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Influence of the Quality of Recycled Aggregates on Microstructures and Strength Development of Concrete

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Abstract

The quality of recycled aggregate is affected by original concrete strength and the manufacturing process of recycled aggregates. In this study, the porosity of old and new mortar, and the compressive strength of concrete were investigated to examine the influence of recycled aggregate on the concrete. Six kinds of recycled coarse aggregates were produced from concrete blocks of differing strength levels (A:60.1MPa, B:41.7MPa, C:25.5MPa).

Original concrete strength and the bond mortar of recycled aggregate influences the pore structures of both old and new mortar. The pore size distribution of old mortar was found to be greatly affected by age, and the reduction of the porosity of bond mortar on low strength recycled aggregate increased at a greater rate than that of bond mortar on high strength recycled aggregate. The pore size distribution of new mortar in recycled aggregate concrete changed in comparison with that of new mortar in virgin aggregate concrete. The total porosity of new mortar using B level recycled aggregates was smaller than that of new mortar with A, and C level recycled aggregates. Moreover, the compressive strength of recycled aggregate concrete was found to have been affected by original concrete strength. The compressive strength of concrete only changed slightly in the porosity of new mortar over 15%, but increased rapidly in the porosity of new mortar fewer than 15%.

***Keywords:** recycled aggregate, original concrete strength, bond mortar, pore size distribution, compressive strength*

1. Introduction

Recently, a large amount of concrete waste has been produced around the world due to dismantling of concrete structures. While global research on recycling waste concrete has progressed actively, most waste concrete has been used for road bases, back-fills, and reclamation purposes.

As a response, recycled aggregate concrete has been researched to solve the problem of the lack of natural aggregate resources and of environmental contamination.[1-3)] However, recycled aggregate concrete exhibits a decrease in durability and strength development. The influence of recycled aggregate on the properties of concrete has not been fully established.[4)] The presence of internal pores in the aggregate particles was mentioned in relation to the specific gravity of aggregate, and indeed the characteristics of these pores are very important in the study of aggregate properties. The porosity, permeability, and absorption of aggregate influences such properties as the bond between it and hydrated cement paste, the resistance of concrete to freezing and thawing, its chemical stability, and its resistance to abrasion.[5)] Specifically, these factors become defects in the material, although they can sometimes bear a positive influence on the properties of the material.

Furthermore, recycled aggregate consists of original aggregate and mortar. Therefore, its properties will necessarily be affected by the bond mortar properties. For example, the porosity and pore size distribution of mortar and concrete affect the quality of the concrete. The entrained air and capillary pore within the range of 100nm～1μm increases frost resistance, whereas large capillary pores in the range of 10～90μm decrease frost resistance. Capillary pores in the range of 50nm～2μm correlate well with compressive strength. Otherwise, the qualities of recycled ag-

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gregate like as mortar content, crushing value, and soundness influence the microstructural, mechanical, and durability properties of new concrete. [6-8]

In this study, the porosity of bond mortar on recycled aggregate was examined, and the pore size distribution and compressive strength of recycled aggregate concrete and the control concrete sample were investigated. An observation of the influence of characteristics of recycled aggregate on concrete properties was also conducted.

2. Experimental work

2.1 Materials and mix proportion

Ordinary Portland cement shown in Table 1 was used. The fine aggregate with a specific gravity of 2.64 and a fineness modulus of 2.97, natural coarse aggregate (NA), and six kinds of recycled coarse aggregate were used in the study. The manufacturing processes of recycled coarse aggregates are explained as follows. Concrete blocks with dimensions of 30cm×30cm×30cm were manufactured to three different strength levels (A:60.1MPa, B:41.7MPa, C:25.5MPa). Crushing process 1 recycled aggregate was made from concrete blocks crushed by a jaw crusher and an impact crusher. Crushing process 2 recycled aggregate was made from crushing process 1 recycled aggregate crushed by a Porouder crushing machine. The properties of natural and recycled coarse aggregates are summarized in table 2.

