which was the major chemical composition of 65.4%. Moreover, it had MgO, SO_3, and LOI of 1.3, 2.7, and 1%, respectively, which were not higher than those specified by ASTM C 150 (2001) of 6, 3.5, and 3%, respectively.

Table 4.2 Chemical compositions of Portland cement type I, ground fluidized bed fly ash, and ground bagasse ash

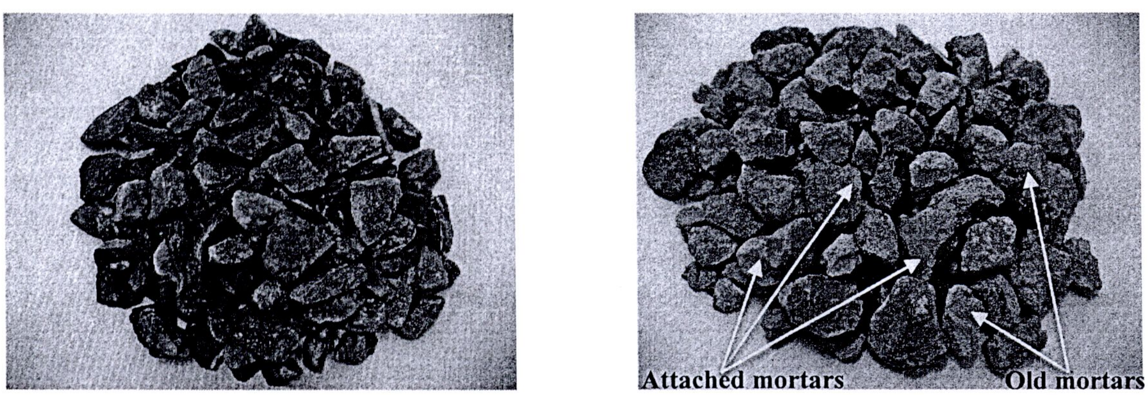
Chemical Composition (%)	Cement Type I	GFA	GBA
Silicon Dioxide (SiO_2)	20.9	45.5	59.9
Aluminium Oxide (Al_2O_3)	4.8	16.8	4.7
Ferric Oxide (Fe_2O_3)	3.4	6.0	3.1
Calcium Oxide (CaO)	65.4	20.9	10.5
Magnesium Oxide (MgO)	1.3	1.2	1.3
Phosphorous Oxide (P_2O_5)	-	0.3	0.91
Sulfur Trioxide (SO_3)	2.7	4.0	0.04
Loss On Ignition (LOI)	1.0	5.3	19.6
Tricalcium Silicates (C_3S)	62.9	-	-
Dicalcium Silicates (C_2S)	12.5	-	-
Tricalcium Aluminate (C_3A)	6.8	-	-
Tetracalcium Aluminoferrite (C_4AF)	10.4	-	-
Strength Activity Index at 7 days (%)	-	100.9	87.4
Strength Activity Index at 28 days (%)	-	113.6	112.7

The sum of SiO_2, Al_2O_3, and Fe_2O_3 of GFA is 68.3%. SO_3 and LOI of GFA were 4.0 and 5.3%, respectively which were not higher than those specified by ASTM C 618 (2001). For GBA, the sum of SiO_2, Al_2O_3, and Fe_2O_3 is 67.7% and other chemical compositions of GBA qualified to the requirement of ASTM C 618 (2001) except for the loss on ignition (LOI), 19.6%, which was higher than the limitation of natural pozzolan (10%). Although use of ground bagasse ash with high LOI (20.36%) to partially replace cement resulted in increasing of setting time of paste (Montakarntiwong, et al., 2005), the high LOI content in bagasse ash (up to 20%) slightly affected the compressive strength of mortar when the age of mortar was more than 28 days (Chusilp, et al., 2009a). Moreover, the results of strength activity indices of GBA mentioned in the previous section also confirmed that GBA could be used as a pozzolanic material.

4.3 Properties of Aggregates

Coarse aggregates (crushed limestone and recycled aggregate) used in this study are shown in Figure 4.5. The properties of the aggregates are shown in Table 4.3 and the particle size distributions of the aggregates are compared with the size required by ASTM C 33 (2001), as shown in Figure 4.6. Local river sand was used as a natural fine aggregate. It had fineness modulus of 3.07, specific gravity in saturated surface dry state (SSD) of 2.62, water absorption of 0.91%, moisture content of 0.27%, and dry-rodded weight of 1,725 kg/m^3.

Natural coarse aggregate (crushed limestone) had specific gravity, water absorption, and moisture of 2.73, 0.45%, and 0.20%, respectively, while those of the recycled aggregate (RCA) were 2.49, 4.81%, and 0.85%, respectively. Low specific gravity of the RCA compared to the crushed limestone is due to the high porosity and low density of attached cement paste or mortar on the surface of the old aggregates (Shayan and Xu, 2003). The water absorption of RCA was much higher than that of crushed limestone by about a factor of 10 while many investigations reported the water absorption of recycled coarse aggregate of about 6-10 times higher than natural coarse aggregate (Otsuki, et al., 2003; Poon, et al., 2004b; Levy and Helene, 2004; Tangchirapat, et al., 2008). This is due to the fact that the old attached mortar in RCA had a higher water absorption capacity than that of crushed limestone (Salem, et al., 2003). Additionally, the Los Angeles abrasion loss of RCA was found to be 37%, which was marginally higher than that of crushed limestone (23%). This was also attributable to cement paste or mortar over RCA which was weaker than that of crushed limestone.



a) Crushed Limestone b) Recycled Aggregate

Figure 4.5 Coarse aggregates

Table 4.3 Properties of Aggregates

Properties	River Sand	Crushed Limestone	Recycled 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
Moisture (%)	0.27	0.20	0.85
Dry-Rodded Weight (kg/m^3)	1725	1650	1480
Void (%)	33.9	39.3	40.4
Los Angeles Abrasion Loss (%)	-	23	37
Material Finer than 75 Micron (%)	N/A	N/A	0.42

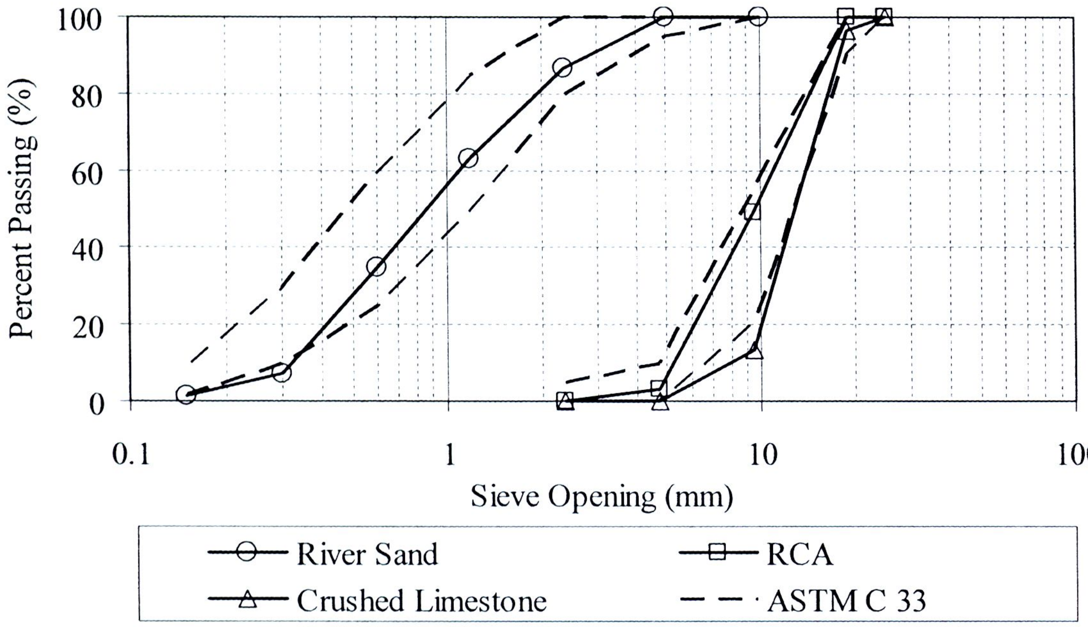


Figure 4.6 Gradation of aggregates

4.4 Fresh Concrete

In order to maintain the slump of fresh concrete between 50-100 mm, superplasticizer was used in some of concrete mixtures. All conventional concrete mixtures did not require superplasticizer to keep the required slump (see Table 3.1).

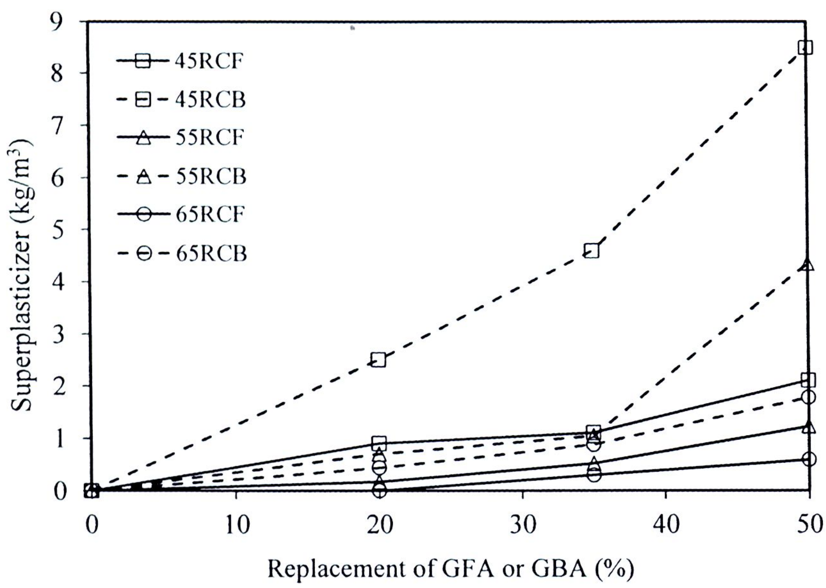


Figure 4.7 Relationship between superplasticizer used to maintain the slump of fresh concrete between 50-100 mm and replacement of GFA or GBA

Figure 4.7 shows the relationship between superplasticizer used to maintain the slump of fresh concrete between 50-100 mm and replacement of GFA or GBA. The results showed that all recycled aggregate concretes without the ashes did not need any superplasticizer, while the recycled aggregate concrete containing GFA needed superplasticizer to maintain the slump of fresh concrete between 50-100 mm. The required superplasticizer of the recycled aggregate concrete containing GFA increased when the replacement of GFA increased, especially, in the concrete which had a low W/B ratio. For instance, at W/B ratio of 0.45, the amounts of superplasticizer of the concretes containing GFA 20, 35, and 50% by weight of binder were 0.9, 1.1, and 2.1 kg/m^3, respectively, while the amounts of the one of the concretes with W/B ratio of 0.65 containing GFA 20, 35, and 50% by weight of binder were 0.0, 0.3, and 0.59 kg/m^3, respectively. Similar results were found in recycled aggregate concrete containing GBA, the superplasticizer content was increased when the replacement of GBA in recycled aggregate concrete increased. For instance, recycled aggregate concretes with W/B ratio of 0.45 containing GBA of 20, 35, and 50% by weight of binder required the superplasticizer to maintain the slump of 50-100 mm of 2.5, 4.6, and 8.5 kg/m^3, respectively. When the W/B ratio was increased to 0.65, the concretes containing GBA of 20, 35, and 50% by weight of binder required superplasticizer of 0.44, 0.88, and 1.77 kg/m^3, respectively. This is due to the angle, irregular shape, and porosity of the GFA and GBA particles resulting in increasing of the friction between surface of cement particles and GFA or GBA particles. The results showed a similar trend in recycled aggregate concrete using ground rice husk-bark ash as a pozzolanic material (Tangchirapat, et al., 2008).

