Durability of Concretes Containing Supplementary Cementitious Materials

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Abstract

An experimental investigation was carried out to study the influence of constituent materials on concrete durability. Three groups of concrete specimens with silica fume/fly ash were cast and tested. In this study, compressive strength test, water absorption test, rapid chloride penetration test（RCPT）, chloride ion diffusion test and gas permeability test were performed. Various test results were compared. It shows that the water/binder ratio is still a key factor to influence the durability of concrete. The application of pozzolanic materials can reduce the permeability and improve the mechanical properties of concrete, and silica fume is more beneficial than fly ash. Besides, the cement content and aggregate size are also significant factors affecting concrete durability.

Keywords：pozzolanic materials, strength, permeability, durability.

1. Introduction

Concrete is the most widely used construction material because there is a general perception that concrete is strong and durable, performing well throughout its service life. However, sometimes it doesn't perform adequately because of poor design, poor construction, inadequate curing, severe exposure or combination of these factors. Numerous cases of structure deterioration resulted from concrete degradation, crack and corrosion[1-4]. Recently the durability of concrete structures has attracted considerable interest in concrete practice and materials research[3, 5, 6]. Concrete durability is an important factor to determine the service life of the structures. ACI Committee 201 [7] defines the durability of portland cement concrete is as its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration; that is, durable concrete can experience a long service life in most natural environments without deterioration.

For a new construction, it is important to select materials and proportions. In addition, it is also necessary to maintain water tightness of the structure as long as possible throughout the intended service life. Concrete is composed principally of cement, water, and aggregates. Most concretes produced are multicomponent products containing one or more admixtures along with three basic components. It is known that the constituent materials have a significant effect on both the pore structure and the pore solution of hardened concrete[8-11]. Therefore, before mixing concrete, proper selection and proportion of constituent materials are extremely important.

The durability is always a major concern for concrete structure exposed to aggressive environments. Factors to be considered in concrete durability include constituent materials, construction processes, and the environment to which the concrete structure is exposed [4, 12-14]. Based on the performance of concrete in marine environment and the causes of concrete deterioration, it is evident that concrete permeability is the most important factor affecting durability. Thus evaluation of concrete permeability can be used to estimate its durability[15-20]. There are many testing methods for measuring concrete permeability, each method has its basic testing principle. In this study, compressive strength test, water absorption test, rapid chloride penetration test, chloride ion diffusion test and gas permeability test were performed to evaluate the influence of constituent material on concrete durability.

2. Experimental program

2.1 Materials, mixing and preparation of specimens

Type Ⅰ portland cement was used in all mixes. Fly ash（class F）and silica fume with 96 % SiO_2, a specific gravity of 2.15 (±0.01) and the surface area of 24m^2/g were used. Coarse aggregate ranged from 2.36mm to 19mm. Fine aggregate was river sand with a maximum size of 4mm. Type G superplasticizer was used with a specific gravity of 1.2 (±0.05) and a solid content of 39 ~ 41%, the pH value was 8.0 ~ 9.0 and the content of chloride ion is less than 1000ppm. Three groups of concrete mixes were designed. Details of mix proportions are given in Table 1. The water to binder ratio was kept at 0.35,0.45 and 0.60, respectively, and the slump was maintained in the range of 14±2cm. During casting, all the specimens were compacted by rodding and vibration. During the first 24 hours, the specimens were left in the molds. Then the specimens were removed and cured in water until the time of testing. Eighteen 100x200 mm cylindrical specimens were cast for each mix.