The mix proportions of the concrete were selected as follows: water-cement ratio of 0.55, air content of 4±0.5%, and slump of 8±2cm. A water-reducing agent and an AE agent were used to compensate for the slump and air content.

2.2 Experimental work

2.2.1 Specimen preparation, curing and compressive strength test

Concrete specimens were cast in φ10×20cm steel moulds and compacted vibration for 10 seconds. After casting, the specimens were covered with cling film to prevent water loss. After 24 hours, the specimens were de-moulded. Once de-moulded, the specimens were cured in water at 20±2℃ until testing. The compressive strength testing of specimens was conducted at 7 and 28 days, respectively, in accordance with KS F 2403.

2.2.2 Mercury Intrusion Porosimetry

The samples for investigating the porosity of both new mortar and bond mortar of recycled aggregate concrete were carefully extracted from the concrete specimens. Fig. 1 shows the section of concrete specimen. These samples were immersed in acetone for 24 hours in order to prevent cement hydration. The samples were then dried in oven at 105±5℃ for 24 hours. Porosimetry was conducted by using a mercury intrusion porosimetry. The contact angle and surface tension between the mercury and the pore wall were taken as 130° and 484dyne/cm, respectively.

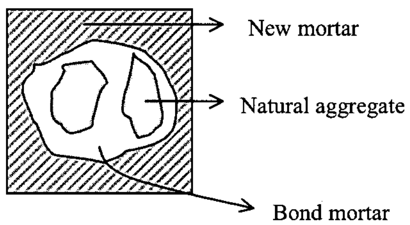


Fig.1 Section of concrete specimen

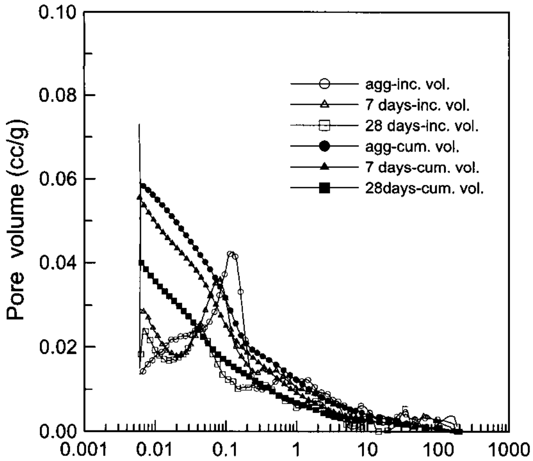
Table 1 Chemical and physical properties of ordinary portland cement

SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Na_2O (%)	K_2O (%)	LOI (%)	Density (g/cm^3)	Blaine (cm^2/g)
21.4	4.8	2.9	64.2	1.0	2.2	0.3	0.5	2.0	3.15	3,200

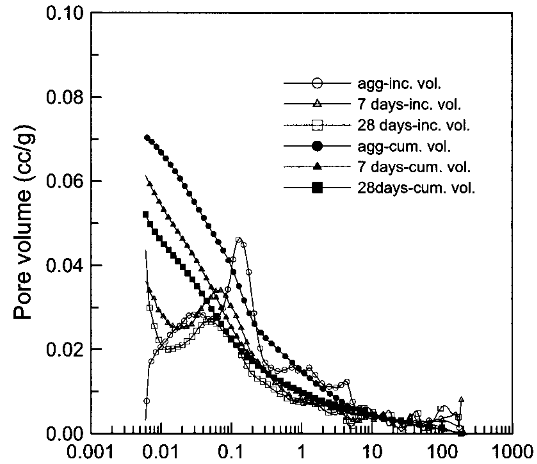
Table 2 Physical properties of natural coarse aggregate and recycled coarse aggregate

