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Evaluation of Seawater Mixing and Curing on Strength Characteristics and Porosity of Fly Ash Concrete

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ABSTRACT

This paper presents the strength characteristics and porosity of concrete mixed with seawater and tap water incorporating Fly Ash (FA) with a water binder ratio of 40%, 50%, and 60%. The effect of seawater mixing, FA, and curing conditions such as tap water curing (TC), seawater curing (SC), and air curing (AC) on the strength performance of concrete was evaluated. Moreover, the total pore volume (porosity) and thermogravimetric-differential thermal analysis (TG-DTA) were also observed to verify the results of compressive strength of concrete cylinder specimens. Eight series of concrete mixtures using tap water or seawater as mixing water were prepared by OPC and FA as a binder specified in Japan Industrial Standard. Concrete specimens were demolded at 24 hours after casting, then cured in tap water, in seawater, and in air (20ºC, R.H. 60% controlled room). After certain curing of 28 days and 365 days, compressive strength was measured in accordance with Japan Industrial Standard. Based on the investigation result, it was obtained that seawater mixing improved the strength of OPC concrete and FA concrete up to 365 days in all curing conditions, in TC, SC, and AC. The Porosity of seawater-mixed OPC concrete and FA concrete was decreased compared to tap water-mixed concrete. It was also found that the mass change (weight loss) of hydration product (CH) of seawater-mixed OPC concrete was higher than that of tap water-mixed OPC concrete in TC and AC.

KEYWORDS: *Seawater mixing, curing condition, strength, porosity, fly ash concrete*

1. Introduction

Globally, approaching 30 billion tons of concrete produced annually (Monteiro et al 2017), which are several billion tons of fresh water are annually used for mixing water, curing water, and cleaning water in the concrete industry (Otsuki et al 2011, Miller et al 2016). It is well known that marine area takes up about two-thirds of the total earth area, which is consists of 96.5% ocean (sea water) of total global water. Seawater has an approximately total salinity of 3,5%, which is 78% sodium chloride (NaCl) (Neville 2001, Younis et al 2017). The utilization of seawater in the concrete industry is prohibited, cause of the initial corrosion risk of steel bars in concrete that induced by chloride in seawater. Nevertheless, in case of unavoidable circumstances, seawater may be used as mixing water, not only for plain concrete, but also for reinforced concrete (JSCE 2005, BIS 2000, Bertolini et al 2013). Accordingly, if the use of seawater is permitted in concrete production, it will be highly beneficial, it is not only in saving freshwater to anticipate water scarcity, but also in the construction costs of concrete infrastructures at mainly distant islands. By applicability of seawater as mixing and curing water in concrete, it could certainly also reduce emissions of CO2 gas of material transportation (Katano 2013, Yang 2019).

In terms quality of concrete, strength is a fundamental property to evaluate the durability of concrete. The durability and strength of concrete structures are interrelated, which may always be predicted by the relationship of the strength and durability of concrete (Adiwijaya et al 2017). Moreover, porosity is one of the important factors influencing the compressive strength of concrete, thus the porosity of concrete influences both its strength and durability (Kumar and Bhattacharje 2003, Kodraivendhan et al 2013). The investigation of concrete mixed with seawater on strength performance has been stated by some studies. Nishida et al (2013) reported that from 1974 to 2011, 68 papers have been published related to concrete mixed with seawater, which are 42 papers among them revealed strength performance. However, the studies on the strength of seawater-mixed concrete are not still achieved the agreement among researcher, whether seawater-mixing improve the strength development of concrete is still unclear in approximately 40 years period.

Therefore, in present study, strength performance of seawater-mixed and tap water-mixed concrete incorporating fly ash under three curing conditions such as tap water curing, seawater curing, and air curing were investigated. The aim of this study is to evaluate the effectiveness of seawater mixing, fly ash, and curing conditions on strength characteristics and porosity of concrete. This paper also elaborates the composition of hydration product (CH) in hardened cement-based material, which is considered as a parameter in evaluating the compressive strength of concrete mixed with seawater.

2. Experimental Methodology

2.1 Materials

In this study, Ordinary Portland Cement (OPC) and Fly Ash (FA) were used as binder, specified in Japan Industrial Standard (JIS Standard). The physical properties of binders and concrete materials such as coarse aggregate (G), fine aggregate (S), and natural seawater as mixing water (W) and curing water are described in Table 1. The source of seawater was taken in the seaside area in Itoshima, Fukuoka Prefecture, Japan under the summer season.