2.2.Experimental method

The slump test of concrete was performed in accordance with ASTM C143-10a [21]. The compressive strength was determined according to ASTM C39-12 [22]. The water absorption test by drying and immersion was conducted according to ASTM C642-06 [23]. Absorption is measured by drying concrete to a constant mass, and then immersing it in water, and measuring the mass increase as a percentage of dry mass. The rapid chloride penetration test （RCPT） was carried out following the standard ASTM C1202-12 [24]. Sodium hydroxide solution (0.3 N NaOH) and sodium chloride solution (3% NaCl by mass) were placed in the chambers on both sides of concrete specimen (100 mm diameter and 50 mm thickness), and a direct current voltage of 60 V was applied. The current passing through the concrete specimen was monitored at every thirty minutes over a six-hour period and the total charge passed (Coulombs) was computed. The chloride diffusion test was carried out at the age of 28 days using a thin concrete plate (2 cm thick). The plate was placed between two chambers and the edges were sealed with epoxy resin. The solution used was 3.5% NaCl as the cathodic electrolyte and distilled water as the anodic electrolyte[25]. A potential difference of 20 V was applied to accelerate the chloride ion migration and the chloride concentration was measured every twelve hours. The experimental arrangement is shown in Fig. 1. The gas permeability test was carried out using the Cembureau method. Testing equipments consist of a gas supply, a pressure regulator, testing cells and flow meter. Fig. 2 shows the test arrangement. Before testing, the specimens（100 mm in diameter and 30 mm in thickness）were oven-dried at 100℃ for 3 days and then placed in a environmental chamber with a temperature of 25 ℃ and relative humidity of 100% for 2 days. After sealing the specimen in the cell, oxygen gas was pumped at constant pressure of 3 bar($3x10^5 N/m^2$). The gas flow was recorded and the gas permeability coefficient was computed. In order to get constant drying conditions

Table 1.-Mix proportion of concrete (kg/m^3)

mix No.	w/b	cement	water	fly ash	silica fume	sand	aggregate	super plasticizer	slump (cm)
A0		552	185	---	---	680	963	8	16
AS05	0.35	524	185	---	28	668	963	8	16
AS10		497	188	---	56	656	963	8	15
B0		429	190	---	---	783	963	3	15
BF10		386	190	43	---	764	963	5	14
BF20	0.45	344	188	86	---	745	963	3	12
B385		385	170	---	---	874	963	3	13
B340		340	150	---	---	964	963	3	13
C0		312	193	---	---	882	963	---	12
CS	0.6	312	193	---	---	882	963[a]	---	13
CG		312	193	---	---	882	963[b]	---	13

Note:1 . [a] Coarse aggregate size is between 2.36 mm and 9.5 mm.
[b] Coarse aggregate size is between 4.75 mm and 19.0 mm.

2 . A0, B0 and C0 stand for the concretes with w/b ratios of 0.35, 0.45 and 0.6, respectively. AS05 and AS10 stand for the concretes by replacing Portland cement with 5% and 10% silica fume, respectively. BF10 and BF20 stand for the concretes by replacing Portland cement with 10% and 20% fly ash, respectively. B385 and B340 stand for the concretes with cement contents of 385 kg/m^3 and 340 kg/m^3, respectively. CS and CG stand for the concretes with various aggregate sizes.

