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CORRELATION OF POROSITY AND PROPERTIES OF RECYCLED FINE AGGREGATE CONCRETE WITH FLY ASH

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Abstract.

In this paper, we presented the experimental discussion of samples of recycled aggregate concrete with replacement of natural fine aggregate by recycled fine aggregate. Three mix kinds were produced and, for each of these three kinds, two levels of water to blinder ratio were used with 0%, 10% and 20% of FA. The result of the tests of drying shrinkage and compressive strength of recycled concrete were used for comparison with tests of mercury intrusion porosimetry (MIP), in which the cumulative pore volume and different intervals of pore volume were studied at ages of 28 and 91 days. Correlation graph of compressive strength and cumulative pore volume might be predicted with given W/B, days and FA of the concrete or none given and drying shrinkage might be predicted with given FA.

Keywords: Fly ash, drying shrinkage, porosity, recycled aggregate concrete.

1. INTRODUCTION

At present, the decrease in strength and increase in drying shrinkage are major problems for recycled aggregate concrete, and it was considered that managing these will lead to an increase in the use of recycled aggregate concrete (RAC) to building structures. Many studies have shown that using recycled aggregates in concrete suffered from durability problems. Some people reported that, compared with the reference concrete, the shrinkage of recycled aggregate concrete was increased by up to 60% [1].

In past research, the replacement rate for replacing natural aggregate with recycled aggregate (RA) and replacing cement with fly ash (FA) were considered roughly or simply. In this research, I focused on the compressive strength and drying shrinkage of concrete both with fine recycled aggregate and fly ash. Then I made correlation graphs between porosity and properties of the concretes. Then the correlation process was carried out on the properties obtained from the mercury intrusion porosimetry (MIP) tests, and shrinkage and compressive strength. Finally carrying out the graphs that gave rise to the correlations of the shrinkage and compressive strength and the porosity obtained in the mercury intrusion porosimetry MIP tests.

1.1. EXPERIMENTAL OUTLINES

Table 1 showed the physical properties of the materials used in this experiment. As cement, ordinary Portland cement was used, and sea sand and recycled fine aggregate as the fine aggregate (M standard of JIS A 5022) and crushed stone as coarse aggregate were used. Table 3 showed the mix proportions. In the mix proportions, the unit water amount was 180kg/m^3, the unit cement amount was 327kg/m^3, the water to binder ratio was 55% and 44%, and the replacement rate of the regenerated fine aggregate was 2 levels of 50, 100%. In this experiment, recycled aggregate was used only for fine aggregate, and natural aggregate crushed stone was used for coarse aggregate in all mix proportions. Regarding the compounding symbols, N was the mix proportions using natural aggregate for both the coarse aggregate and the fine aggregate. The replacement rate of the recycled fine aggregate was indicated in this order, M50 was a mix proportions using 50% recycled fine aggregate Class M and 50% sea sand. The replacement rate of the fly ash was indicated in this order, N-FA10 was a mix proportions replacing cement with 10% fly ash. The compressive strength test was carried out according to JIS A 1108.

The sample for the MIP rests were extracted from the center of the cylinder ($\varnothing = 0.05\ \mathrm{m} \times \mathrm{h} = 0.1\ \mathrm{m}$) which were dried by putting them in curing room for 28 and 91 days. The cylinder was then cut with a vise to obtain particles from 2 mm to 5 mm in diameter. The samples were dehydrated by submerging them in acetone for 2 h. After this stage, the samples were dried by putting them in an oven at 105 °C for 1 h. Finally, the samples were put into a vacuum pump for 48 h. The MIP tests were done on AutoPore V which subjected the samples to maximum pressure of

Property	Coarse aggregate	Fine aggregate	Fine recycled aggregate	Contents	Cement	FA
Density (g/cm^3)	2.69	2.59	2.23	Loss of ignition (%)	2.40	2.1
Fineness modulus	6.9	2.58	4.3	Density (g/cm^3)	3.16	2.2
Water absorption (%)	1.14	1.04	7.38	Specific surface area (cm^2/g)	3310	3270

Table 1. Materials.