Table 1 Physical properties of material

Material	Description
Cement (OPC)	Density = 3.16 g/cm^3 Specific Surface Area = 3330 cm^2/g
Fly Ash	Density = 2.26 g/cm^3 Specific Surface Area = 3970 cm^2/g
Coarse Aggregate, G (Crushed stone)	Density (SSD) = 2.84 g/cm^3 , MSA = 20 mm FM = 6.68, Water absorption = 0.71 %
Fine Aggregate, S (Washed sea sand)	Density (SSD) = 2.56 g/cm^3 FM = 2.69, Water absorption = 1.61 %
Mixing Water, W (Natural seawater)	Density = 1.02 g/cm^3 Cl^- = 18.72 g/l , pH = 7.71

2.2 Series of concrete mixture

In this research, Eight concrete mixture series were investigated as shown in Table 2. Concrete mixtures with a water-binder ratio (W/B) of 40%, 50%, and 60% using tap water (T) and natural seawater (S) as mixing water were prepared. Three types of curing conditions such as tap water curing at 20°C (TC), seawater curing at 20°C (SC), and air curing (controlled room at 20°C, 60% R.H.) (AC) were used as curing conditions. Table 3 demonstrates the proportion of concrete mixtures, which was designed according to Japan Society of Civil Engineering (JSCE 2005).

Table 2 Mixture series of concrete

Mixture	W/B (%)	s/a (%)	Mixing water	Binder proportion (%)	
				OPC	FA
T40-F	40	45	Tap water	80	20
S40-F			Seawater	80	20
T50-N	50		Tap water	100	-
S50-N			Seawater	100	-
T50-F			Tap water	80	20
S50-F			Seawater	80	20
T60-F	60		Tap water	80	20
S60-F			Seawater	80	20

Table 3 Mix proportion of concrete

Mixture	Unit content (kg/m³)								Fresh properties		
	W	Binder		S	G	WR	AE* (liter)	Sp	Slump (cm)	Air (%)	Temp. (°C)
		OPC	FA								
T40-F	160	320	80	764	1028	1.75	1.15	-	5.0	3.1	23.0
S40-F	165	330	82	760	1022	-	0.79	5.36	12.5	5.6	24.0
T50-N	160	320	-	805	1087	1.00	2.00	-	8.0	6.2	16.0
S50-N	165	330	-	802	1083	1.03	1.27	-	8.0	6.0	18.0
T50-F	160	256	64	795	1074	1.00	2.00	-	9.5	5.8	17.0
S50-F	165	264	66	791	1068	1.03	1.68	-	10.0	3.8	20.0
T60-F	160	213	53	811	1099	0.50	1.28	-	7.0	3.3	23.0
S60-F	165	220	55	808	1095	0.58	1.45	-	6.0	3.5	23.0

WR: Water reducer (AE+WR), *100 times dilution

2.3 Test methods

Concrete cylinder specimens in size of ϕ100x200 mm were prepared for compressive strength. 24 hours after casted, concrete specimens were demolded, then cured in TC, SC, and AC as curing conditions. After a certain curing period of 28 days and 365 days, concrete specimens were tested in compressive strength in according to Japan Industrial Standard (JIS A 1108). The strength of each mixture was obtained from the compressive strength value of three specimens.

Porosity of concrete specimens was conducted at testing age of 28 days and 365 days, which were tested by Mercury Intrusion Porosimetry (MIP). Accordingly, complete drying of the samples was required to obtain results without error. In this study, the maximum applied pressure of MIP test was 33.000 psi (227 MPa), and the surface tension and contact angle of mercury was 485 dynes/cm and 130º, respectively.

In order to investigate the amount of hydration product of cement paste such as calcium hydroxide $Ca(OH)_2$ or CH, some concrete specimens at 28 days curing were selected. Slice specimens in size of approximately 0.5 cm in thickness were prepared, then the fragments were immersed in acetone for 24 hours before it was powdered. After that, the hydration product of powdered specimens was tested by simultaneous thermal analyzer (TG-DTA) apparatus.