Type of Aggregate	Density in SSD[1] (g/cm^3)	Density in BD[2] (g/cm^3)	Absorption (%)	Bond mortar (%)	Crushing value in 100kN (%)	Soundness loss (%)	Compressive strength of OC[3] (MPa)
NA	2.64	2.62	0.84	-	3.57	9.4	-
A1	2.42	2.31	4.48	52.3	3.83	29.7	60.1
A2	2.51	2.43	3.14	30.2	1.53	8.1	60.1
B1	2.41	2.28	5.58	55.0	5.19	48.3	41.7
B2	2.50	2.42	3.19	32.4	1.73	18.4	41.7
C1	2.37	2.23	6.27	52.3	6.30	49.1	25.5
C2	2.48	2.39	3.76	32.3	2.28	22.5	25.5

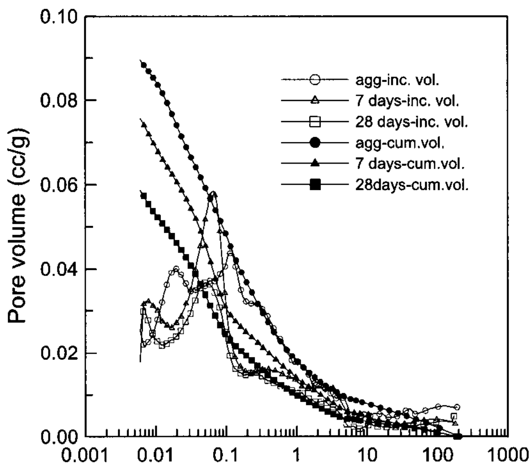
1: Saturated and surface dry (SSD), 2 : Bone dry (BD), 3 : Original concrete (OC)



(a) A1 bond mortar



(b) B1 bond mortar



(c) C1 bond mortar

Fig. 2 Pore size distribution of bond mortar of recycled aggregate

3. Results and discussion

3.1 Pore size distribution of bond mortar

The bond mortar of recycled aggregate made from concrete blocks has porous structures, which greatly affects the quality of the cement. The pore size distribution of bond mortar in concrete with three different recycled aggregates at 7 and 28 days respectively is illustrated in Fig. 2.

The porosity and pore size distribution of bond mortar changes according to age, and to the type of recycled aggregate. The cumulative pore volume (cum. vol.) of bond mortar over 90nm at 28 days reduced in comparison with that at 0 days (reference bond mortar). Moreover, the porosity of bond mortar more than 90nm tended to increase more than that of the reference bond mortar. The maximum pore size distribution of reference bond mortar was where the pore radius was at 200nm, but that of bond mortar according to age shifts to a smaller pore radius, and the incremental pore volume (inc. vol.) of the maximum peak is lower than that of the reference bond mortar.

It is suggested that the porosity of bond mortar over 90nm is reduced by the effects of hydration of unhydrated cement particles, and by the effect of movement of small cement particles and Ca^{+1} ion.

The total porosity of bond mortar increases by the ratio of the original concrete strength, and bears an inverse relationship with the bond mortar ratio. The relationship between the characteristic strength ratio, $\{(\text{strength of original concrete block) over (bond mortar ratio})^{1/5}\}^{-0.5}$, of recycled aggregate, and the total pore volume ratio of the bond mortar, is presented in Fig. 3.

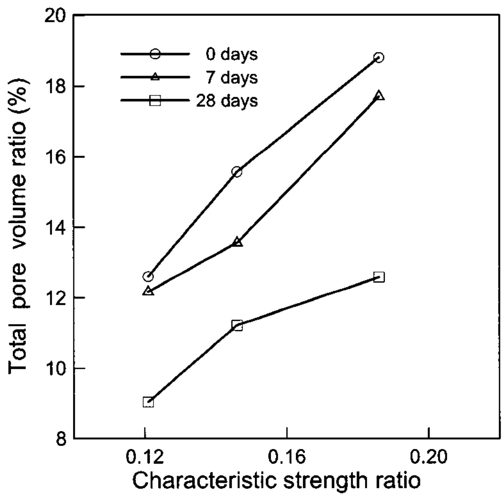


Fig. 3 Relationship between characteristic strength ratio of recycled aggregate and total pore volume ratio

The total pore volume ratio of bond mortar on recycled aggregates increased with the characteristic strength ratio of recycled aggregates. When the characteristic strength ratio was 0.2, total pore volume ratio reduced by about 4.5-7.5% in comparison with total pore volume ratio at the characteristic strength ratio of 0.16 and 0.12. The total pore volume ratio after 28 days reduced about 4% in comparison with total pore volume ratio at the characteristic strength ratio of 0.16.