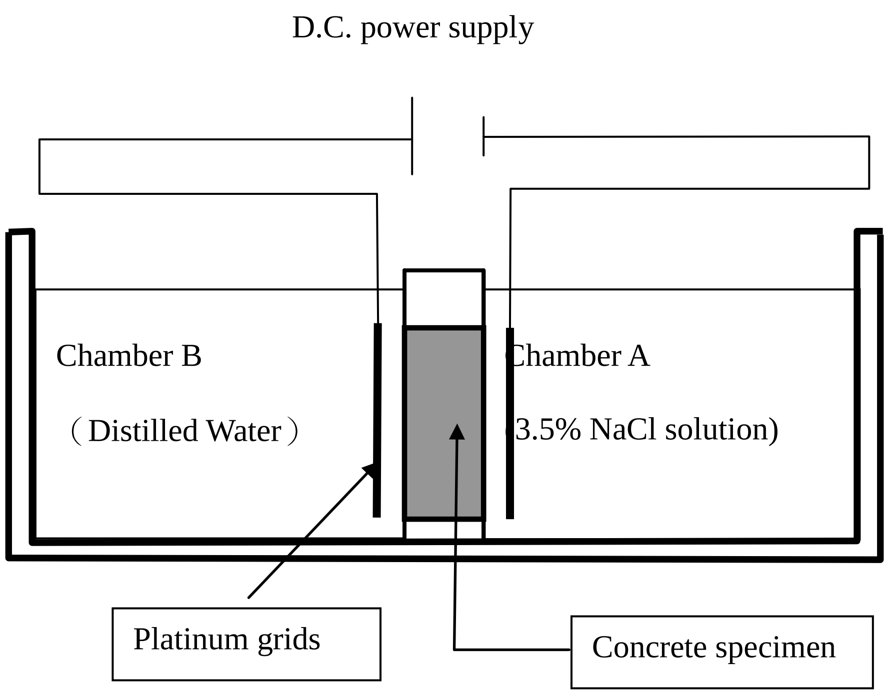

Fig. 1.- Set-up of chloride ion diffusion test

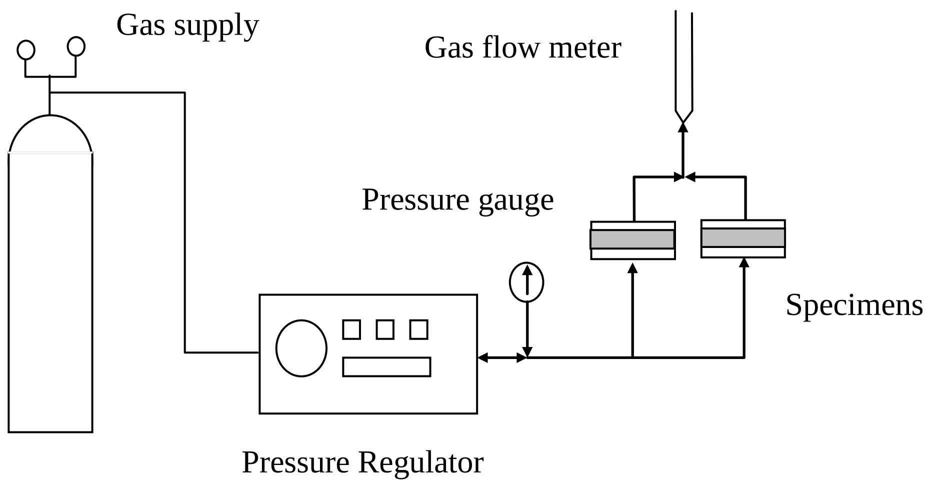

Fig. 2.- Set-up of gas permeability test

3. Results and discussions

3.1 Strength development

Concrete specimens (100 x 200mm) were tested for compressive strength at the age of 7, 14, 28, 56 and 91 days as shown in Fig. 3. The compressive strength increases with age and the water/binder ratio is still a key factor affecting concrete strength development. It indicates that low water/binder ratios contribute significantly to early strength development, due to the rapid and dense growth of calcium silicate hydrate (C-S-H) gel and low porosity. The use of other cementitious materials influences concrete strength development. Partial silica fume replacement for cement results in higher strength development because the pozzolanic reaction and filling effect are beneficial in minimizing the pore size and volumes, thus improving the strength. The differences of 91-day compressive strength among all mixes become less than those at the age of 28 days.