The results indicated that the use of GFA and GBA to partially replace cement had more effect on required superplasticizer than W/B ratio in order to keep slump of fresh concrete between 50-100 mm.

4.5 Compressive Strength

4.5.1 Compressive Strengths of Concretes without GFA and GBA

Table 4.4 shows the compressive strengths of concretes at 7, 28, 60, 90, and 180 days. The results showed that at the same curing age and W/B ratio, all recycled aggregate concretes without GFA and GBA (RC concretes) had compressive strength lower than that of conventional concretes (CON). It was similar to the study of many researchers (Katz, 2003; Ann, et al., 2008; Tangchirapat, et al., 2008). For instance, at W/B ratio of 0.45, the compressive strengths at 7, 28, 60, 90, and 180 days of 45CON concrete were 37.6, 44.4, 49.1, 52.8, and 53.1 MPa, respectively while those of 45RC concrete were 34.1, 41.0, 46.7, 50.7, and 51.3 MPa, respectively.

Since the recycled aggregate had old and attached mortars, which had a higher porosity and was weaker than crushed limestone (Katz, 2004; Poon, et al., 2004a), it resulted in decreasing of the compressive strength of recycled aggregate concrete. Additionally, the bond between new cement paste and recycled coarse aggregate was also obstructed by the residual impurities on the surface of the recycled coarse aggregate (Katz, 2004). The decrease in the W/B ratio clearly increased the compressive strength of recycled aggregate concrete similar to that of conventional concrete.

4.5.2 Compressive Strengths of Recycled Aggregate Concretes Containing GFA

The use of GFA in the recycled aggregate concrete had more effect on the compressive strength of concrete with a high W/B ratio than that with a low W/B ratio. As shown in Table 4.4, for instance, 65RC concrete had the compressive strength at 90 days of 33.6 MPa and decreased to 28 MPa when 50%-ground fly ash was used to replace cement (65RCF50 concrete). The compressive strength of concrete with W/B ratio of 0.45

(45RC) was 50.7 MPa and was 47.4 MPa for 45RCF50 concrete at 90 days. At a low W/B ratio, the compressive strengths of the recycled aggregate and conventional concretes were found slightly different, especially in long-term strength. This indicates that the low W/B ratio and long curing age efficiently improved the compressive strength of the recycled aggregate concrete containing ground fly ash.

Table 4.4 Compressive strength of concretes

Mix	Compressive Strength, MPa				
	7 days	28 days	60 days	90 days	180 days
45CON	37.6	44.4	49.1	52.8	53.1
45RC	34.1	41.0	46.7	50.7	51.3
45RCF20	35.2	42.7	48.0	51.8	52.5
45RCF35	33.9	40.8	46.4	50.4	50.9
45RCF50	32.5	39.3	43.9	47.4	48.1
45RCB20	34.5	41.2	47.1	51.3	51.9
45RCB35	32.3	38.6	43.4	46.9	47.5
45RCB50	29.0	35.1	40.4	43.8	44.4
55CON	28.7	36.7	41.7	44.9	45.0
55RC	24.8	33.3	38.1	41.6	42.5
55RCF20	24.4	34.7	39.9	43.6	44.0
55RCF35	22.2	30.8	36.2	39.8	40.3
55RCF50	21.5	29.3	33.8	36.8	37.3
55RCB20	22.3	32.2	39.2	42.7	43.2
55RCB35	19.7	29.0	34.7	38.1	38.6
55RCB50	18.2	26.8	31.6	34.9	35.4
65CON	25.7	30.4	37.2	38.8	40.7
65RC	19.9	24.8	31.0	33.6	36.4
65RCF20	19.9	25.0	31.7	34.3	37.9
65RCF35	17.4	21.6	28.2	30.6	33.3
65RCF50	15.9	19.4	25.9	28.0	30.5
65RCB20	19.5	24.6	30.8	33.5	36.2
65RCB35	16.6	20.8	26.7	29.0	31.5
65RCB50	15.1	18.6	24.1	25.9	27.7

The effect of GFA on the percentage compressive strength of recycled aggregate concrete is shown in Figure 4.8. The result showed that the compressive strength of recycled aggregate concrete decreased with increasing of GFA replacement. For each W/B ratio, the lowest compressive strength was found in the recycled aggregate concrete containing GFA of 50% by weight of binder, especially at the higher W/B ratio. For example, 65RC, 65RCF20, 65RCF35 and 65RCF50 concretes had the compressive strengths at 28 days of 83.3, 85.2, 75.8, and 69.6% of 65CON concrete, respectively. Since the use of recycled aggregate to fully replace crushed limestone and high W/B ratio in concrete resulted in increasing of voids and lowering the strength of concrete.

At the same W/B ratio and curing ages, the recycled aggregate concrete containing GFA 20% by weight of binder had higher compressive strength than those concretes without GFA. This result indicated that the compressive strength of recycled aggregate concrete could be slightly improved by using 20% GFA to replace Portland cement type I. For instance, 45RCF20, 55RCF20 and 65RCF20 concretes had the compressive strengths at 90 days of 98.1%, 97.1% and 88.4% of the conventional concretes (45CON, 55CON, and 65CON concretes), respectively, while the recycled aggregate concretes without GFA (45RC, 55RC, and 65RC concretes) had the compressive strengths of 96.1%, 92.8% and 86.7% of the conventional concretes with the same W/B ratio, respectively.

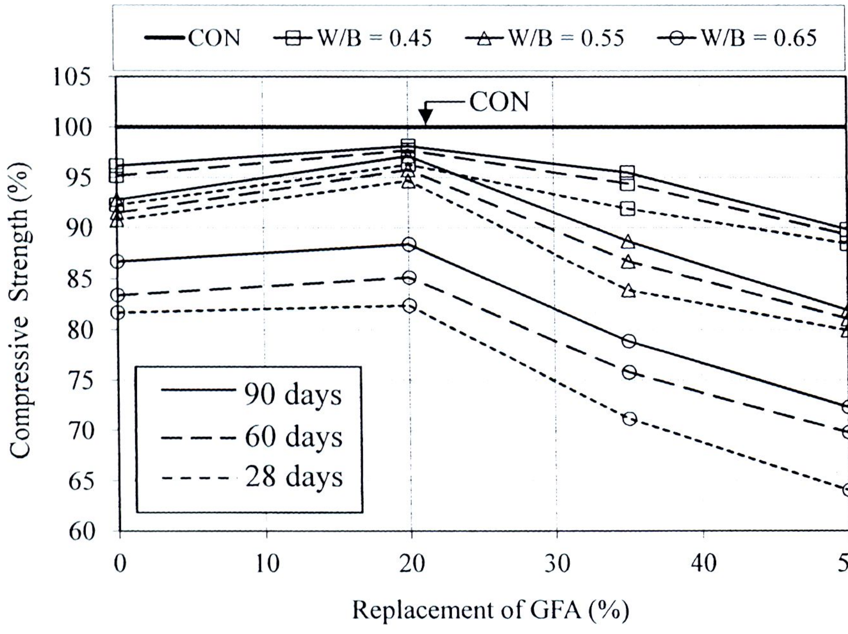


Figure 4.8 Percentage compressive strengths at 28, 60, and 90 days of recycled aggregate concretes containing GFA as compared to conventional concretes

In addition, the recycled aggregate concrete with W/B ratio of 0.45 with high volume of GFA (50% replacement) had a compressive strength more than 90% as compared to 45CON concrete. Thus, a high volume GFA was more suitable for use in recycled aggregate concrete with a low W/B ratio than that with a high W/B ratio since a high W/B ratio (more than 0.50) and a high content of fly ash do not favor the pozzolanic reaction. Since high W/B ratio dilutes the concentration of Ca^{2+} in the pore solution of the paste, and reduces the contact between the particles (Lam, et al., 2000).

GFA could slightly improve the compressive strength of recycled aggregate concrete because it could reduce the average pore diameter and pore size distribution in the concrete, resulting in the denser of recycled aggregate concrete (Chindaprasirt, et al., 2005). Moreover, the pozzolanic reaction between GFA and calcium hydroxide yielded extra calcium silicate hydrate, which produced the compressive strength of concrete and could fill in the voids of concrete.

Although, the use of GFA to partially replace Portland cement could slightly improve the compressive strength of recycled aggregate concrete, the W/B ratio also affected the compressive strength. To produce the same level of the compressive strength of recycled aggregate concrete without GFA, the replacement of GFA should not be used more than 20% by weight of binder. However, at this replacement (20%) of GFA and at W/B ratios of 0.45, 0.55, and 0.65, the compressive strengths at 28 days of the concretes were lower than those of conventional concrete about 4, 5, and 18%, respectively and at 180 days, the compressive strengths were lower than those of conventional concrete about 1, 2, and 7%, respectively.

4.5.3 Compressive Strengths of Recycled Aggregate Concretes Containing GBA

For recycled aggregate concretes containing GBA, the decrease in W/B ratio clearly increased the compressive strength of recycled aggregate concrete. It can be seen in Table 4.4 that the use of GBA in the recycled aggregate concrete had more effect on the compressive strength of concrete with a high W/B ratio than that with a low W/B ratio similar to the results of using GFA in recycled aggregate concrete. The compressive strengths of the recycled aggregate concrete and conventional concrete were found slightly different at a low W/B ratio (0.45), especially in long-term strength. When the W/B ratio was increased up to 0.65, the compressive strength of recycled aggregate concretes with GBA decreased to be lower than that of conventional concrete. This is due to use of recycled aggregate to fully replace crushed limestone resulted in increasing void in concrete (Gomez-Soberon, 2000) and concrete having high W/B ratio, the voids occurred when the excessive water evaporated from the concrete.