The relationship between age and the total pore volume ratio of bond mortar is illustrated in Fig. 4. Total porosity of bond mortar declined linearly with age until 28days. Total porosity of bond mortar of A1, B1, and C1 recycled aggregate at 28 days reduced by 4, 4.5, and 7.5% respectively, in comparison with that of the reference bond mortar.

In short, when recycled aggregate was manufactured using high strength original concrete, the porosity of bond mortar was less than that of bond mortar on recycled aggregate made from low strength original concrete.

3.1 Pore size distribution of new mortar

Pore structure of concrete comprises entrapped air, entrained air by the AE agent, and capillary and gel pore by the hydration reaction of cement. These pores influence strength and durability of concrete.

The cumulative and incremental pore volumes of new mortar of concrete at seven and 28 days is illustrated in Fig. 5. Porosity over 100nm of recycled aggregate was fewer than that of the virgin concrete. The maximum incremental porosity peak tended towards a smaller pore size with age. Hydrate of Ca $(OH)_2$ was produced on aggregate interface

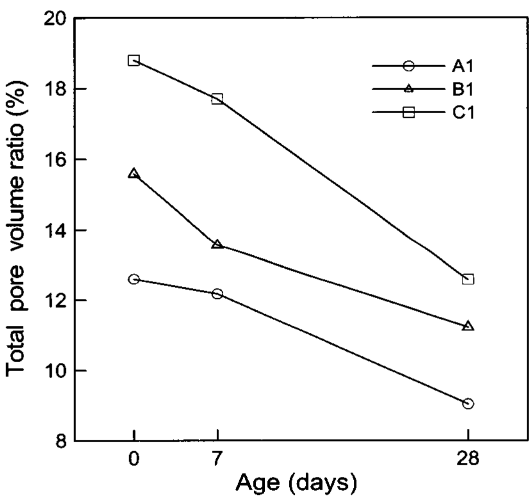


Fig. 4 Relationship between age and total pore volume ratio of bond mortar

by means of Ca ion leaching, so that the interfacial transition zone was shaped in the range of 50nm~200nm pore size.[9, 10)] Porosity over 100nm of recycled aggregate reduced further than the virgin concrete sample because the bond mortar had higher water absorption, and consisted of porous structures.

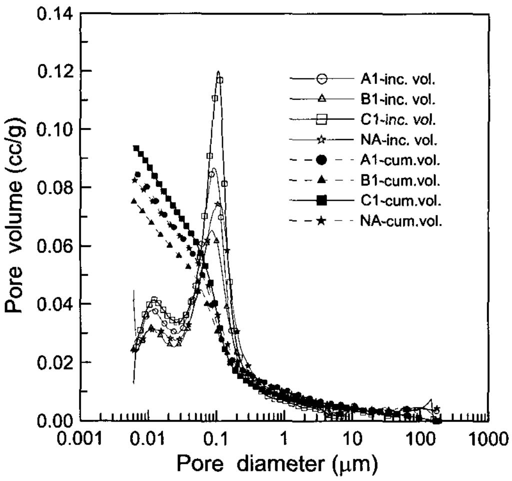
On the other hand, the total pore volume of concrete of crushing process 2 recycled aggregates was lower than that of concrete with crushing process 1 recycled aggregates. When B1 and B2 recycled aggregates were used, the total pore volume ratio of the concrete exhibited the greatest reduction (Fig. 6).