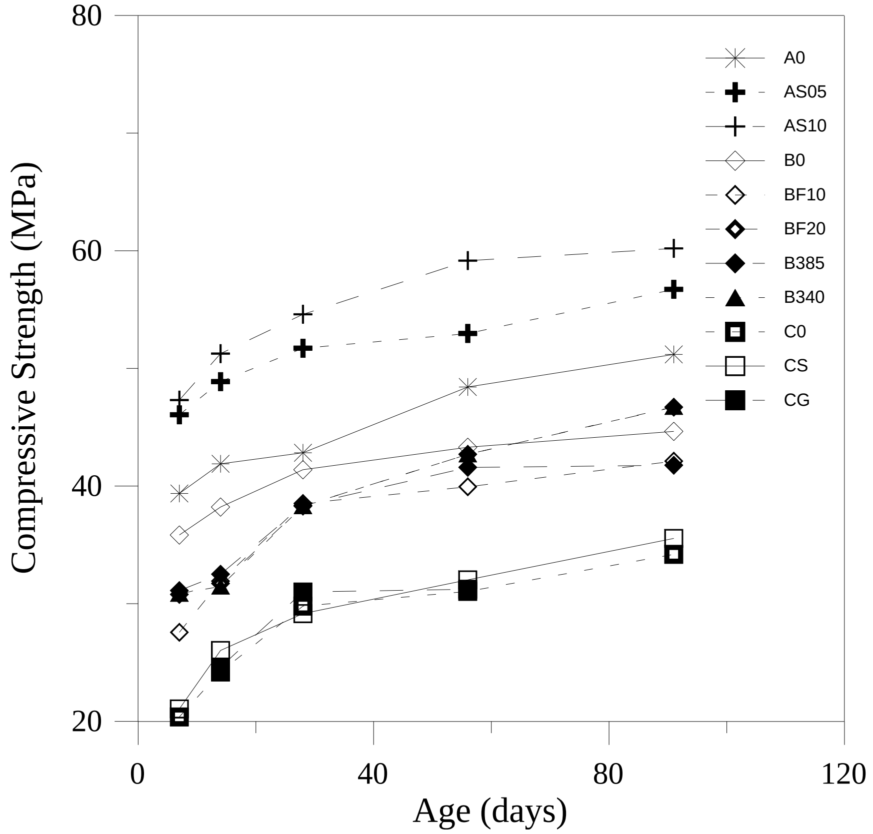

Fig. 3.- Compressive strength development

3.2 Absorption

Concrete is a porous material in which water can be absorbed by penetration, diffusion and capillary absorption. The volume of pore under concrete surface can be measured by absorption rate. The absorption rates are shown in Table 2. It can be seen that absorption rate increases with an increase in water/binder ratio and decreases with an increase in silica fume and fly ash application. However, the absorption rates of specimens with different aggregate sizes are almost the same. In general, high absorption rate implies high-porosity concrete, which may have potential durability problems. And the silica fume and fly ash application may increase the tightness of mortar.

Table 2.-Absorption rate, charge passed, diffusion coefficient and gas permeability coefficient

mix No.	absorption rate (%)	charges passed (coulombs)	diffusion coefficient, D ($\times10^{-9}cm^2/sec$)	gas permeability coefficient, K_0 ($\times10^{-17}m/s$)
A0	4.84	4467	4.69	1.225
AS05	4.64	1384	3.01	1.141
AS10	4.29	568	2.68	1.088
B0	5.22	4701	5.07	1.532
BF10	5.02	3178	4.81	1.502
BF20	4.95	1788	4.27	1.169
B385	5.37	7994	7.41	1.537

B340	5.56	10218	8.99	2.750
C0	6.12	14603	9.56	3.145
CS	5.90	11200	8.95	2.708
CG	6.07	15352	10.56	2.845

3.3 Rapid chloride penetration

The RCPT is a convenient test method to evaluate concrete permeability. The total charges passed in six hours through various concrete mixtures are shown in Table 2. It is evident that the amount of charge passed in six hours through various concretes decrease with a decrease in water/binder ratio and decreases with an increasing silica fume and fly ash replacement for cement. Concrete with a low water/binder ratio has a lower charge passed than concrete with a high water/binder ratio due to the denser microstructure. In addition, the transport of ions in concrete depends on the pore structure of concrete. Silica fume and fly ash affect both pore structure and the ion concentration in the pore solution, so the reduction of total charge passed for concrete with silica fume and fly ash is owing to the change in the conductivity of pore solution as well as the change in the pore volume and tortuosity. For specimens with various cement contents, the total charges passed in six hours decrease by increasing cement contents and increase by an increasing aggregate size. It implies the concrete with less cement content has a higher chloride penetration rate and the concrete with greater aggregate size has lower resistance against chloride penetration. The concrete with higher cement content may have greater ability to bind chlorides to form Friedel's salt owing to the higher tricalcium aluminate (C_3A) content. Higher chloride binding in concrete leads to the deposition of the voluminous chloride bearing phase such as Friedel's salt in the larger pores causing greater pore constriction and tortuosity.

3.4 Chloride diffusion

In chloride diffusion test, the accumulated concentrations of chloride ions increase with time. The chloride ion diffusion of all mixes reached a steady state during the test. Linear regression can be carried out for the steady state portions of chloride ion concentration-time curve. The slope is the flow rate of chloride ions for each concrete mix. If the slope of chloride concentration-time curve in the steady state is known, the diffusion coefficients can be calculated using Fick's second law. The diffusion coefficients of all mixes are listed in Table 2. The diffusion coefficient decreases with a decrease in water/binder ratio and with increase in silica fume or fly ash replacement. Concrete with a low water/binder ratio is less permeable to chloride than concrete with a high water/binder ratio due to the denser microstructure. For the silica fume or fly ash addition to concrete, the resistance against chloride penetration increases by an increase in silica fume or fly ash replacement. It is explained by greater degree of pore refinement and filler action owing to silica fume or fly ash and silica fume is more beneficial than fly ash. In addition, specimens with various cement contents, the diffusion coefficient decreases by increasing cement content and aggregate sizes. It indicates the cement content and aggregate sizes also have a significant influence on the diffusion coefficient of concrete. The penetration of external chloride ions into concrete is influenced by the paste/aggregate interfacial effects and aggregate sizes.