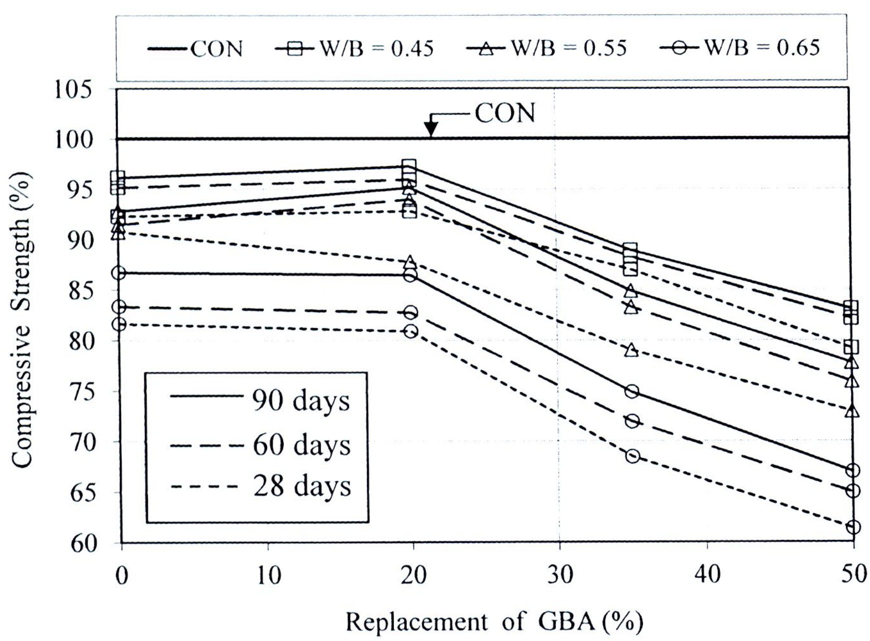


Figure 4.9 Percentage compressive strengths at 28, 60, and 90 days of recycled aggregate concretes containing GBA as compared to conventional concretes

The increasing of GBA replacement resulted in decreasing of the compressive strength of recycled aggregate concrete. For instance, 45CON, 45RC, 45RCB20, 45RCB35, and 45RCB50 concretes had the compressive strengths at 28 days of 44.4, 41.0, 41.2, 38.6, and 35.1 MPa, respectively. At 180 days, the compressive strengths of 45RCB35, 45RCB50, 55RCB35, 55RCB50, 65RCB35, and 65RCB50 concretes were 89, 84, 86, 77, 77, and 68% of the CON concretes, respectively. It was similar to the results of Montakarntiwon, et al. (2005) who found that conventional concrete with W/B of 0.50 containing GBA at the rate of 20, 30, and 40% by weight of binder had compressive strength at 28 days of 97, 91, and 74% of conventional concrete, respectively.

The use of high volume of GBA to replace cement in recycled aggregate concrete would decrease the cement content in the mixture thus, decreased the $Ca(OH)_2$ from the hydration reaction of cement. This resulted in the quantity of $Ca(OH)_2$ was not sufficient for the pozzolanic reaction (Lam, et al., 2000) and low compressive strengths of recycled aggregate concretes containing GBA 35 and 50% by weight of binder were obtained.

However, the use of GBA to replace cement at the rate of 20% by weight of binder could improve the strength of recycled aggregate concrete to be as high as that of recycled aggregate concrete without GBA at the same W/B ratio. For instance, the compressive strengths of 45RCB20, 55RCB20, and 65RCB20 concretes at 90 days were 51.3, 42.7, and 33.5 MPa or 97, 95, and 86% of CON concretes with the same W/B ratio, respectively. The compressive strengths of 45RC, 55RC, and 65RC concretes were 96, 93, and 86% of CON concretes with the same W/B ratio. Since at this replacement level of GBA (20% by weight of binder), the $Ca(OH)_2$ for the hydration reaction may be enough for the pozzolanic reaction between GBA and calcium hydroxide to yield extra calcium silicate hydrate. Moreover, GBA particles could fill in the voids of concrete. Both reasons resulted in increasing the compressive strength of concrete.

In conclusion, the suitable replacement of GBA to improve the compressive strength of recycled aggregate concrete was 20% by weight of binder. This replacement level was similar to the results of many researchers finding for concrete using natural aggregates (Ganesan, et al., 2007; Chusilp, et al., 2009a). Moreover, use of low W/B ratio for mixing recycled aggregate concrete could also help to improve the compressive strength to be better than that using of high W/B ratio. The compressive strengths at 28 days of recycled aggregate concretes with W/B ratios of 0.45, 0.55, and 0.65 containing GBA at 20% were lower than those of conventional concretes of 3, 12, and 19%, respectively.

4.6 Modulus of Elasticity

Relationship between modulus of elasticity and square root of compressive strength of conventional concretes and recycled aggregate concretes containing GFA and GBA at 28, 60, and 90 days is shown in Figure 4.10 The results showed that the moduli of elasticity of conventional concretes (45CON, 55CON, and 65CON concretes) and recycled aggregate concretes with and without GFA and GBA increased with the increased of compressive strength. Moreover, for the compressive strengths between 30 to 52 MPa (a square root of compressive strength between 5.5 and 7.2 MPa), the conventional concretes had the modulus of elasticity higher than that of the recycled aggregate concretes with and without GFA and GBA by about 16 to 22%. This result was similar to those of many researchers who reported that the modulus of elasticity of recycled aggregate concrete was lower than that of conventional concrete by about 15 to 30% (Hansen and Boegh, 1985; Ravindrajah, et al., 1987; Barra De Oliveira and Vazquez, 1996). This is due to the fact that the modulus of elasticity of recycled aggregate is lower than that of natural aggregate (crushed limestone). In addition, recycled aggregate has a higher uncompacted void content, providing a low modulus of elasticity to the recycled aggregate concrete (Topcu and Sengel, 2004). Moreover, Neville (1997) also reported that the modulus of elasticity of concrete depended not only on the compressive strength of concrete but also the modulus of elasticity and quality of the aggregate used in the concrete mixture. Furthermore, the important factor affecting the modulus of elasticity of concrete was the bonding between aggregates and cement pastes which tended to be better when the age of concrete increased.

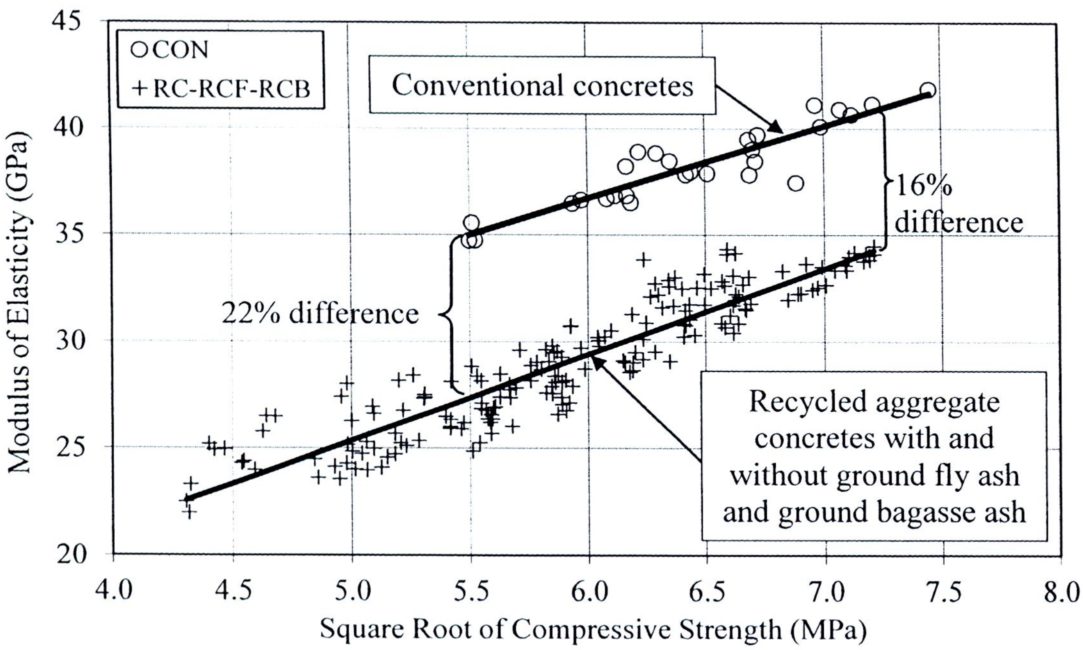


Figure 4.10 Modulus of elasticity of conventional concretes and recycled aggregate concretes with and without GFA and GBA

In Figure 4.10, it is found that the trend line equation represents the modulus of elasticity of recycled aggregate concrete with and without GFA and GBA ($E_{RC,RCF,RCB}$) is lower than that of the conventional concrete (E_{CON}) by about 19% in an average. This result could be used to generate an empirical equation for predicting the modulus of elasticity of recycled aggregate concrete with and without GFA and GBA in terms of conventional concrete, as shown in equation (4.1).

$$E_{RC,RCF} = 0.81 \cdot E_{CON} \qquad \text{------------------------(4.1)}$$

where E_{CON} = Modulus of elasticity of conventional concrete, GPa

$E_{RC,RCF,RCB}$ = Modulus of elasticity of recycled aggregate concrete with and without ground fly ash and ground bagasse ash, GPa

f_c' = Compressive strength of concrete between 30 and 50 MPa.

The above results showed that the use of GFA and GBA in recycled aggregate concrete could not improve the modulus of elasticity of recycled aggregate concrete to be as high as that of conventional concrete. The modulus of elasticity of recycled aggregate concretes with and without GFA and GBA increased when the compressive strength of the concretes increased and were lower than that of conventional concrete about 19%.

4.7 Water Permeability

4.7.1 Effect of W/B Ratios and Replacements of GFA and GBA on Water Permeability Coefficient of Concretes

The water permeability coefficients of concretes at 28 and 90 days are shown in Table 4.5. It was found that the water permeability coefficient at 28 days of 45CON, 55CON, and 65CON concretes were 7.20×10^{-13}, 9.19×10^{-13}, and 13.35×10^{-13} m/s, respectively. When the curing age increased up to 90 days, the water permeability coefficient of those concretes decreased to be 2.69×10^{-13}, 5.82×10^{-13}, and 7.81×10^{-13} m/s, respectively. For recycled aggregate concrete without GFA and GBA (RC concrete), decreasing the W/B ratio from 0.65 (65RC concrete) to 0.45 (45RC concrete) could reduce the water permeability coefficient at 28 days from 82.66×10^{-13} to 8.33×10^{-13} m/s, respectively, which was approximately reduced by a factor of 10. Moreover, the water permeability coefficient of these concretes decreased to be 20.84×10^{-13} and 3.69×10^{-13} m/s, respectively when the age of concretes was 90 days.

Table 4.5 Water permeability coefficients of concretes

Mixes	Water Permeability Coefficient ($\times10^{-13}$ m/s)	
	28 days	90 days
45CON	7.20	2.69
45RC	8.33	3.69
45RCF20	1.98	1.23
45RCF35	1.87	1.14
45RCF50	1.93	1.72
45RCB20	2.27	1.77
45RCB35	2.87	1.95
45RCB50	8.65	3.48
55CON	9.19	5.82
55RC	14.63	8.60
55RCF20	4.06	2.62
55RCF35	2.27	2.13
55RCF50	2.20	2.09
55RCB20	3.81	2.66
55RCB35	2.68	2.38
55RCB50	2.70	2.63
65CON	13.35	7.81
65RC	82.66	20.84
65RCF20	6.79	5.88
65RCF35	4.44	4.10
65RCF50	3.81	3.65
65RCB20	7.73	5.67
65RCB35	4.33	4.29
65RCB50	5.13	4.78

The results clearly demonstrated that a decrease in W/B ratio and an increase in curing age could reduce the water permeability coefficient of the concretes. This is due to the reduction of W/B ratio could reduce void obtained from capillary pores resulting in a denser concrete. Moreover, increase of curing time resulted in increasing hydration products (CSH and CAH) to fill the concrete matrix to be denser than that in the early age.