The relationship between the total porosity ratio of new mortar and the reduced porosity of bond mortar is illustrated in Fig. 7. Both the reduced porosity ratio of bond mortar, as well as the total pore ratio of new mortar exhibits a linear relationship. The reduced pore ratio of bond mortar in communications recycled aggregate was higher than that of bond mortar with A1 and B1 recycled aggregates, and the total pore ratio of new mortar tended to increase. In short, the pore structure of C1 aggregate concrete changed more significantly compared with that of A1 and B1 recycled aggregate concrete because the water absorption of low strength recycled aggregate was higher than that of high strength recycled aggregate. This is explained by porous structure differences.

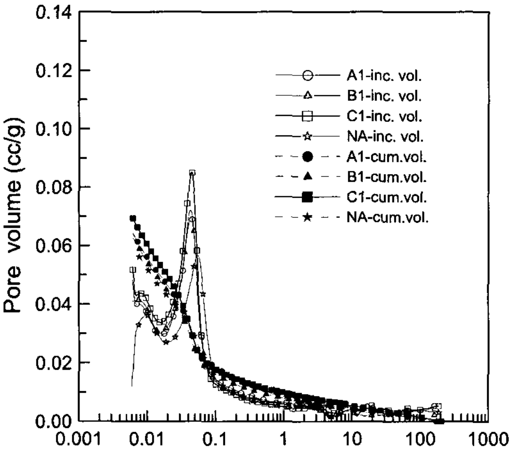
3.3 Compressive strength of concrete

The compressive strength ratio of recycled aggregate concrete around the 28-day mark to virgin concrete with natural aggregate is illustrated in Fig. 8. The compressive strength ratio of recycled aggregate concrete was in excess of that of virgin concrete after 7 days. After 28 days, the compressive strength ratio of recycled concrete was also shown to be slightly higher than that of virgin concrete, with the exception of that of concrete using C1 and C2 recycled aggregate.

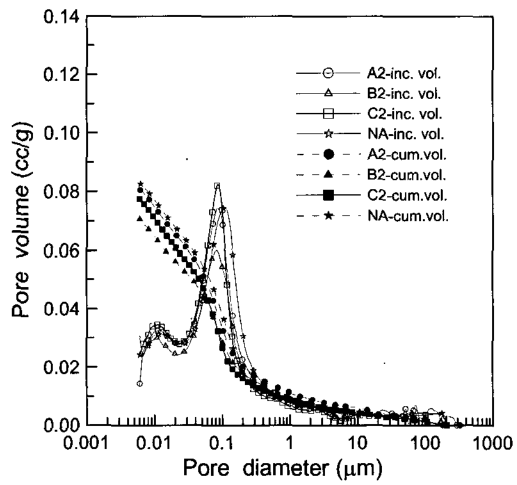
Fig. 9 illustrates the relationship between the compressive strength of recycled aggregate concrete, and the characteristics of recycled aggregate for determining how the quality of recycled aggregate affects the strength of concrete. The characteristic strength ratio of recycled aggregate did not influence the compressive strength of recycled aggregate concrete after 7 days, but did greatly influence the strength after 28 days. Where the strength of the original concrete was higher than the strength of the new concrete, the strength of the recycled aggregate concrete was higher than that of the virgin concrete.



(a) Crushing process 1 recycled aggregate

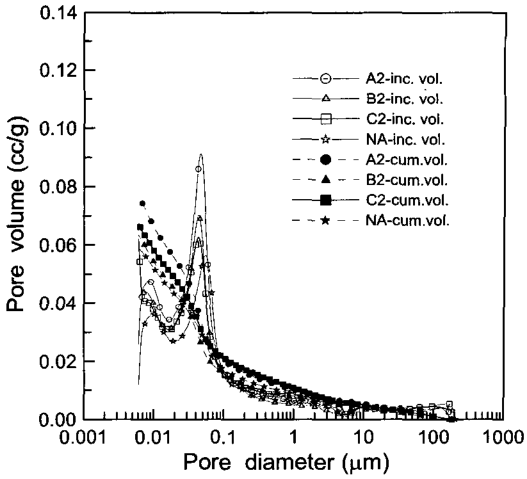


(b) Crushing process 1 recycled aggregate concrete at 7 days concrete at 28 days



(c) Crushing process 2 recycled aggregate

Fig. 5 Pore size distribution of new mortar of recycled aggregate concrete (continued)



(d) Crushing process 2 recycled aggregate concrete at 7 days concrete at 28 days

Fig. 5 Pore size distribution of new mortar of recycled aggregate concrete

However, when the strength of the original concrete was lower than that of the new concrete, the strength of the original concrete had a weakening influence on the new concrete.