W/B (%): 55	N	M50	M100	N-FA10	M50-FA10	M100-FA10	N-FA20	M50-FA20	M100-FA20
FA	0	0	0	45	45	45	90	90	90
S	731	350	0	723	346	0	716	342	0
RFA	0	350	672	0	346	665	0	342	658

W/B (%): 40	N	M50	M100	N-FA10	M50-FA10	M100-FA10	N-FA20	M50-FA20	M100-FA20
FA	0	0	0	33	33	33	65	65	65
S	832	398	0	826	396	0	820	392	0
RFA	0	398	765	0	396	759	0	392	754
G	945								
W	180								

Table 2. Unit mass of Mix proportions.

up to 60,000 pisa.

2. Experimental results and discussion

2.1. Compressive Strength

2.1.1. Influence of fine RA on the compressive strength

Figure 1 showed the compressive strength at 28 and 91 days for concrete mixes with various levels of fine RA. For 28 days, it showed that incorporating fine RA in concrete mixes decreased the compressive strength in FA10% W/C 0.40 series and FA 20% W/C0.55 series. But other four series showed that incorporating fine RA in concrete mixes almost had no decreased the compressive strength. For 91 days, it showed that incorporating of fine RA in concrete mixes decreased the compressive strength in W/B-0.40 FA-10% series and W/B-0.55 FA-20% series. And the incorporating of fine RA in concrete mixes made no effect on the compressive strength in W/B-0.40 FA-0% series and W/B-0.55 FA-10% series. This might be explained by two main factors, namely the RCA being more porous and weaker than the NA [2] and/or due to the increase of the effective W/C ratio in RCA concrete mixes to maintain the workability of an equivalent conventional concrete [3].

2.1.2. Influence of FA on the compressive strength

Figure 2 showed the compressive strength at 28 and 91days for concrete mixes with various levels of FA. For 28 days, it showed that the incorporation of FA in concrete mixes was detrimental in terms of compressive strength, but slightly decreased. For 91 days, it showed that the incorporating of FA in concrete mixes made no effect on increasing the compressive strength on W/B-0.40 RA-100% series, W/B-0.55 RA-100% series and W/B-0.55 RA-0% series. Generally, the incorporation of a low volume of FA filled the voids between cement particles, thus decreasing the voids, and slightly increased the fresh density. This was likely to happen because FA particles are finer than cements, so that FA not only can improve the particle size distribution, but also filled the micro pores in the interfacial transition zones around the aggregates [4].

2.2. Drying shrinkage

2.2.1. Influence of fine RA on the drying shrinkage

Figure 3 showed the drying shrinkage at 182 days for concrete mixes with various levels of fine RA. Each presented value was the average of three measurements. The results showed that incorporating fine

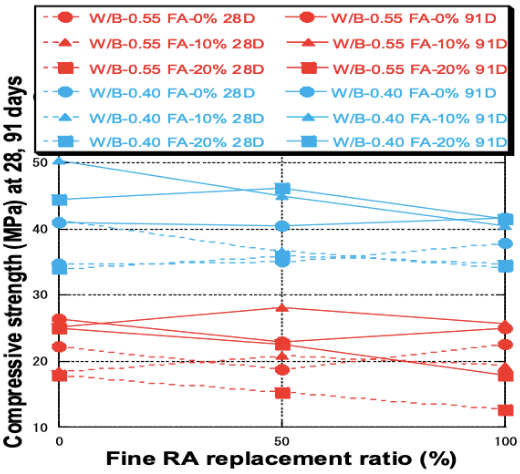

Figure 1. Effect of fine RA on the compressive strength.

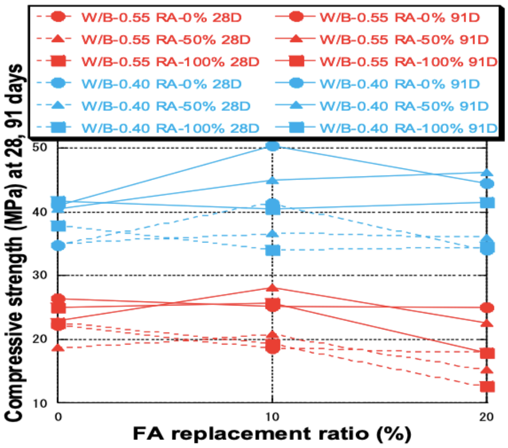

Figure 2. Effect of FA on the compressive strength.