3. Results and Discussion

3.1 Strength characteristics

In this research, the strength performance of concrete mixed seawater (S) and concrete mixed tap water (T) for OPC concrete and FA concrete in TC, SC, and AC was observed up to curing period of 365. All concrete specimens were developed in compressive strength up to 365 days from 28 days in each W/B of 40%, 50%, and 60% as exhibited in Figure 1. This result expresses that strength development up to 365 days of OPC concrete and FA concrete is not influenced by type of mixing water, tap water or seawater. The increment in compressive strength of seawater-mixed concrete and tap water-mixed concrete in water curing is larger than that of in air curing.

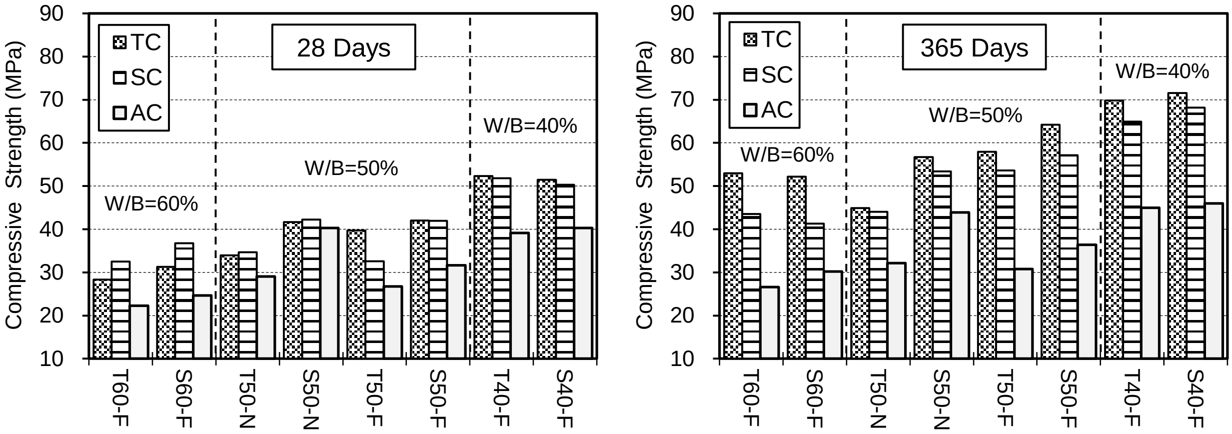

Figure 1. Strength development of concrete specimens

The effect of seawater mixing on the strength development up to 365-day of concrete was also found, which is the strength ratio of seawater mixing to tap water mixing (S/T) was more than one (above the line of equality) as shown in Figure 2. It means that strength performance up to 365 days of seawater-mixed concrete was higher compared to tap water-mixed concrete for both OPC and FA concrete. However, in case of strength ratio of seawater mixing to tap water mixing of the concrete specimen with 60% W/B in SC was slightly less than one. However, it can generally be stated that strength enhancement up to 365-day from 28 days of seawater-mixed FA concrete is improved compared to tap water-mixed FA concrete in all curing conditions, TC, SC, and AC. The ratio of the strength of OPC concrete was higher than that of FA concrete in all curing conditions. This result suggests that effectiveness of seawater mixing on strength enhancement up to 365 days is larger for OPC concrete than FA concrete.

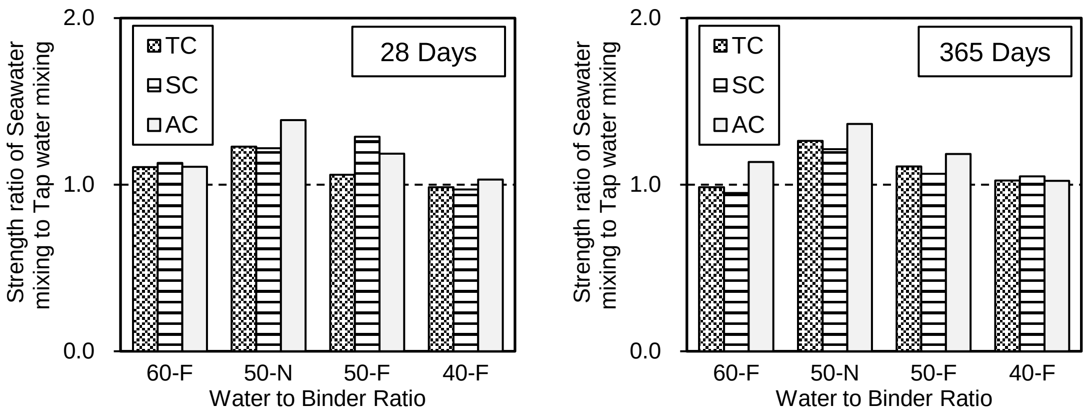

Figure 2. Strength ratio of seawater-mixed concrete to tap water-mixed concrete (S/T)