Fig.10 illustrates the increased compressive strength and the reduced porosity ratio of bond mortar, which helps us understand the increased strength of concrete. The increased strength of concrete was calculated by a proposed exponential function. The strength of concrete increased as the porosity ratio of bond mortar was reduced. The increased strength of crushing process 1 aggregate concrete was higher than that of crushing process 2 aggregate concrete. The relationship between compressive strength and the porosity ratio of new mortar is illustrated in Fig. 11. The relationship between the porosity ratio and concrete strength was similar to the prior results. In the case of porosity ratio greater than 15%, strength barely changed. In the case of a porosity ratio less than 15%, however, strength greatly increased.

As the above results show, the pore structure of old and new mortar of recycled aggregate concrete, and the compressive strength of recycled aggregate concrete were affected by the quality of recycled aggregates such as bond mortar ratio, water absorption ratio, etc. Additionally, it is reported that changes in the pore structure of old and new mortar may influence the resistance to freezing-thawing, and permeability of concrete.[9]

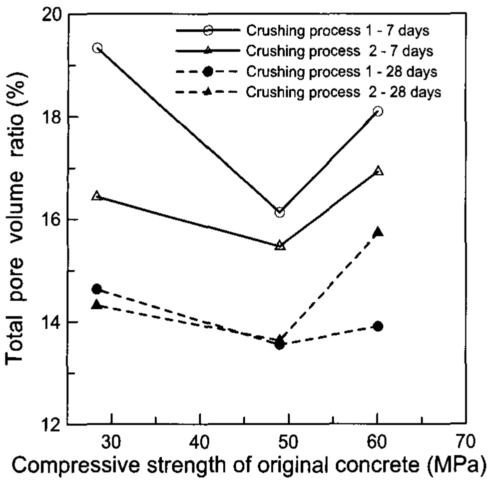


Fig. 6 Relationship between original concrete strength and total pore volume ratio

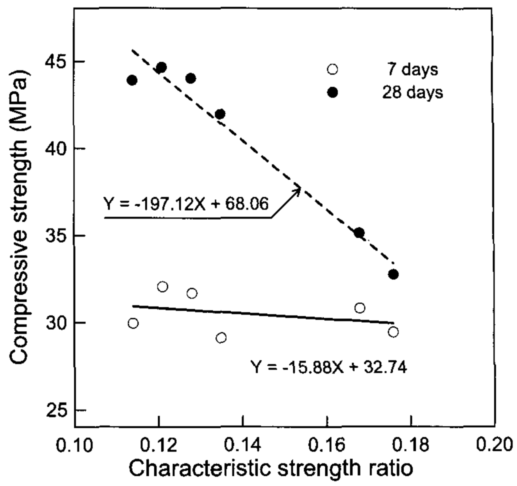


Fig. 9 Relationship between characteristic strength ratio of recycled aggregate and compressive strength

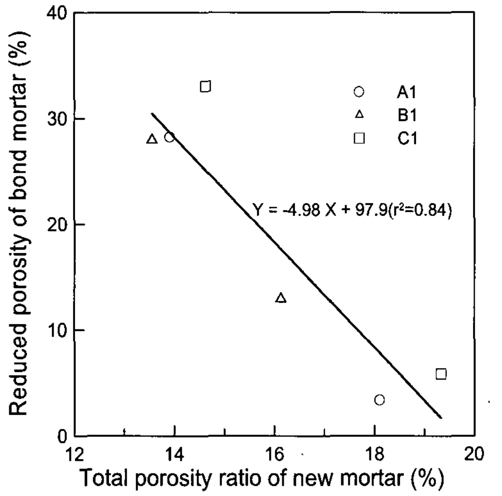


Fig. 7 Relationship between reduced porosity of bond mortar and total porosity ratio of new mortar