3.5 Gas permeability

Measuring the porosity of concrete with gas requires that the main pores were filled with gas because the flow of gases is much more rapid in empty pores than in pores filled with water. Therefore, it is necessary to precondition the specimens at constant temperature and humidity before the gas permeability test. Gas permeability is measured at a degree of water saturation close to "zero". In this study, the gas permeability coefficients through the various concrete mixtures at the age of 91 days were obtained as listed in Table 2. The test results show that the gas permeability coefficient decreases with a decrease in water/binder ratio and with increase in silica fume or fly ash replacement. It implies that the higher water/binder ratio has the higher porosity and the coarser pore structure because the volume of C-S-H gel decreases with increasing water/binder ratio for a given concrete. Besides, concrete, based on cement containing silica fume or fly ash, exhibits lower or similar gas permeability coefficients compared with the pure cement concrete. It indicates that the addition of silica fume and fly ash in the cement seems to improve the permeability of concrete. For the same water/binder ratio specimens of various cement contents, the gas permeability coefficient decreases with increasing cement content. The higher the cement content, the denser is the cement paste. But for the same water/binder ratio specimens with various aggregate sizes, the gas permeability coefficients are not much different. The porosity of aggregate is much less than the porosity of cement paste. Thus the gas permeability of concrete may be influenced by the mortar.

3.6 Constituent materials versus concrete durability

Within the scope of this study, the durability evaluation indices of concrete are proposed from Figs. 4 ~ 8. Fig. 4 shows the relationship between water/binder ratio and durability. Relative ratio of test result based on A0=1（w/b=0.35）was compared with those of B0 （w/b=0.45） and C0 （w/b=0.6）. It shows that the compressive strengths of B0 and C0 were about 0.8 and 0.7 times as much as that of A0, respectively. The charge passed of C0 is about 3.2 times as much as that of A0. Both of the chloride diffusion coefficient and gas permeability coefficient of C0 are about 2.5 times as much as that of A0. It can be seen that the water/binder ratio is still a key factor affecting the strength and durability of concrete in this study. The lower w/b ratio is, the better durability obtained.

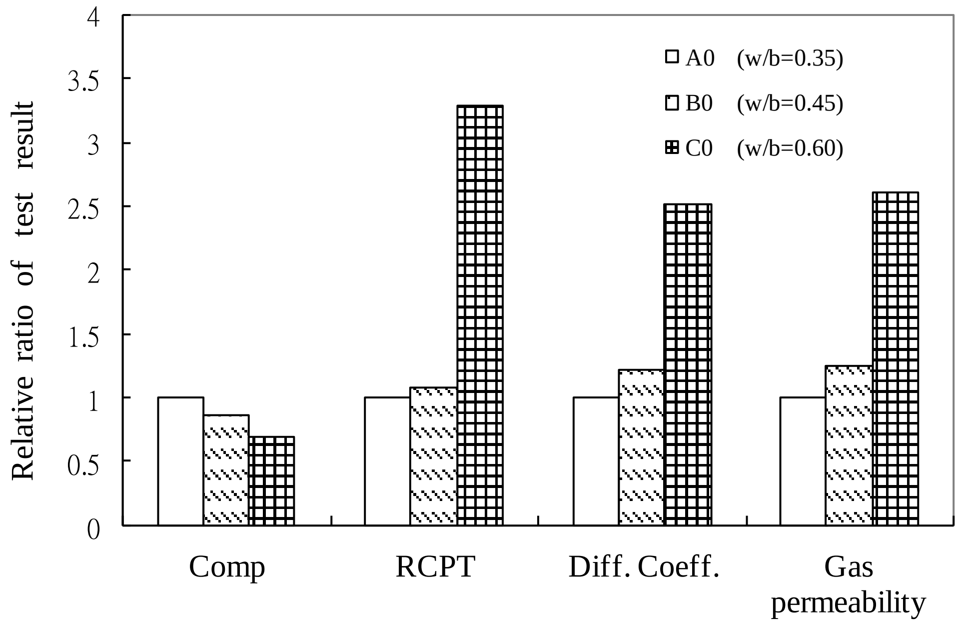

Fig. 4 - Water/binder ratio vs durability

Fig. 5 shows the effect of silica fume application on durability. Relative ratio of test result based on A0=1 （w/b=0.35, 0% by weight cement replacement with silica fume） was compared with those of AS05 （w/b=0.35, 5% by weight cement replacement with silica fume）and AS10 （w/b=0.35, 10% by weight cement replacement with silica fume）. The compressive strengths of AS05 and AS10 show an increase of 18% and 20% compared to that of A0, respectively. The charge passed and the chloride diffusion coefficient of AS05 decreased to about 30% and 60% the results of A0, respectively. The charge passed and the chloride diffusion coefficient of AS10 were about 10% and 50% lower the result of A0. The gas permeability coefficient of AS05 and AS10 are about 90% and 85% the result of A0, respectively. It indicates that the application of silica fume may reduce the diffusivity and permeability of concrete, thus improving the paste-aggregate interface.