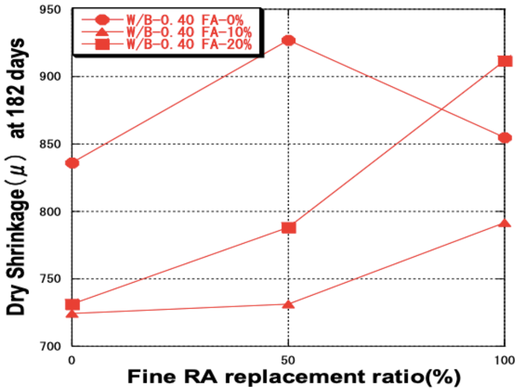

Figure 3. Effect of fine RA on the drying shrinkage.

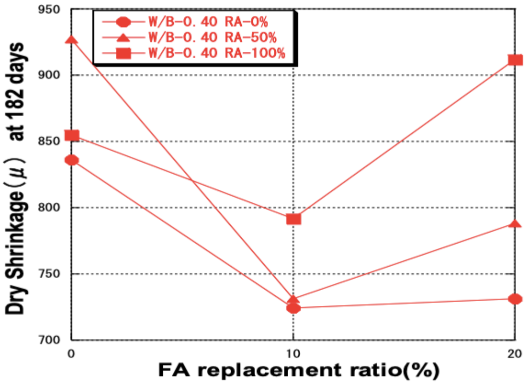

Figure 4. Effect of FA on the drying shrinkage.

RA in concrete mixes increased the drying shrinkage of the concretes in W/C-0.40 FA-0% series and W/C-0.40 FA-10% series. On W/C-0.40 FA-0% series, 50% fine RA replacement ratio made more effect on increasing concrete' durability than 100% fine RA replacement ratio. This was probably the result of the combination of half recycled aggregate and half normal aggregate. The mortar adhered to the recycled aggregate contributed to an increase in the volume of the paste (old + new), thus increasing the drying shrinkage of the resulting concrete [5].

2.2.2. Influence of FA on the drying shrinkage

Figure 4 showed the drying shrinkage at 182 days for concrete mixes with various levels of FA. The results showed that incorporating FA in concrete mixes decreased the drying shrinkage in W/C-0.40 RA-0% series and W/C-0.40 RA-50% series. Both in two series, 10% FA replacement ratio made more effect on decreasing concrete' durability than 20% FA replacement ratio. This was probably the result of high FA replacement ratio. According to Atis et al. [6], the reduction in the drying shrinkage was attributed to the dilution effect of the fly ash particles. On W/C-0.40 RA-100% series, 10% FA replacement ratio would decrease concrete's durability. This was same as other two series. When 20% FA was replaced, the FA made no effect on decreasing the drying shrinkage of the concrete. It might the that fly ash and recycled aggregates will inhibit each other when they both in high replacement ratio.

Figure 6 had water to binder ratio 0.40. At 28 days, only 100% fine RA replacement ratio cause the increase of the pore volume when pore diameter was in 0.003 ∼ 0.03 μm in 0% FA replacement ratio series. In 10% FA replacement ratio series, 50% fine RA replacement ratio had the biggest influence on pore volume in 0.003 ∼ 100 μm pore diameter interval.

At 91 days, the results showed that the cumulative pore volume increased with the increase of the fine RA replacement ratio when pore diameter was in 0.003 ∼ 100 μm except 0% FA replacement ratio series.

2.2.3. Correlation of porosity and properties

The pore diameter was divided into many different intervals by its different changed points of the cumulative curve. In Figure 7, for example, each line