The influence of curing water (TC and SC) on the strength performance of seawater mixing and tap water mixing FA concrete is illustrated in Figure 3. It is also found that strength characteristics of FA concrete in TC and SC were almost similar in all concrete mixtures, which is the difference in compressive strength less than 10 percent. It reveals that there is no significant effect of type of curing water on compressive strength up to 365 days from 28 days. In other words, the compressive strength of seawater mixed and tap water mixed FA concrete is not affected by the type of curing water, TC or SC.

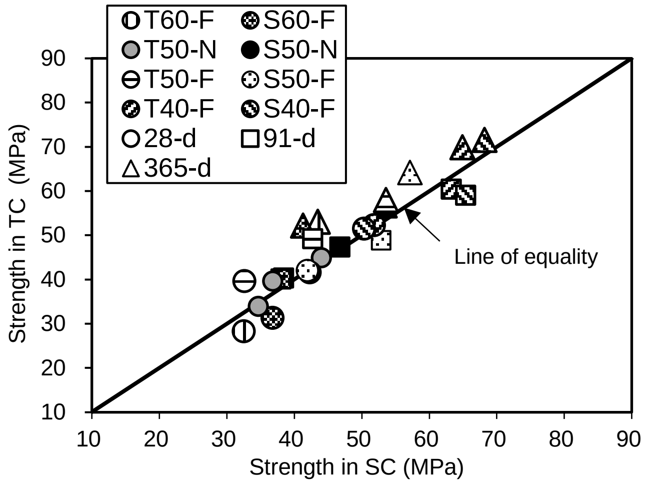

Figure 3. Strength in seawater curing (SC) vs. tap water curing (TC)

3.2 Thermogravimetric-Differential thermal analysis

Figure 4 represents the result of Thermogravimetric-Differential thermal analysis (TG-DTA) of selected concrete specimen at 28 days was carried out in this study. From this figure, it was observed that the mass change (weight loss) of the hydration product of portlandite $Ca(OH)_2$ or CH of seawater-mixed OPC concrete was higher than that of tap water-mixed concrete. It means that the percentage of portlandite (CH) of seawater mixing is increased compared to tap water mixing. The increasing hydration product of portlandite of OPC concrete mixed seawater in TC and AC was respectively enhanced 22% and 30% compared with tap water mixed OPC concrete, as depicted in Table 4. It was clearly obtained that strength is developed with increasing portlandite (CH), and it produces more calcium silicate hydrate (C-S-H), certainly.

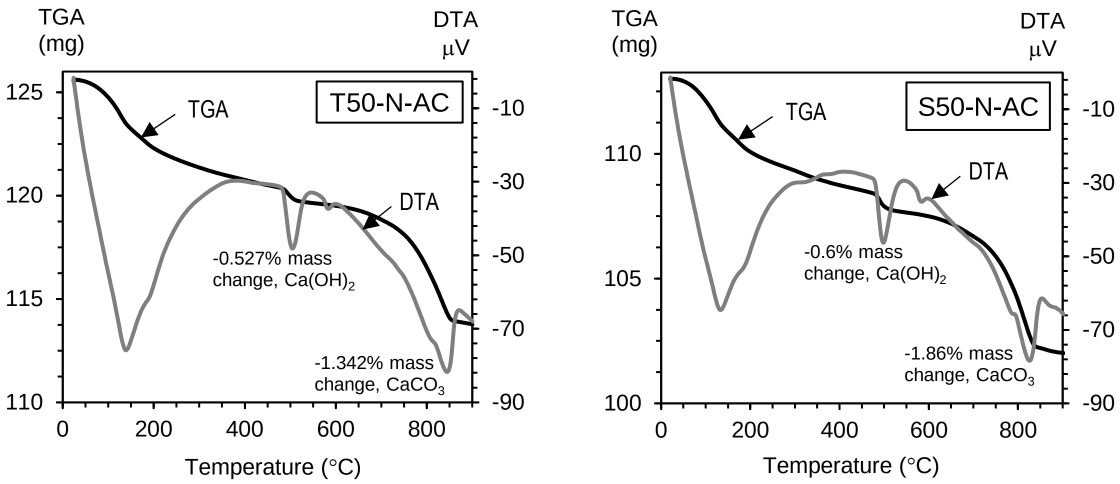

Figure 4. Results of TG-DTA curve of OPC concrete specimens

Table 4 Results of TG-DTA analysis of OPC concrete specimens (at 28 days)