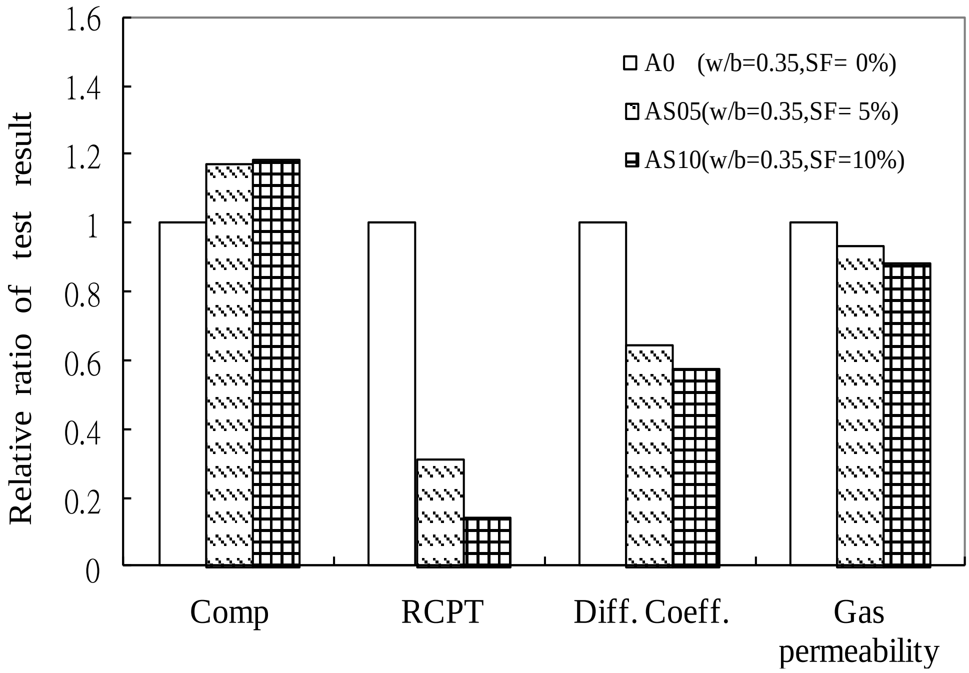

Fig. 5- Silica fume application vs durability

Fig. 6 shows the effect of fly ash application on durability. Relative ratio of test result based on B0=1 （w/b=0.45, 0% by weight cement replacement with fly ash） was compared with those of BF10 （w/b=0.45, 10% by weight cement replacement with fly ash） and BF20 （w/b=0.45, 20% by weight cement replacement with fly ash）. It shows that there is not much difference in compressive strength of concretes among B0, BF10 and BF20. But the charge passed and the chloride diffusion coefficient of BF10 were reduced to about 65% and 85% the results of B0, respectively. The charge passed and the chloride diffusion coefficient of BF20 were about 40% and 70% lower the result of B0. The gas permeability coefficient of BF10 and BF20 are about 95% and 70% the result of B0, respectively. It shows that the application of fly ash, like as silica fume, still can reduce the permeability and diffusivity of concrete, but silica fume is more beneficial than fly ash.

Fig. 7 shows the effect of cement content on durability. Relative ratio of test result based on B0=1（w/b=0.45, 430 kg cement content per cube meter）was compared with those of B385 （w/b=0.45, 385 kg cement content per cubic meter） and B340 （w/b=0.45, 340 kg cement content per cubic meter）. It shows that the compressive strengths of B0, B385 and B340 are very closed. However, the charge passed, chloride diffusion coefficient, and gas permeability coefficient of B0, B385 and B340 are more or less different. As the cement contents are reduced from 430 kg/m^3 to 340 kg/m^3 for specimens, the charge passed of B340 is about 2.2 times as much as that of B430. Both of the chloride diffusion coefficients and gas permeability coefficients of B340 are about 1.6 and 1.7 times as much as that of B430. It can be seen that for a given water/binder ratio concrete with higher cement content has a higher resistance to chloride ion penetration and less gas permeability. Both of the sizes and total volumes of pores were determined by the water/binder ratio and the degree of hydration. For a given water/binder ratio, concrete with higher cement content may have denser microstructure resulting from C-S-H filling effect.