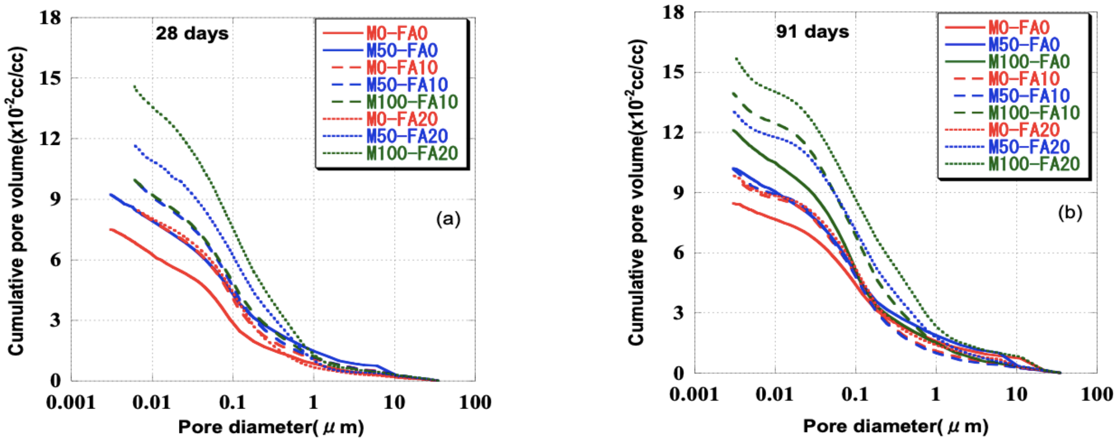

FIGURE 5. Influence of fine RA replacement ratio on cumulative pore volume(W/B0.55).

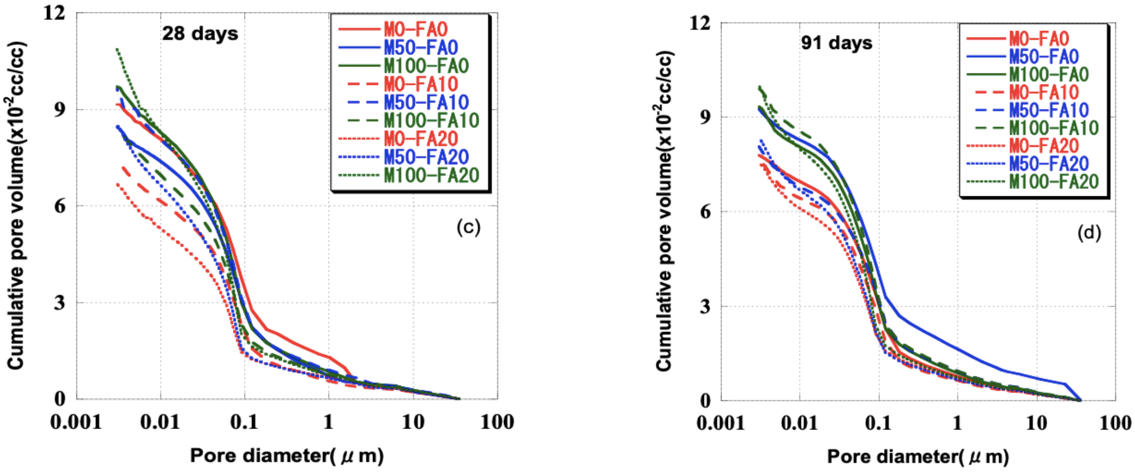

FIGURE 6. Influence of fine RA replacement ratio on cumulative pore volume(W/B0.40).

has two changed points which were named after point a and b. The compressive strength has relationship with pore diameter interval which left endpoint was after point a. The drying shrinkage has relationship with pore diameter interval which right endpoint was before point b.

2.3. POROSITY

2.3.1. RESULT OF POROSITY

The tests were carried out at 28 and 90 days. Figure 5 showed the influence of recycled aggregate replacement ratio on cumulative pore volume with water to binder ratio 0.55. At 28 days, the results showed that the pore volume, when pore diameter was in $0.003 \sim 100\,\mu$m, increased with the increase of the fine RA replacement ratio.

At 91 days, the results showed that the pore volume, when pore diameter was in $0.003 \sim 100\,\mu$m, increased with the increase of the fine RA replacement ratio, except 0% FA replacement ratio series. 50% fine RA replacement ratio made more effect on increase of pore volume when pore diameter was in $0.2 \sim 100\,\mu$m in FA 0% replacement ratio series.