Mixtures	Mass change of $Ca(OH)_2$		Mass change of $CaCO_3$		Comp. Strength at 28-day
	(mg)	(%)	(mg)	(%)	(MPa)
T50-N-TC	1.035	1.058	1.966	2.010	33.926
S50-N-TC	1.303	1.067	2.228	1.825	41.663
T50-N-AC	0.663	0.527	1.688	1.342	29.031
S50-N-AC	0.682	0.600	2.117	1.860	40.297

3.3 Porosity

Figure 5 shows the results of pore structures analysis of seawater mixing and tap water mixing of FA concrete in all curing conditions, which are tested by Mercury Intrusion Porosity (MIP) at a curing period of 28 days and 365 days. It was observed that the pore size distribution of tap water mixed and seawater mixed FA concrete in TC and SC was not significantly different. This exhibits that pore size distribution of tap water mixed and seawater mixed FA concrete is not influenced by kind of curing water, TC and SC. The maximum pore volume (porosity) and the large pore size of the concrete specimen were attained by FA concrete specimens in AC. This phenomenon is to be logical as hydration of cement paste in air curing, AC is not perfectly hydrated. The trend result of seawater mixed and tap water-mixed concrete was significantly distinct in pore distribution. However, the distinction of curing age of 28 days up to 365 days altered the pore size distribution of FA concrete for both seawater mixing and tap water mixing.

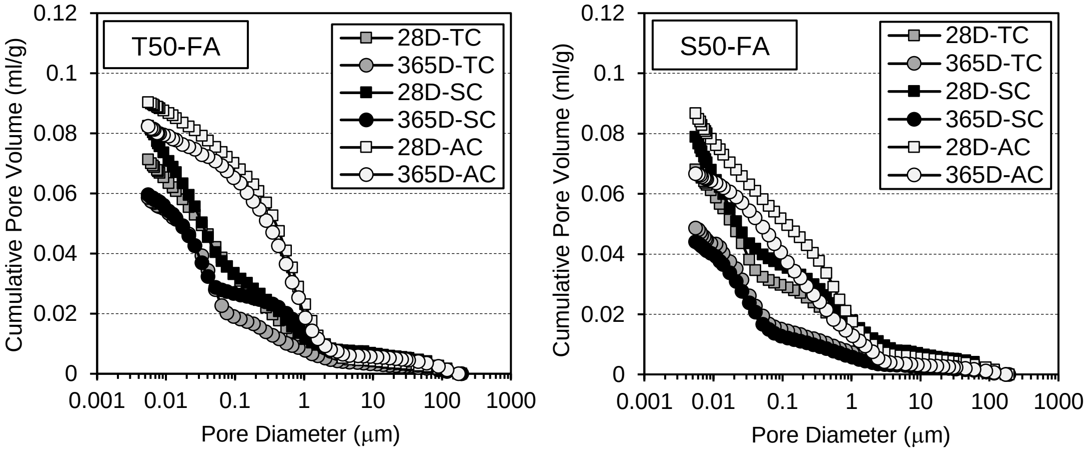

Figure 5. Pore size distribution of FA concrete specimens (W/B of 50%)

The total volume of pores (porosity) of all concrete specimens is depicted in Figure 6. Based on the result, It was observed that the porosity of 28 days up to 365 days of seawater-mixed concrete and tap water-mixed was reduced for both OPC and FA concrete in all curing conditions, TC, SC, and AC. The porosity up to 365 days of all concrete specimens in water curing (TC and SC) was lowered compared to concrete specimens in air curing (AC) in both seawater-mixed FA concrete and tap water-mixed FA concrete. The effect of FA as a binder on the porosity of seawater mixing and tap water mixing was also found. The porosity up to 365 days of seawater mixed and tap water mixed FA concrete was lower than that of OPC concrete with a W/B of 50%. In other words, mineral admixtures of fly ash decrease the porosity up to 365 days of seawater-mixed and tap water-mixed concrete. Furthermore, when FA concrete specimens were cured in air, the porosity of concrete mixed with tap water was higher than that of concrete mixed with seawater. This phenomenon expresses that the porosity of concrete at up to 365 days is decreased by seawater mixing in AC. It is possibly inferred by accelerating the hydration of seawater mixed concrete, which densifies the pore structure and reduces the pore volume of concrete.