In order to consider the effect of replacement of GFA and GBA, the relationships between water permeability coefficient and replacement of GFA or GBA of concrete at 28 and 90 days are plotted in Figures 4.11 and 4.12, respectively. It was clearly indicated that the water to binder ratios influenced on the water permeability of recycled aggregate concrete containing GFA and GBA similar to the results of concretes without ones. When GFA was used to partially replace cement at 20, 35, and 50% by weight of binder, the water permeability of recycled aggregate concretes greatly decreased. For example, the water permeability coefficient at 28 days of 45RCF20, 45RCF35, and 45RCF50 concretes were 1.98×10^{-13}, 1.87×10^{-13}, and 1.93×10^{-13} m/s, respectively, which were approximately decreased by a factor of 4 times of 45RC concrete, respectively. Moreover, the similar results were observed in recycled aggregate concrete containing GBA. For example, the water permeability coefficient at 90 days of 65RCB20, 65RCB35, and 65RCB50 concretes were 5.67×10^{-13}, 4.29×10^{-13}, and 4.78×10^{-13} m/s, respectively, which were a decrease by a factor of about 3.7, 4.8, and 4.4 times of 45RC concrete, respectively.

The results in Figures 4.11 and 4.12 also show that the water permeability coefficients at the same W/B ratio of recycled aggregate concretes containing GFA and GBA were slightly different with the different replacements. Moreover, the water permeability coefficients of recycled aggregate concretes containing GFA and GBA were lower than that of CON concrete at the same W/B ratio except for that of 45RCB50 concrete. The results indicated that use of GFA and GBA to partially replace cement could reduce the water permeability of recycled aggregate concrete to be lower than that of CON and RC concretes when the same W/B ratio was considered.

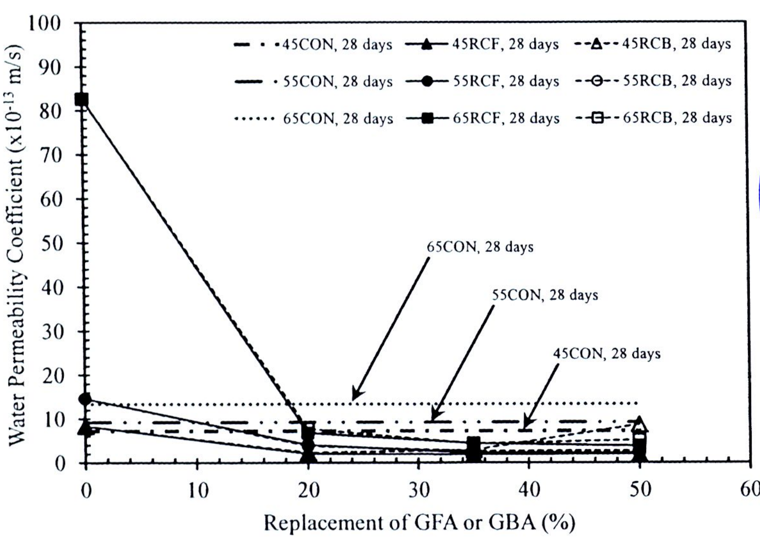


Figure 4.11 Relationship between water permeability coefficient and replacement of GFA or GBA in concretes with W/B ratios of 0.45, 0.55, and 0.65 at 28 days

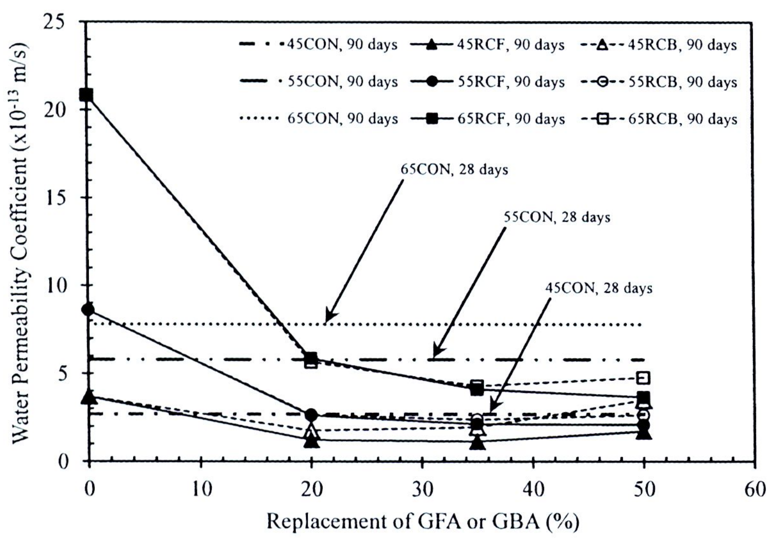


Figure 4.12 Relationship between water permeability coefficient and replacement of GFA or GBA in concretes with W/B ratios of 0.45, 0.55, and 0.65 at 90 days

The W/B ratio is not only a unique effect on the water permeability coefficient of recycled aggregate concrete containing GFA and GBA, but also the replacement of GFA or GBA significantly affect the water permeability coefficient of the concrete as well. The use of GFA and GBA in recycled aggregate concrete can, gradually, reduce the water permeability coefficient. This is associated with the level of GFA and GBA content. The higher is the GFA and GBA replacement ($\leq$ 50% by weight of binder), the lower is the coefficient of water permeability of concrete.

The reduction in water permeability coefficient found in recycled aggregate concrete with GFA and GBA is probably due to the refinement of the pore structures as a result of the pozzolanic reaction and the filler effect of small particles of GFA and GBA. Moreover, the recycled aggregate concretes containing GFA and GBA at 20%, 30%, and 50% by weight of binder had water permeability coefficients lower than those of conventional concretes at the same W/B ratio. It should be noted that use of GFA and GBA were more effective for reducing water permeability coefficient of recycled aggregate concrete than reduction of W/B ratio and increased of curing age of concrete, especially at 28-day curing age. Moreover, the compressive strength is a factor which affects the water permeability coefficient of concretes. Therefore, the next section considered the effect of compressive strengths on the water permeability of concretes.

4.7.2 Effect of Compressive Strengths on Water Permeability of Concretes

The relationship between compressive strength and water permeability coefficient of recycled aggregate concrete is shown in Figure 4.13. The data are separated into 3 groups: CON, RC, and RCF-RCB concretes. The RC group is the recycled aggregate concretes without GFA and GBA, the CON group is the conventional concretes, and the RCF-RCB group is the recycled aggregate concretes containing GFA and GBA.

The water permeability coefficients of the CON group are located between those of RC and RCF-RCB groups when the compressive strengths of concretes are the same. The water permeability coefficient of the CON group was decreased when the compressive strength of concrete was increased. This is because the voids in conventional concrete were decreased when the compressive strengths increased. For the RC group, at the same compressive strength, the water permeability coefficients were higher than both of the CON and RCF-RCB groups, and tended to highly increase when the compressive strength was less than 35 MPa.

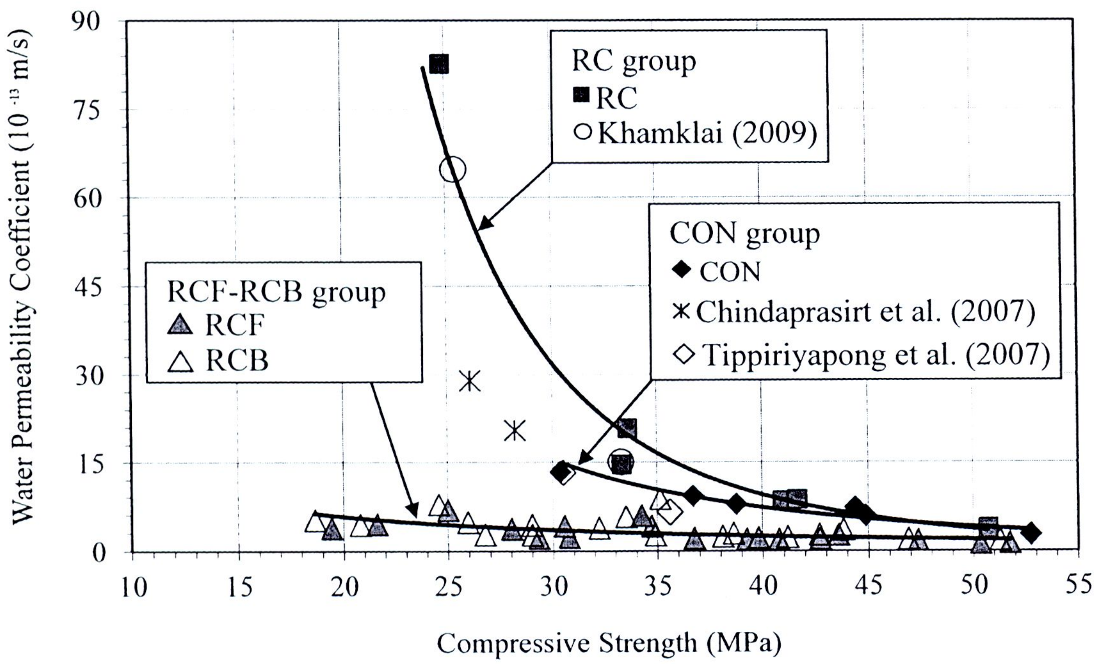


Figure 4.13 Relationship between compressive strength and water permeability coefficient of recycled aggregate concrete

In addition, the RCF-RCB group had low water permeability coefficients when the compressive strengths of concretes between 20 and 50 MPa. It was suggested that the compressive strength of concrete in RCF-RCB group had slightly effect on the water permeability coefficient. This result showed that the use of GFA and GBA to replace cement at the rate of 20 to 50% was very effective method to reduce the water permeability in recycled aggregate concrete. For the compressive strengths of 45 to 50 MPa, the water permeability coefficients of the CON, RC, and RCF-RCB groups were not much different. It indicated that the compressive strengths of concretes in these ranges do not significantly affect the water permeability of concrete.

In Figure 4.13, the data of water permeability coefficients of concretes from Chindaprasirt, et al. (2007) and Tippiriyapong, et al. (2007) are also plotted and compared with the trend line of the CON group. The data from Chindaprasirt, et al. (2007) are near the trend line of the CON group when it is extended to the lower compressive strength while the data from Tippirirapong, et al. (2007) are slightly lower than the trend line. When the data from Khamklai (2009) are plotted in Figure 4.13, the trend line of the RC group is confirmed, and it can be used to predict the value of the water permeability coefficient of recycled aggregate concrete since the data of Khamklai (2009) are very close to the trend line of the RC group.

4.8 Chloride Resistance

4.8.1 Chloride Penetration Depth

The results of the chloride penetration depth of concretes immersed in 3% sodium chloride (NaCl) solution for 3, 6, 9, 12, and 18 months are shown in Table 4.6.