Table **??** showed correlation coefficients (R^2) when using different interval division methods (W/B, days and FA) and after the use of different interval division methods, it seemed that W/B, days and FA had no influence on correlations of the compressive strength and pore volume. And the best interval's endpoint for the pore diameter were $0.05\,\mu$m and $100\,\mu$m. Figure 8 showed the graph that gave rise to the correlations of the compressive strength and the $0.05 \sim 100\,\mu$m pore volume obtained in the MIP tests (28 and 91days).

$$y = -3.94x + 54.60, \quad R^2 = 0.45 \tag{1}$$

- y: compressive strength (MPa).
- x: $0.05 \sim 100\,\mu$m pore volume ($\times 10^{-2}$ cc/cc)

$$y = -2.48x + 57.28, \quad R^2 = 0.32 \tag{2}$$

- y: compressive strength (MPa)
- x: cumulative pore volume ($\times 10^{-2}$ cc/cc)

The correlation process was carried out on the drying shrinkage of the recycled concrete (91 days). The correlation between porosity and drying shrinkage of the concretes can be divided two degrees: recycled concrete without fly ash and with fly ash replacement.

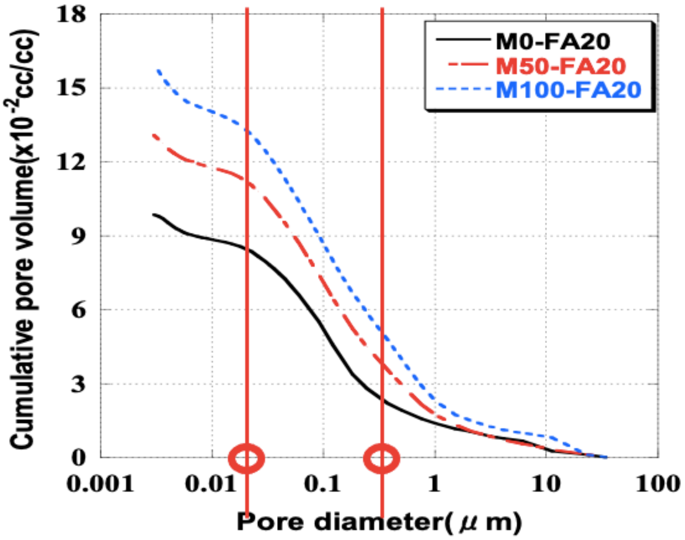

FIGURE 7. 'Changed points' of the cumulative curve.