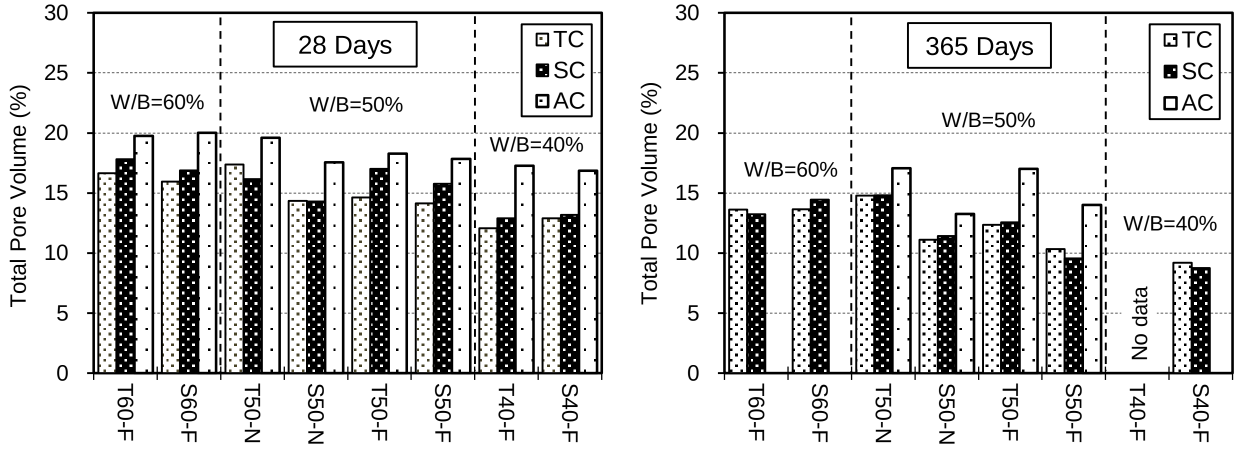

Figure 6 Total pore volume (porosity) of concrete specimens

Up to the 365-day curing period, the effect of seawater mixing and tap water mixing on the porosity of concrete could obviously be found as pointed out in Figure 7. The porosity ratio of seawater mixing to tap water mixing of OPC concrete and FA concrete was less than one (below line of equality). This result means that the porosity of seawater-mixed FA concrete up to 365 days is reduced compared to tap water-mixed FA concrete in all curing conditions, TC, SC, and AC. Even though, the porosity ratio of the concrete specimen with W/B of 60% in SC was more than one. Nevertheless, It may be generally revealed that the porosity of seawater mixed FA concrete is decreased compared with tap water mixed FA concrete.