Table 4.6 Chloride penetration depths of concretes

Mix	Chloride Penetration Depth (mm)				
	Immersion Time				
	3 months	6 months	9 months	12 months	18 months
45CON	14.5	23.3	30.5	32.5	35.0
45RC	18.5	29.5	40.0	43.3	45.6
45RCF20	10.0	16.3	21.0	24.3	25.6
45RCF35	8.8	10.7	14.0	16.0	17.8
45RCF50	8.0	8.6	10.0	11.0	12.9
45RCB20	6.4	11.5	12.8	13.2	18.0
45RCB35	6.1	10.0	10.0	10.8	14.2
45RCB50	6.0	7.0	7.2	8.0	10.8
55CON	18.6	30.0	44.5	47.8	51.2
55RC	20.3	43.0	51.5	56.2	59.8
55RCF20	12.0	17.4	25.0	26.8	29.4
55RCF35	10.1	11.9	17.0	17.5	17.8
55RCF50	9.7	10.0	11.4	13.0	13.7
55RCB20	9.7	13.0	15.0	16.8	22.0
55RCB35	7.2	11.6	12.8	14.7	18.0
55RCB50	6.6	7.6	8.2	10.5	11.2
65CON	22.5	32.0	49.0	52.0	60.0
65RC	31.7	44.8	66.0	70.0	75.0
65RCF20	16.4	18.0	25.8	29.6	32.8
65RCF35	11.5	15.0	17.8	18.0	19.5
65RCF50	13.0	14.1	14.8	15.0	16.4
65RCB20	14.5	16.5	18.8	20.3	26.8
65RCB35	13.1	14.1	14.5	16.4	20.5
65RCB50	8.0	11.0	11.3	12.0	14.0

Chloride penetration depths of 45CON at 3, 6, 9, 12, and 18 months were 14.5, 23.3, 30.5, 32.5, and 35.0 mm, respectively while those of 45RC concretes were 18.5, 29.5, 40.5, 43.3, and 45.6 mm, respectively. When W/B ratio was increased up to 0.55 and 0.65, the chloride penetration depths at 18 months of 55CON and 65CON concretes were 51.2 and 60.0 mm, respectively and those of 55RC and 65RC concretes were 59.8 and 75.0 mm, respectively. The results indicated that the chloride penetration depth of RC concrete was higher than that of CON concrete, similar to what has been reported by other studies (Shayan and Xu, 2003; Kou, et al., 2007; Ann, et al., 2008). The use of recycled aggregate as coarse aggregate to fully replace crushed limestone contributed to increase in porosity and cracks in recycled aggregate concrete causing chloride ions to penetrate easier into RC concrete (Gomez-Soberón, 2002).

Figures 4.14 to 4.16 show the results of chloride penetration depths of concretes immersed in 3% sodium chloride solution at 6, 12, and 18 months, respectively. Chloride penetration depths at 6 months of 45RCF20, 55RCF20, and 65RCF20 concretes were 16.3, 17.4, and 18.0 mm, respectively. When the immersed time increased up to 18 months, the chloride penetration depths of 45RCF20, 55RCF20, and 65RCF20 concretes were 25.6, 29.4, and 32.8 mm, respectively. These results showed that the chloride penetration depth of recycled aggregate concrete containing GFA increased with increasing W/B ratio. Considering the chloride penetration depths of concretes with W/B ratio of 0.65, the ones at 18 months of 65RCF20, 65RCF35, and 65RCF50 concretes were 32.8, 19.5, and 16.4 mm, respectively. It is indicated that chloride penetration depth decreased with the increasing replacement of GFA.

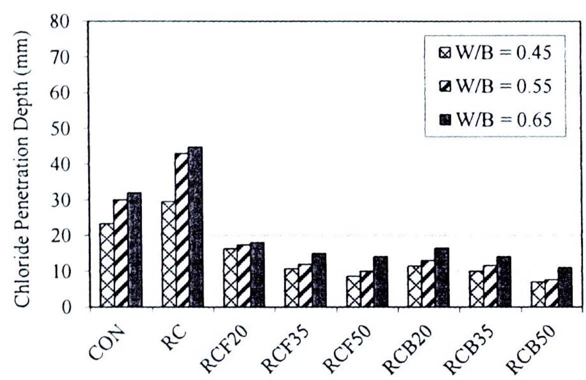


Figure 4.14 Chloride penetration depths of concretes after immersed in 3% NaCl solution for 6 months

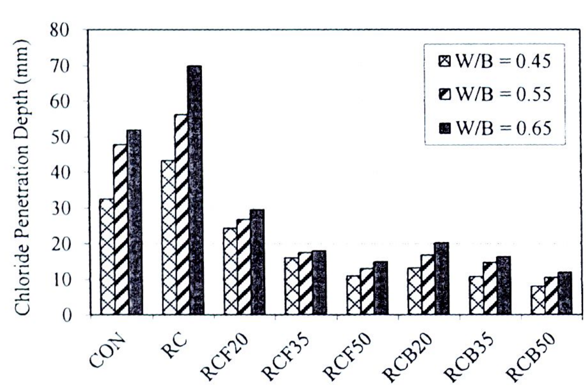


Figure 4.15 Chloride penetration depths of concretes after immersed in 3% NaCl solution for 12 months

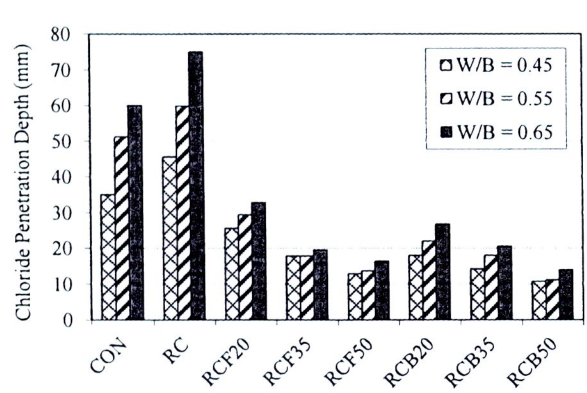


Figure 4.16 Chloride penetration depths of concretes after immersed in 3% NaCl solution for 18 months

The results of chloride penetration depths of the recycled aggregate concretes containing GBA were similar to those of the recycled aggregate concrete containing GFA. Chloride penetration depths of all recycled aggregate concretes highly decreased and were lower than those of CON and RC concretes when GBA was used to partially replace cement. It was similar to the result obtained by Ganesan, et al. (2007) who reported that use of ground bagasse ash to partially replace cement in conventional concrete could reduce the chloride migration diffusion coefficient of the concrete. For example, chloride penetration depths of 45RCB35, 55RCB35, and 65RCB35 concretes at 12-month immersed time were 10.8, 14.7, and 16.4 mm, respectively. When the replacement of GBA was increased up to 50%, the chloride penetration depths of those concretes were 8.0, 10.5, and 12.0 mm, respectively.

The above results show that when the W/B ratio of concretes increased, the chloride penetration resistance of concretes decreased. Since the concrete having higher W/B ratio, the water content was more than that required to react with binder resulting in remaining water in the concrete. When this water evaporated from the concrete, the voids were taken place. Therefore, the higher chloride penetration depth of concrete occurred in concrete with higher W/B ratio. Moreover, the results also obviously show that both GFA and GBA are good pozzolanic materials and can be used to increase 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 (Chindaprasirt, et al., 2005) 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 (Leng, et al., 2000).

Therefore, the chloride penetration depth of concrete immersed in 3% NaCl solution could be decreased by using GFA and GBA to partially replace cement in recycled aggregate concrete. Moreover, the chloride penetration depth of recycled aggregate concrete decreased with the increased of GFA and GBA replacement. Although the chloride resistance of recycled aggregate concrete increased with increasing replacement of GFA and GBA, the compressive strength of recycled aggregate concrete also decreased. Therefore, the suitable percentage replacement of GFA and GBA to obtain suitable compressive strength and suitable chloride resistance was 20% by weight of binder.

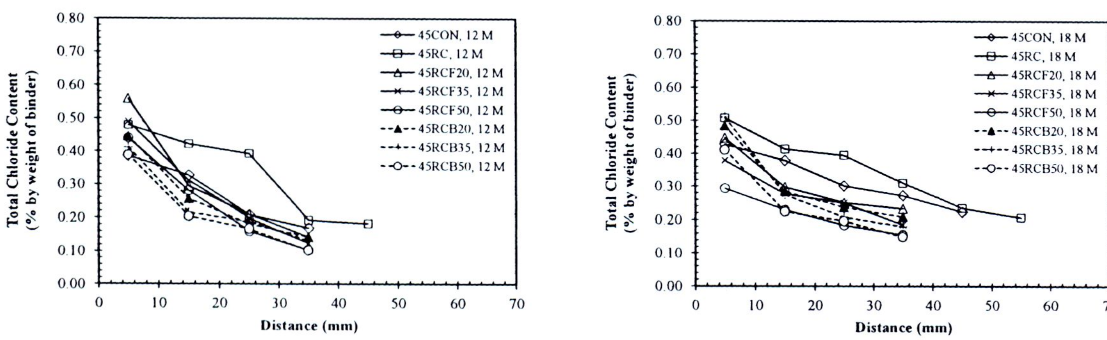
4.8.2 Chloride Content

4.8.2.1 Total Chloride Content

Total chloride content is the sum of fixed chloride (bound chloride) and free chloride. The fixed chloride is chloride which is fixed in hydrated cement paste and changes the form to chloroaluminate hydrate or Friedel's salt by chemical reaction. Moreover, fixed chloride cannot be dissolved by water. Therefore, the nitric acid as suggested by ASTM C 1152 (2001) was used to extract chloride in concrete powder for investigating the total chloride content in concrete. The results of total chloride content in concretes are discussed in this section.

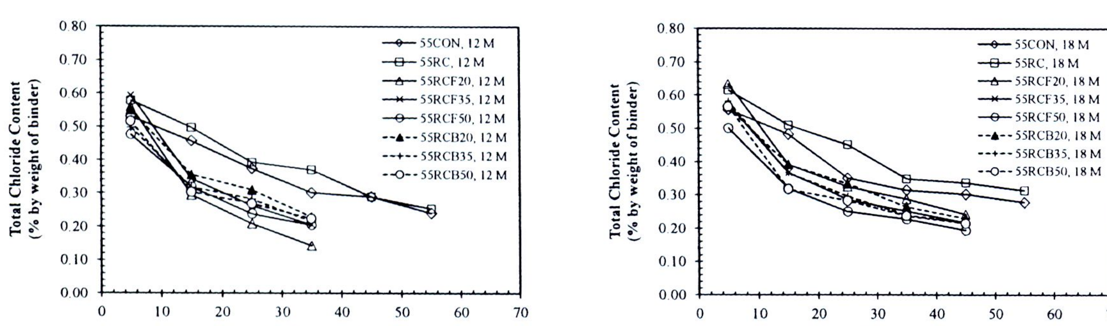
Figures 4.17 to 4.19 show total chloride contents at each distance from the surface of concretes with W/B ratios of 0.45, 0.55, and 0.65 immersed in 3% NaCl solution for 12 and 18 months, respectively. It was found that at a distance of 5 mm from the surface of concretes, the total chloride contents were difficult to determine because they somewhat varied, while the trends were found in the next distances of concretes.

The 12-month total chloride contents at a distance of 35 mm from the surface of 45CON, 55CON, and 65CON concretes were approximately 0.17, 0.30, and 0.38% by weight of binder, respectively. At the same distance and immersed time, the ones of 45RC, 55RC, and 65RC concretes were approximately 0.19, 0.37, and 0.42% by weight of binder, respectively. The results indicated that decrease of W/B ratio resulted in decreasing total chloride content of concrete. Because use of low W/B ratio to mix concrete resulted in a denser concrete and chloride ions were difficult to penetrate into the concrete. Moreover, use of recycled aggregate in concrete resulted in increasing total chloride content since recycled aggregate had higher porosity than that of crushed limestone resulting in serving chloride ions to easier penetrate into concrete.