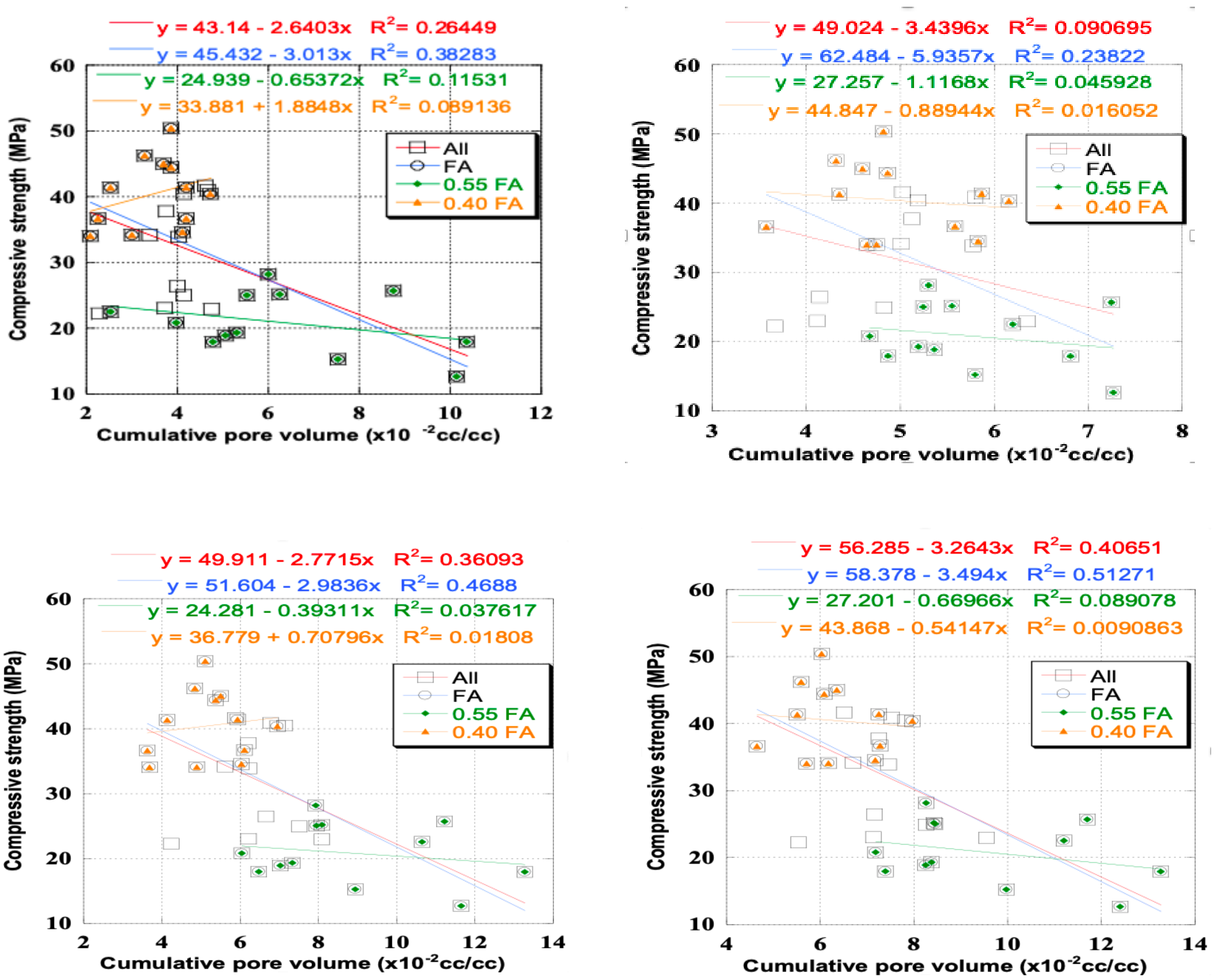

FIGURE 8. Coefficients of determination (R^2) of compressive strength and cumulative pore volume at interval division: (a) a–b μm; (b) a–36 μm; (c) 0.02 – 0.2 μm; (d) 0.02 – 36 μm.

Pore volume	W/B, Days, FA	0.55, 28, 0%	0.55, 91, 0%	0.55, 28, 10%	0.55, 91, 10%	0.55, 28, 20%	0.55, 91, 20%
a $\sim$ b μm	R^2	–	0.08	0.87	0.07	0.99	0.91
	W/B, Days, FA	0.40, 28, 0%	0.40, 91, 0%	0.40, 28, 10%	0.40, 91, 10%	0.40, 28, 20%	0.40, 91, 20%
	R^2	0.99	0.58	0.66	0.54	0.01	0.64
	W/B, FA	0.55, 0%	0.55, 10%	0.55, 20%	0.40, 0%	0.40, 10%	0.40, 20%
	R^2	0.53	0.31	0.29	0.00	0.49	0.02
a $\sim$ 2 μm	R^2	0.10	0.25	0.26	0.00	0.08	0.04
a $\sim$ 100 μm	R^2	0.12	0.22	0.15	0.05	0.09	0.03

Table 3. Correlation coefficients (R^2).

$$y = 52.38x + 371.79, \quad R^2 = 0.89 \qquad (3)$$

- y: drying shrinkage (μ) (with FA)
- x: $0.003 \sim 0.1\,\mu$m pore volume ($\times 10^{-2}$ cc/cc)

$$y = 48.62x + 257.28, \quad R^2 = 0.71 \qquad (4)$$

- y: drying shrinkage (μ) (with FA)
- x: cumulative pore volume ($\times 10^{-2}$ cc/cc)

The researchers studied the porosity and pore structure of cement paste. Z.W. Wu thought pores have four intervals: $<$ 20nm which is named after harmless pore, 20-50nm which is named after less-harm pore, 50-200nm which is named after harmful pore, $>$ 200nm which named after much-harm pore [7]. Capillary pores with a diameter greater than $0.011\,\mu$maffect the strength, and gel pores with a diameter of fewer than $0.01\,\mu$m affect the durability of mortar [8]. Consequently, the correlation between the properties of the RAC and the pore volume can be evaluated by dividing various pore intervals. Wu's theory was used for comparison; and the left and right points of the pore diameter intervals were defined as 0.02 and $0.2\,\mu$m, respectively. Simple linear regression also was performed to evaluate the correlation between the results of MIP and the results of compressive strength or drying shrinkage tests under four interval division methods according to the object is strength or dry shrinkage.