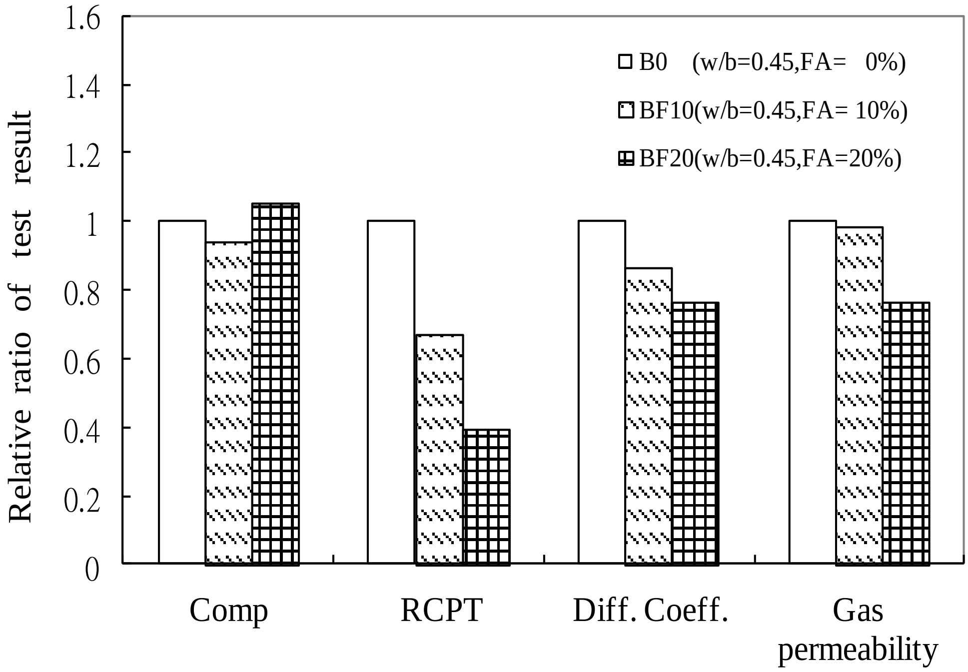

Fig.6 - Fly ash application vs durability

Fig. 8 shows the relationship between aggregate size and durability. Relative ratio of test result based on CS=1 （w/b=0.6, Coarse aggregate size is between 2.36 mm and 9.5 mm）was compared with those of C0（w/b=0.6, Coarse aggregate size is between 2.36 mm and 19.0 mm.） and CG （w/b=0.6, Coarse aggregate size is between 4.75 mm and 19.0 mm.）. It shows that the compressive strengths of CS, C0 and CG are closed at the same water/binder ratio. In addition, less difference was observed in the charges passed, chloride diffusion coefficient, and gas permeability coefficient of CS, C0 and CG. It indicates the effect of aggregate size on concrete durability is less important than those of water/binder ratio and contents of silica fume/fly ash. However, aggregate size has an influence on workability, unit weight and modulus of elasticity by grading, fine aggregate ratio (S/A) and aggregate porosity.