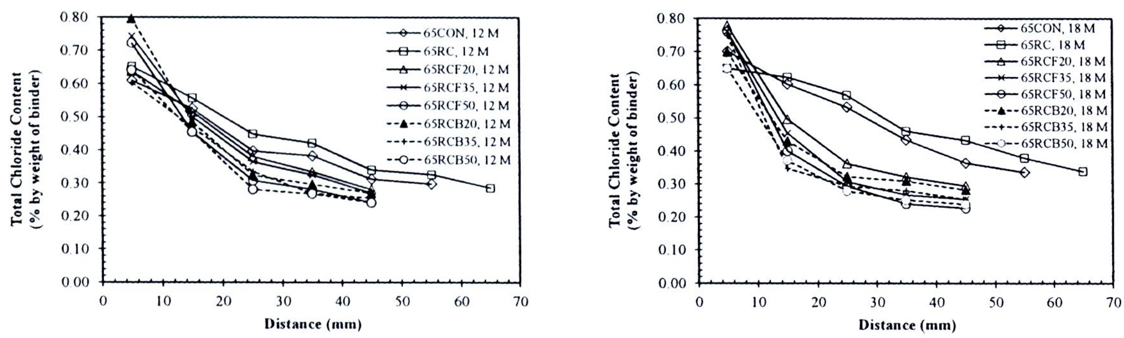
(a) 12 months (b) 18 months

Figure 4.17 Total chloride contents at each distance from surface of concretes with W/B ratio of 0.45 immersed in 3% NaCl solution for 12 and 18 months



(a) 12 months (b) 18 months

Figure 4.18 Total chloride contents at each distance from surface of concretes with W/B ratio of 0.55 immersed in 3% NaCl solution for 12 and 18 months



(a) 12 months (b) 18 months

Figure 4.19 Total chloride contents at each distance from surface of concretes with W/B ratio of 0.65 immersed in 3% NaCl solution for 12 and 18 months

When GFA was used in recycled aggregate concrete, the 12-month total chloride contents at a distance of 25 mm of 45RC, 45RCF20, 45RCF35, and 45RCF50 concretes were approximately 0.39, 0.21, 0.20, and 0.16% by weight of binder, respectively. The results show that use of GFA could reduce the total chloride content of recycled aggregate concretes and the total chloride content of the concretes decreased with the increasing replacement of GFA. For RCF35 concrete with W/B ratios of 0.45, 0.55, and 0.65 immersed in 3% NaCl solution for 18 months, at the distance of 35 mm from the surface of concrete, the total chloride contents were 0.18, 0.22, and 0.27% by weight of binder, respectively. This shows that the increase of W/B ratio resulted in increasing the total chloride content of concrete.

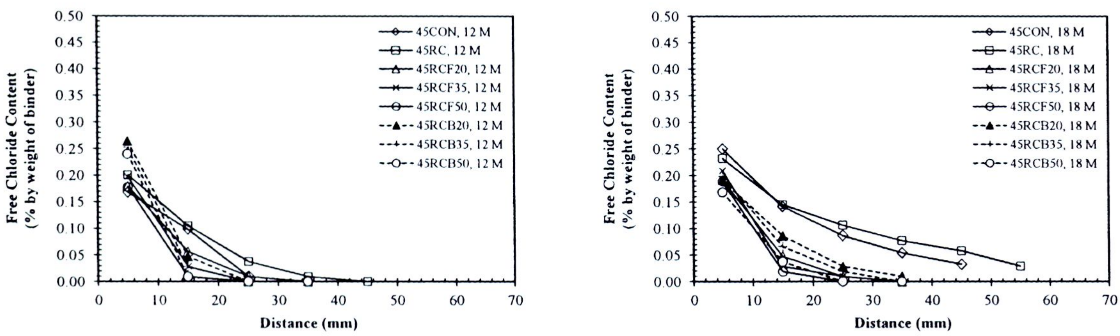
At 12 months, the total chloride contents at a distance 15 mm of 65RC, 65RCB20, 65RCB35, and 65RCB50 concretes were 0.56, 0.49, 0.47, and 0.45% by weight of binder, respectively. When the W/B ratio was decreased to 0.55, the 12-month total chloride contents at the same distance of 55RC, 55RCB20, 55RCB35, and 55RCB50 concretes were 0.50, 0.35, 0.32, and 0.30% by weight of binder, respectively. The results indicated that use of GBA and decreased of W/B ratio could reduce the total chloride content of recycled aggregate concrete. Moreover, the total chloride content decreased with the increasing replacement of GBA.

The above results showed that use of GFA and GBA in recycled aggregate concretes could greatly improve the chloride resistance of recycled aggregate concrete to be lower than that of both CON and RC concretes when the same W/B ratio was increased. This is due to fine particles of GFA and GBA after reacted with $Ca(OH)_2$ could refine the pore size of paste resulting in reducing the porosity of the concretes which was the main factor of chloride detriment. Moreover, calcium silicate hydrate obtained from the hydration and pozzolanic reactions blocked the chloride ions to penetrate into the concretes (Leng, et al., 2000).

4.8.2.2 Free Chloride Content

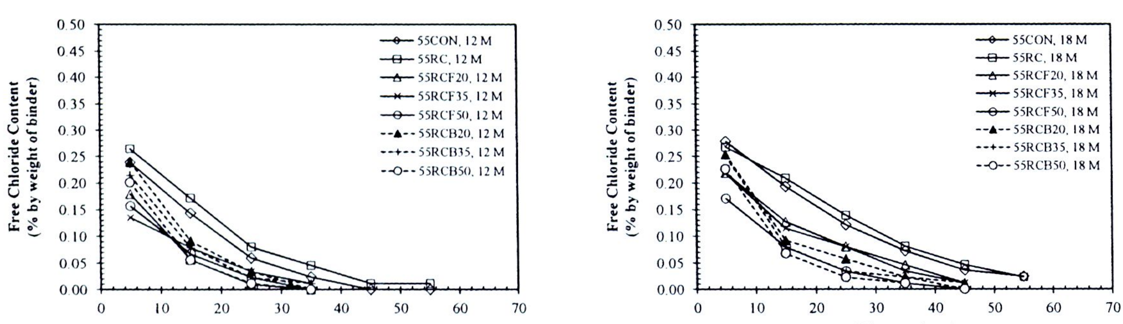
The previous section (4.8.2.1) showed the results of total chloride content of concretes at different distances. In general, the total chloride content is the sum of fixed and free chloride contents. Free chloride or water soluble chloride is chloride which can be dissolved by water, thus it can move to another place by humidity and water and danger to the reinforced steel in concrete structures. However, it can be fixed by tricalcium aluminate (C_3A) by mean of chemical reaction. The results of free chloride content are discussed in this section.

The results of free chloride content at each distance from the surface of concretes with W/B ratios of 0.45, 0.55, and 0.65 are shown in Figures 4.20, 4.21, and 4.22, respectively. It was also noted that free chloride contents at a distance of 5 mm from the surface of concrete were also difficult to determine, similar to that of total chloride content.



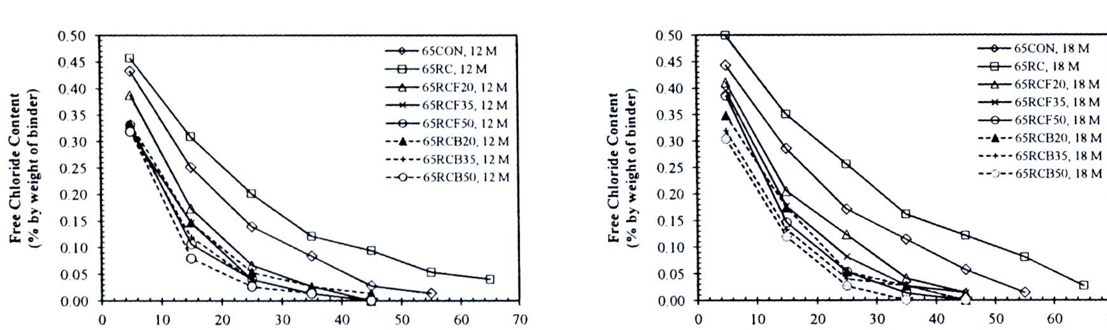
(a) 12 months (b) 18 months

Figure 4.20 Free chloride contents at each distance from surface of concretes with W/B ratio of 0.45 immersed in 3% NaCl solution for 12 and 18 months



(a) 12 months (b) 18 months

Figure 4.21 Free chloride contents at each distance from surface of concretes with W/B ratio of 0.55 immersed in 3% NaCl solution for 12 and 18 months



(a) 12 months (b) 18 months

Figure 4.22 Free chloride contents at each distance from surface of concretes with W/B ratio of 0.65 immersed in 3% NaCl solution for 12 and 18 months

The 12-month free chloride content at a distance of 15 mm from the surface of 45CON concrete was 0.10% while that of 45RC concrete was 0.11%. When the W/B ratio was increased to 0.55 and 0.65, 55CON and 65CON concretes had free chloride contents of 0.14 and 0.25%, respectively while 55RC and 65RC concretes had free chloride contents of 0.17, and 0.31%, respectively. The results indicated that the increase of W/B ratio resulted in increasing of free chloride contents in concrete. These results are similar to the results of total chloride content. Moreover, the free chloride content tended to increase with the increasing immersed time.

When GFA and GBA were used to partially replace cement in recycled aggregate concrete, free chloride contents tended to decrease greatly. The 18-month free chloride contents at a distance of 25 mm from the surface of 45RCF20 and 45RCB20 concretes were 0.01 and 0.03%, respectively. When the W/B ratios were increased to 0.55 and 0.65, 55RCF20, 55RCB20, 65RCF20, and 65RCB20 concretes had free chloride contents of 0.08, 0.06, 0.12, and 0.05%, respectively. The results also indicated that the free chloride content increased with the increasing W/B ratio similar to the results of total chloride content. Moreover, free chloride content decreased with increasing the replacement of GFA and GBA. For instance, 18-months free chloride content at a distance of 15 mm from the surface of 65RCB20, 65RCB35, and 65RCB50 concretes were 0.17, 0.13, and 0.12%, respectively.

In conclusion, to improve the chloride resistance of recycled aggregate concrete, use of GFA and GBA to partially replace cement is very effective. Although the lowest chloride content was also found in recycled aggregate concrete containing 50% GFA and GBA, the lowest compressive strength was also found at this replacement rate. Therefore, the suitable replacement of GFA and GBA to obtain recycled aggregate concrete having both suitable strength and chloride resistance is 20% by weight of binder.

4.9 Expansion of Concrete due to Sulfate Attack

In this study, the expansion of concrete was studied on the mix proportion with W/B ratio of 0.65 only. The concrete specimens were divided into two groups, the first one was immersed in 5% $MgSO_4$ solution and the other was immersed in 5% $NaSO_4$ solution. The results of the expansions of concretes immersed in 5% $MgSO_4$ and 5% $NaSO_4$ solutions are shown in Tables 4.7 and 4.8, respectively.