Figure 8 shows the coefficients of determination between the pore volume and compressive strength at the following interval divisions: a–b μm, a–36 μm, $0.02 - 0.2\,\mu$m, $0.02 - 36\,\mu$m. The pore size range of the MIP test was $0.003 - 36\,\mu$m. The symbols "All", "FA", "0.55FA" and "0.40FA" shown in Figure 8 indicate that the fitted line used the data of the compressive strength and cumulative pore volume of all mixes, mixes with FA, mixes with FA at W/B 0.55 and mixes with FA at W/B 0.40, respectively. For RFA concrete incorporating FA, there was no interval with a high correlation coefficient between the compressive strength and the cumulative pore volume because the correlation coefficients of the four types of intervals ranged between 0 and 0.6 (Figure 8). In other words, there was no significant correlation between cumulative pore volume and compressive strength. Moreover, simple linear regression cannot use cumulative pore volume in a specific interval to determine or predict the strength of recycled concrete. Some researchers use quadratic or exponential regression equations to predict concrete strength. Concrete with FA should be considered separately when considering the correlation between compressive strength and cumulative pore volume because the correlation coefficients of the "FA" lines are higher than that of the "All" line for the four intervals.

Figure 9 shows the coefficients of determination between the cumulative pore volume and drying shrinkage at interval divisions: a–b, a $- 36\,\mu$m, $0.02 - 0.2\,\mu$m, $0.02 - 36\,\mu$m. The symbols "All" and "FA" shown in Figure 9 indicate that the fitted line used the data of the compressive strength and cumulative pore volume of all mixes and mixes with FA, respectively. Concrete with FA should be considered separately when investigating the correlation between drying shrinkage and cumulative pore volume because there are no liner fits with high correlation coefficients in Figure 9 (a) and (c), whereas the "FA" line shows high correlation coefficients in Figure 9 (b) and (d). The drying shrinkage of the concrete incorporating FA is related to the cumulative pore volume of micropores due to the pore diameter of interval divisions shown in Figure 9 (a)and (c), both of which start from $0.003\,\mu$m. In other words, there is a correlation between cumulative pore volume and drying shrinkage due to the incorporation of FA in concrete.

This can be explained by the fact that FA can reduce both the pore size of capillary pores and gel pores in concrete and because the shrinkage rate depends on the amount of water lost in the mesopore, in which the resistance to water loss was determined by the size of the macropore [9]. Hence, the drying shrinkage of concrete with FA is relatively correlated with the pore volume of micropores and mesopores. $0.003 -$ b μm is the optimal interval between the drying shrinkage and the cumulative pore volume of concrete incorporating FA because the "FA" line in Figure 9 (b) has the highest correlation coefficient of