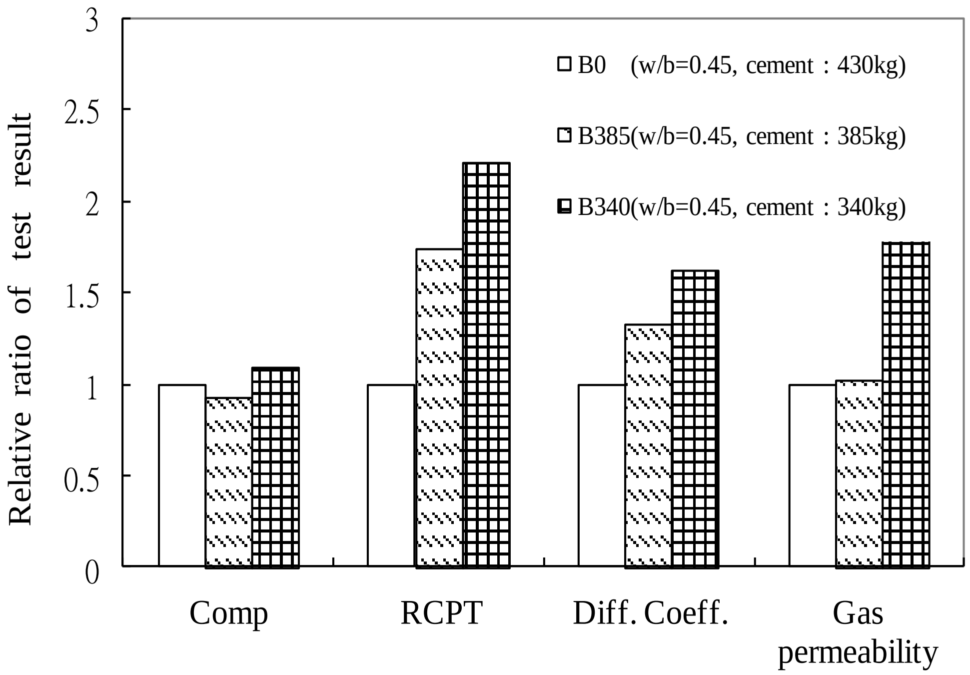

Fig. 7 - Cement content vs durability

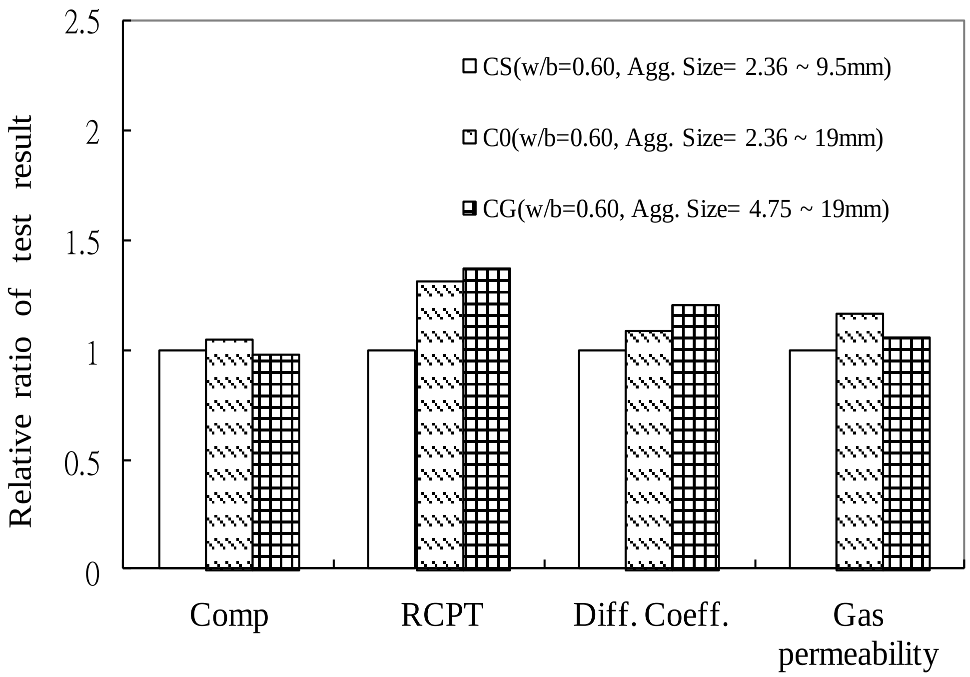

Fig. 8 - Aggregate size vs durability

4. Conclusions

Within the scope of this study, the following conclusions can be drawn.

(1) Concrete durability is affected by water/binder ratio, silica fume/fly ash application, cement content and aggregate size, however, concrete strength is mainly determined by water/binder ratio.
(2) The application of silica fume and fly ash can reduce the permeability and diffusivity and improve the mechanical properties of concrete, and silica fume is more beneficial than fly ash.
(3) Cement content has an influence on concrete durability and concrete with higher cement content has better durability.
(4) Aggregate size has an influence on concrete durability, but is less important than water/binder ratio and silica fume/fly ash application.
(5) Besides concrete compressive strength test, rapid chloride penetration test, chloride ion diffusion test and gas permeability test should be conducted to determine internal pore system and to evaluate concrete durability.

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