Figures 4.23 and 4.24 show the results of the expansions of concretes containing GFA and GBA immersed in 5% $MgSO_4$ solution, respectively while Figures 4.25 and 4.26 show the ones of concretes containing GFA and GBA immersed in 5% Na_2SO_4 solution, respectively. The expansions of 65CON concrete at immersion times of 6, 12, 18, and 24 months in 5% $MgSO_4$ were 0.02673, 0.04172, 0.06046, and 0.07621%, respectively while the ones immersed in 5% Na_2SO_4 solution at the same times were 0.03808, 0.04960, 0.07264, and 0.09919%, respectively. For 65RC concrete, the expansions were higher than those of 65CON concrete immersed in both sulfate solutions. The expansions of 65RC concrete after immersed in 5% $MgSO_4$ for 6, 12, 18, and 24 months were 0.02753, 0.04405, 0.07758, and 0.10011%, respectively. In 5% Na_2SO_4 solution, the expansions of 65RC concrete at the same times were 0.04375, 0.05830, 0.08076, and 0.10613, respectively. The results indicated that 65CON concrete expanded in 5% Na_2SO_4 solution more than in 5% $MgSO_4$ solution similar to the result of expansion behavior of Portland cement mortars immersed in 5% Na_2SO_4 and 5% $MgSO_4$ solutions observed by Santhanam, et al. (2002).

Table 4.7 Expansion of concretes immersed in 5% $MgSO_4$ solution

Immersed Time (months)	Expansion of Concretes (%)							
	65CON	65RC	65RCF20	65RCF35	65RCF50	65RCB20	65RCB35	65RCB50
0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
1	0.00525	0.00451	0.00526	0.00423	0.00348	0.00499	0.00448	0.00276
2	0.00875	0.00976	0.00874	0.00723	0.00522	0.00724	0.00771	0.00527
3	0.01324	0.01276	0.01049	0.01021	0.00895	0.01048	0.01045	0.00929
4	0.01449	0.01502	0.01399	0.01196	0.01069	0.01423	0.01293	0.01079
5	0.01974	0.02177	0.01725	0.01494	0.01243	0.01897	0.01666	0.01406
6	0.02673	0.02753	0.02448	0.01968	0.01815	0.02521	0.02188	0.01833
7	0.02823	0.03103	0.02747	0.02292	0.02114	0.02821	0.02711	0.02586
8	0.03248	0.03403	0.03072	0.02691	0.02488	0.02996	0.02885	0.02786
9	0.03323	0.03454	0.03272	0.03014	0.02711	0.03070	0.02959	0.02786
10	0.03722	0.03754	0.03273	0.03089	0.02761	0.03220	0.03059	0.03012
11	0.03797	0.04104	0.03372	0.03239	0.02960	0.03669	0.03656	0.03238
12	0.04172	0.04405	0.03872	0.03363	0.02935	0.03671	0.03755	0.03414
13	0.04222	0.05230	0.03871	0.03388	0.02985	0.03995	0.03780	0.03439
14	0.04547	0.05380	0.03772	0.03463	0.02985	0.04117	0.04004	0.03589
15	0.05222	0.06282	0.03822	0.03488	0.03135	0.04368	0.04029	0.03489
16	0.05322	0.06807	0.03897	0.03613	0.03184	0.04393	0.04128	0.03640
17	0.05671	0.07108	0.04172	0.03588	0.03134	0.04468	0.04153	0.03590
18	0.06046	0.07758	0.04172	0.03638	0.03233	0.04568	0.04277	0.03791
19	0.06546	0.08084	0.04172	0.03638	0.03183	0.04518	0.04228	0.03765
20	0.06521	0.08584	0.04221	0.03737	0.03233	0.05016	0.04302	0.03816
21	0.07071	0.08959	0.04371	0.03687	0.03382	0.05315	0.04427	0.03891
22	0.06771	0.08910	0.04571	0.04035	0.03382	0.05465	0.04576	0.04016
23	0.07071	0.09135	0.04771	0.04186	0.03532	0.05415	0.04700	0.04092
24	0.07621	0.10011	0.05071	0.04335	0.03755	0.06009	0.04949	0.04700

Table 4.8 Expansion of concretes immersed in 5% Na_2SO_4 solution

Immersed Time (months)	Expansion of Concretes (%)							
	65CON	65RC	65RCF20	65RCF35	65RCF50	65RCB20	65RCB35	65RCB50
0	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
1	0.01002	0.01046	0.00554	0.00599	0.00376	0.00498	0.00797	0.00498
2	0.01854	0.02092	0.01108	0.00974	0.00703	0.01244	0.01046	0.00797
3	0.02254	0.02690	0.01485	0.01448	0.01004	0.01517	0.01694	0.01095
4	0.02455	0.03189	0.02315	0.01748	0.01155	0.02040	0.01993	0.01544
5	0.03156	0.03887	0.02467	0.02347	0.02108	0.02786	0.02242	0.02066
6	0.03808	0.04375	0.03222	0.02497	0.02359	0.03035	0.02491	0.02191
7	0.04008	0.04609	0.03473	0.03096	0.02560	0.03234	0.02939	0.02589
8	0.03908	0.04833	0.03977	0.03495	0.03112	0.03508	0.03188	0.02838
9	0.04308	0.05182	0.03927	0.03845	0.03313	0.03632	0.03537	0.03087
10	0.04484	0.05232	0.04329	0.04094	0.03564	0.03930	0.03886	0.03237
11	0.04759	0.05481	0.04531	0.04194	0.03614	0.04229	0.03986	0.03685
12	0.04960	0.05830	0.04480	0.04344	0.03815	0.04328	0.04235	0.03859
13	0.05160	0.06054	0.04833	0.04619	0.03916	0.04726	0.04434	0.04033
14	0.05461	0.06478	0.04883	0.04494	0.04116	0.04900	0.04608	0.04133
15	0.05962	0.07026	0.04808	0.04694	0.04167	0.04901	0.04534	0.04282
16	0.06262	0.07155	0.04984	0.04544	0.04267	0.05050	0.04688	0.04332
17	0.06713	0.07823	0.05235	0.04793	0.04468	0.05224	0.04783	0.04581
18	0.07264	0.08076	0.05135	0.04993	0.04719	0.05423	0.04882	0.04730
19	0.07565	0.08625	0.05361	0.05043	0.04794	0.05871	0.05281	0.04880
20	0.07690	0.08974	0.05512	0.05093	0.04920	0.06120	0.05430	0.05128
21	0.08341	0.09318	0.05890	0.05343	0.05020	0.06418	0.05580	0.05427
22	0.08792	0.09824	0.05991	0.05442	0.05095	0.06717	0.05779	0.05527
23	0.09268	0.10314	0.06041	0.05393	0.05171	0.07065	0.05978	0.05776
24	0.09919	0.10613	0.06293	0.05792	0.05572	0.07214	0.06277	0.06025

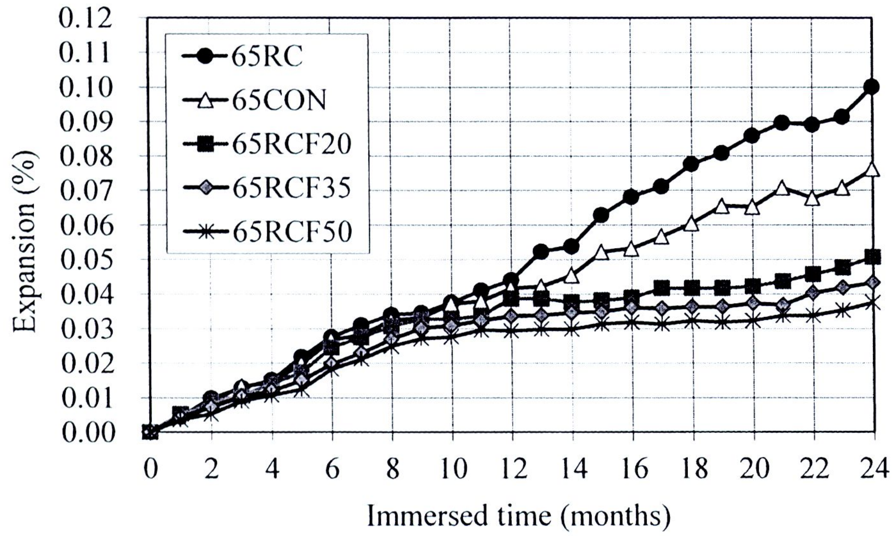


Figure 4.23 Relationship between expansion and immersed time in 5% $MgSO_4$ solution of recycled aggregate concretes with and without GFA

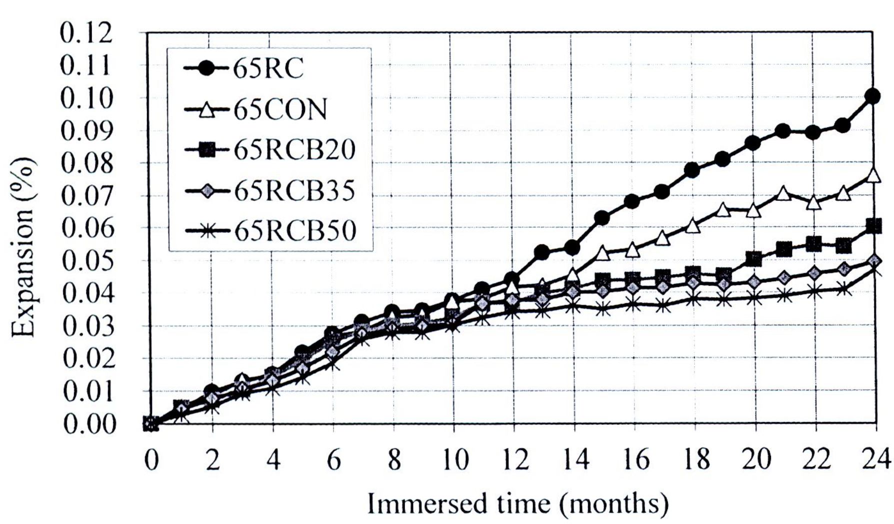


Figure 4.24 Relationship between expansion and immersed time in 5% $MgSO_4$ solution of recycled aggregate concretes with and without GBA

When the immersed time of concretes increased, the highest expansion in each solution occurred in 65RC concrete, the expansions of 65RC concretes in 5% $MgSO_4$ and in 5% Na_2SO_4 solutions at 24 months were 0.10011 and 0.10613% or approximately 1.3 and 1.1 times of 65CON concretes, respectively. Since the voids and cracks on recycled aggregate serving for both of sulfate solutions to easily penetrate into the recycled aggregate concrete and then reacted with the hydration products to form the gypsum and ettringite which can expand and resulted in higher expansion.

When GFA was used to partially replace cement in recycled aggregate concrete, the expansions of 65RCF20, 65RCF35, and 65RCF50 concretes immersed in 5% $MgSO_4$ solution for 24 months were 0.0507, 0.0434, and 0.0375% or approximately 0.67, 0.57, and 0.49 times of 65CON concrete, respectively. For concretes containing GFA immersed 5% Na_2SO_4 for 24 months, the expansions of 65RCF20, 65RCF35, and 65RCF50 concretes were 0.0629, 0.0579, and 0.0557% or approximately 0.63, 0.58, and 0.56 times of 65CON concrete, respectively.