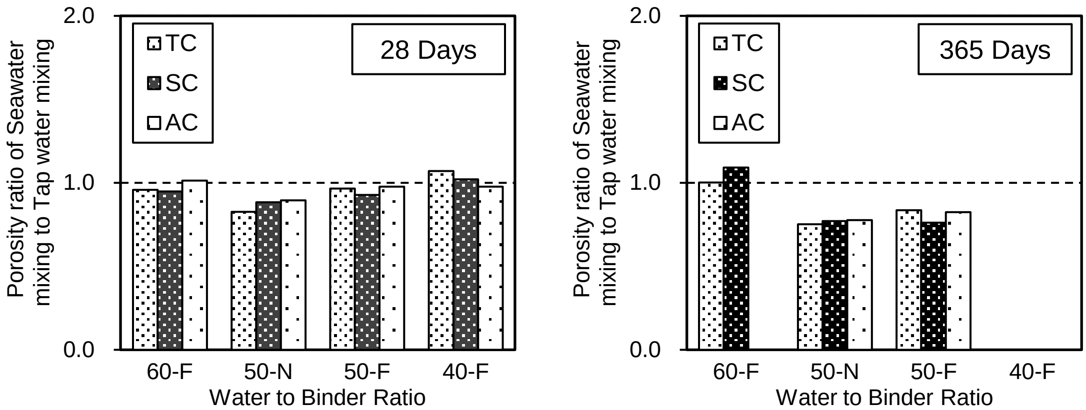

Figure 7 Porosity ratio of seawater-mixed concrete to tap water-mixed concrete

3.4 Relationship between strength and porosity

The relationship between compressive strength and porosity of tap water mixed and seawater mixed FA concrete at 28 days and 365 days in water curing (TC and SC) is demonstrated in Figure 8. From this figure, it can be seen that compressive strength was increased with a decreasing the porosity of concrete in a linear relationship. A very strong correlation is achieved for all concrete specimens in water curing, in which coefficient of correlation, R^2 value in TC and SC were more than 0.94 and 0.92, respectively. It suggests that the compressive strength of seawater mixed FA concrete and tap water mixed FA concrete may be estimated by its porosity. The higher compressive strength is, the lower porosity of concrete is, which is not influenced by mixing water and mix proportion of concrete. Moreover, it was also attained that no significant difference of correlation coefficient, R^2 in both water curing, TC and SC.

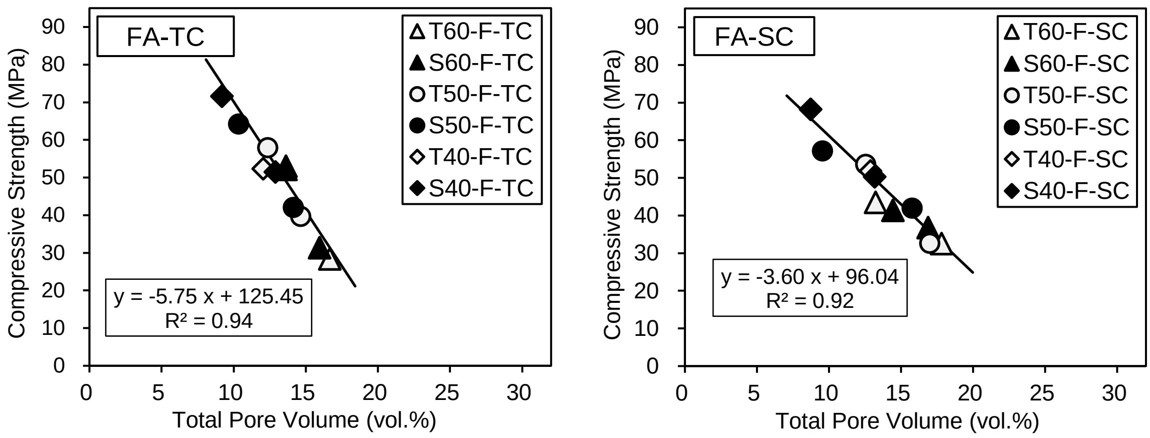

Figure 8 Strength-porosity relationship of FA concrete (at 28-day and 365-day)

4. Conclusions

Based on the results of experimental research, several conclusions can be drawn as follows:

1. Strength performance up to 365-day of seawater-mixed FA concrete is improved compared to tap water-mixed FA concrete in all curing conditions (TC, SC, and AC). The effectiveness of seawater mixing on strength enhancement up to 365 days is larger for OPC concrete than FA concrete.
2. The compressive strength up to 365 days of seawater-mixed and tap water-mixed FA concrete is not influenced by type of curing water (tap water or seawater).
3. The mass change (weight loss) of the hydration product of portlandite (CH) of seawater-mixed OPC concrete was higher than that of tap water-mixed concrete. The percentage of portlandite (CH) of seawater mixing is increased compared to tap water mixing.
4. The porosity up to 365 days of seawater mixed FA concrete is reduced compared to tap water mixed in TC, SC, and AC. The porosity up to 365 days of seawater mixed and tap water mixed FA concrete was lower than that of OPC concrete.
5. A very strong correlation is achieved for all concrete specimens in water curing, in which coefficient of correlation, R^2 value in TC and SC were more than 0.9. The compressive strength of seawater mixed FA concrete and tap water mixed FA concrete may be estimated by its porosity.

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