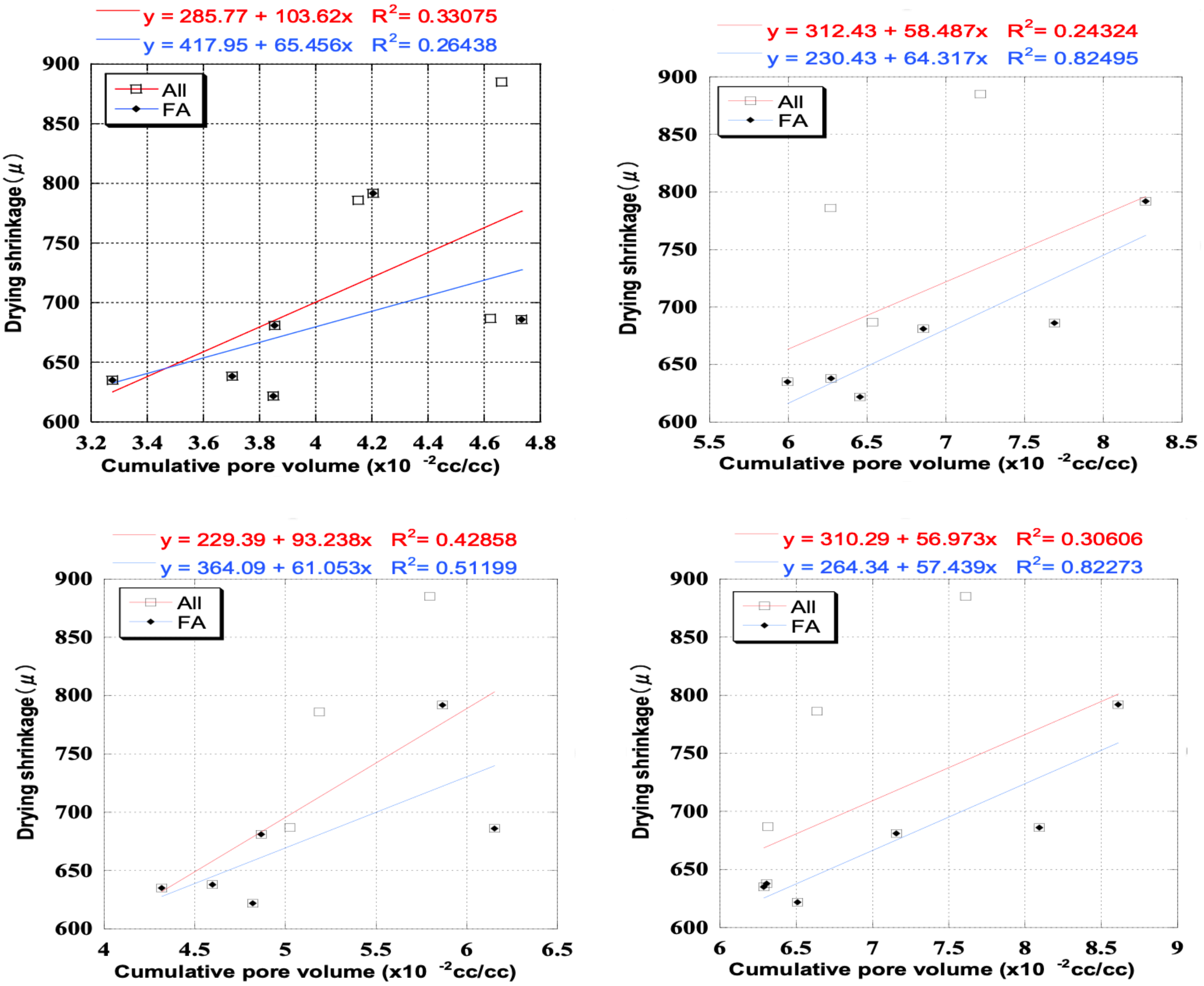

Figure 9. Coefficients of determination (R^2) of drying shrinkage and cumulative pore volume at different interval divisions: (a) a–b μm; (b) $0 - 0.03\,\mu$m; (c) $0.02 - 0.2\,\mu$m; (d) $0.03 - 0.2\,\mu$m.

0.82.

3. Conclusions

Both fly ash and recycled aggregates in concrete mixes were detrimental but at moderate rates; Using FA in RAC production was advisable, especially for percentages of FA exceeding the standard limit, since some of the particles of FA work as a pozzolanic binder ratio instead of a filler. Cumulative pore volume increases with an increase of RFA replacement ratio and decreases with a decrease of the W/B ratio. Concrete incorporating FA should be considered separately when investigating the correlation between cumulative pore volume and compressive strength or drying shrinkage. There is no linear correlation between compressive strength and cumulative pore volume in all interval divisions. There is a linear correlation between cumulative pore volume and drying shrinkage result from the incorporation of FA in concrete and the optimal interval division for investigating the correlation between drying shrinkage and the cumulative pore volume of concrete incorporating FA is $0.003 - \mathrm{b}\,\mu$m. The smallest pore diameter that can be measured by the MIP test is $0.003 - \mathrm{b}\,\mu$m and point b is the right change point of pore diameter in a plot of the cumulative pore volume.

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