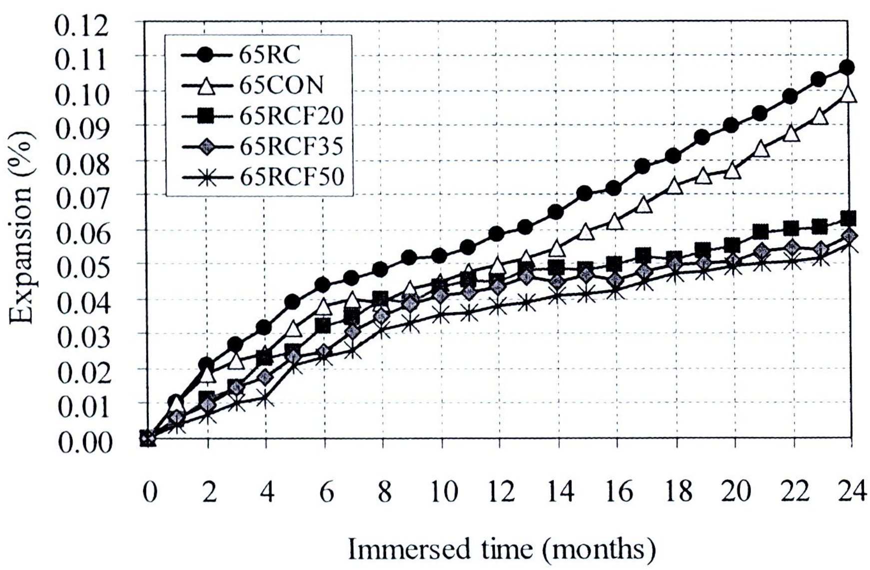


Figure 4.25 Relationship between expansion and immersed time in 5% Na_2SO_4 solution of recycled aggregate concretes with and without GFA

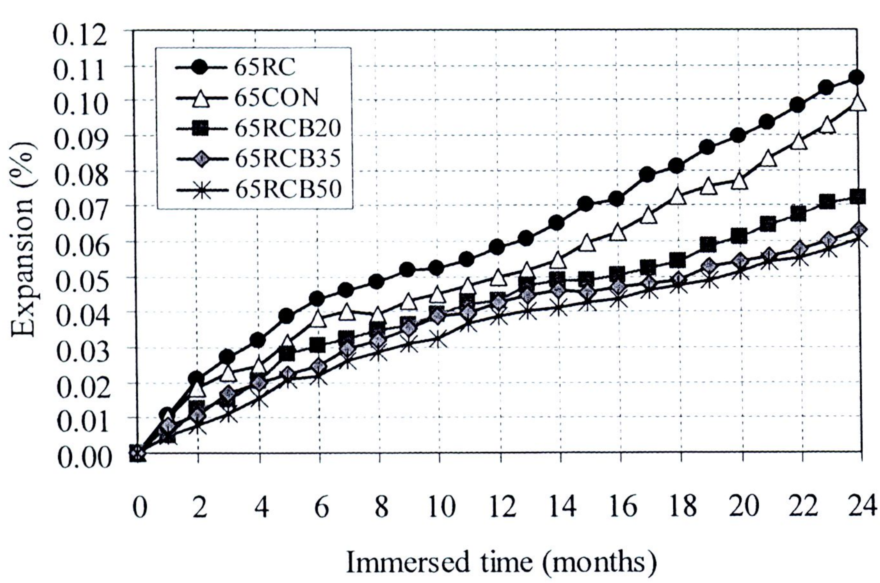


Figure 4.26 Relationship between expansion and immersed time in 5% Na_2SO_4 solution of recycled aggregate concretes with and without GBA

Similarly, the expansions of recycled aggregate concrete immersed in 5% $MgSO_4$ and 5% Na_2SO_4 solutions were lower than those of 65CON concrete when GBA was used to partially replace cement in recycled aggregate concrete. The expansions of 65RCB20, 65RCB35, and 65RCB50 concretes immersed in 5% $MgSO_4$ solution for 24 months were 0.06009, 0.04909, and 0.04700% or approximately 0.79, 0.64, and 0.62 times of 65CON concrete, respectively while the expansions of these concretes immersed in 5% Na_2SO_4 solutions were 0.0721, 0.0628, and 0.0602% or 0.73, 0.63, and 0.61 times of 65CON concrete, respectively.

The results indicated that the use of GFA and GBA to replace cement could decrease the expansion of recycled aggregate concrete to be lower than that of 65CON concretes. Since, the use of GFA and GBA to partially replace cement could reduce tricalcium aluminate (C_3A) which can react with the sulfates to form ettringite and reduce $Ca(OH)_2$ from the hydration reaction which can react with sulfate to form gypsum by consuming $Ca(OH)_2$ in the pozzolanic reaction (Bonen and Cohen, 1992; Cao, et al., 1997). Moreover, products from pozzolanic reaction could also reduce voids in recycled aggregates and cement paste resulting in the denser recycled aggregate concrete thus the sulfate solutions could not easily penetrate into the concrete. The results of the decreasing of the expansions of recycled aggregate concretes containing GFA and GBA were consistent to the results of their water permeability. Moreover, the expansions of recycled aggregate concretes decreased with increasing the replacement of GFA and GBA. For instance, use of GBA at 35 and 50% to replace cement in recycled aggregate concretes (65RCB30 and 65RCB50 concretes) which were immersed in 5% $MgSO_4$ solution for 24 months could reduce the expansions of recycled aggregate concrete by 51 and 53%, respectively as compared to 65CON concrete.

Although the use of GFA and GBA in recycled aggregate concrete is a good method to reduce the expansions due to sulfate attack, the high damage occurred on the surface of the recycled aggregate concretes containing GFA and GBA at 35 and 50% by weight of binder, especially on the surfaces of the concretes immersed in 5% $MgSO_4$ solution. It was similar to the results of Chulsilp, et al. (2009b) who reported the surface damage of mortars containing ground bagasse ash with high LOI (d_{50} = 10 μm) at 30 and 40% by weight of binder immersed in 5% $MgSO_4$ solution for 12 months. For recycled aggregate concrete immersed in 5% Na_2SO_4 solution, the damage was only found in 65RCB50 concrete as cracks at the corner edges. The damage of concrete surface is shown in Figures 4.27 and 4.28. This is due to the low compressive strength of recycled aggregate concrete with high volume of GFA and GBA which served the concrete surface to easy swell, crack, and then spall when the volume of gypsum and ettringite increased. Moreover, magnesium silicate hydrate (MSH), a product from sulfate attack, which had low cementitious contributing to the concrete surface spalled easily when the ettringite expanded.

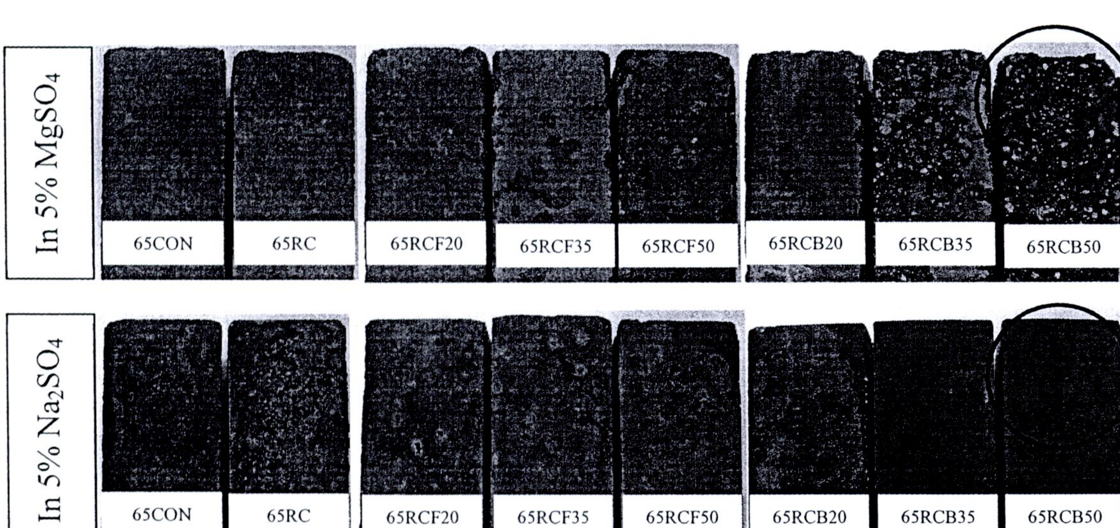


Figure 4.27 Concrete samples after immersing in 5% $MgSO_4$ solution and in 5% Na_2SO_4 solution for 24 months

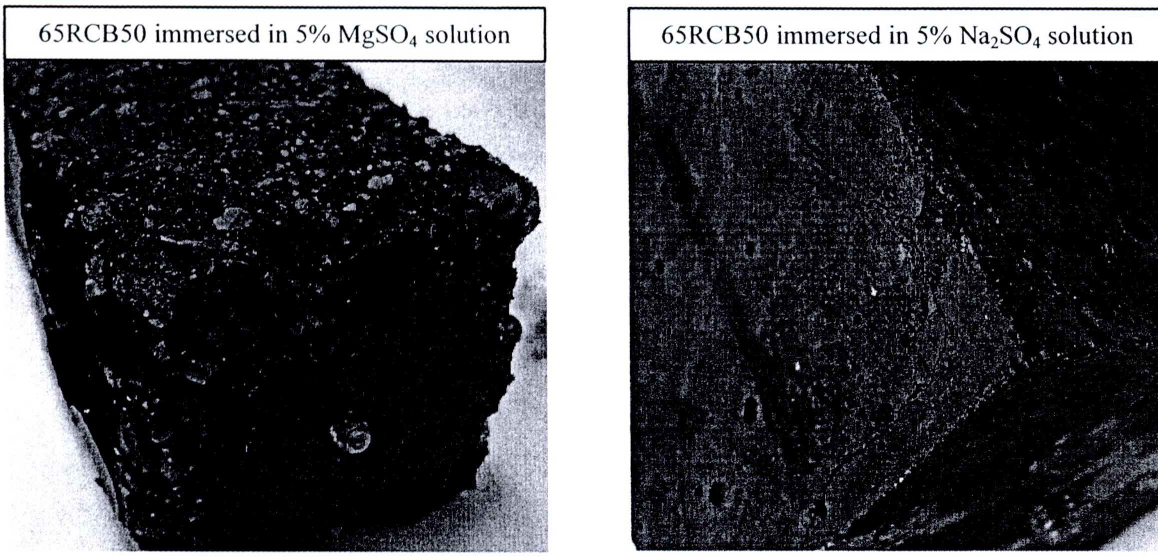


Figure 4.28 The damage of 65RCB50 concretes immersed in 5% $MgSO_4$ and 5% Na_2SO_4 solutions for 24 months

Therefore, GFA and GBA are recommended to be used to partially replace cement in recycled aggregate concrete to reduce the expansion due to sulfate attack. However, it should not be used more than 20% by weight of binder to avoid the damage at the surface of the recycled aggregate concrete.