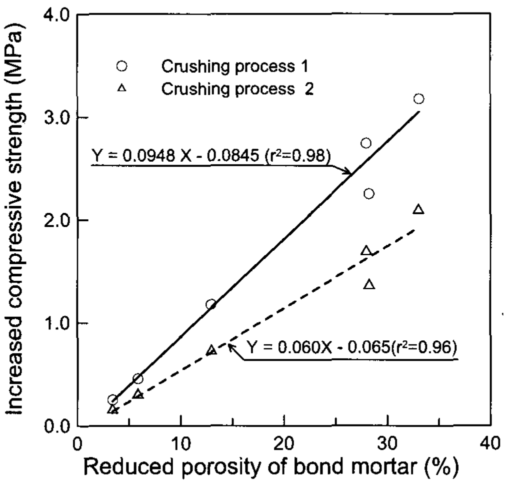


Fig. 10 Relationship between increased compressive strength and reduced porosity of bond mortar

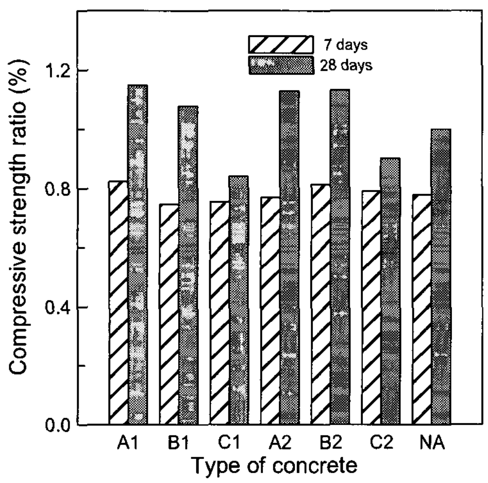


Fig. 8 Compressive strength ratio of recycled aggregate concrete

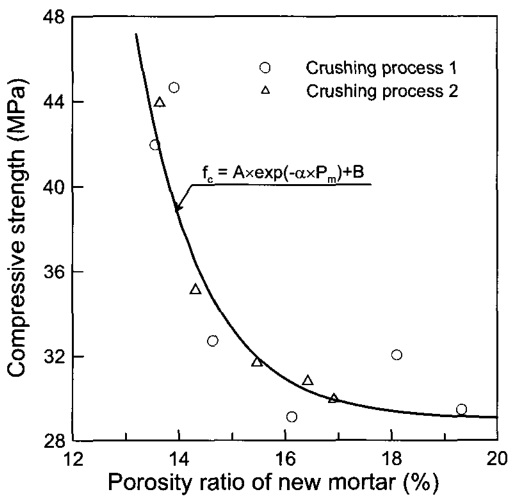


Fig.11 Relationship between compressive strength and porosity ratio of new mortar

4. Conclusions

1) The porosity of recycled aggregate bond mortar beyond 90nm, with increasing age, was much less than that of the reference bond mortar. Reductions of pore in the bond mortar on recycled aggregate increased in the order of A, B, and C, because the recycled aggregate made from lower original strength concrete had higher bond mortar and a greater level of porosity.
2) The porosity of new concrete with recycled aggregate was higher than that of virgin concrete after 28 days. Additionally, the porosity of new concrete changed according to the kinds of recycled aggregate used, meaning the porosity of B1 recycled aggregate concrete exhibited little reduction in comparison with that of concrete using A1 or C1 recycled aggregate.
3) The original concrete strength of recycled aggregate has a large influence on the compressive strength of new concrete after 28 days. Therefore, the compressive strength of concrete using A and B types of recycled aggregate exhibits little increase compared with that of virgin concrete, but the compressive strength of concrete using C1 and C2 recycled aggregate is less than that of virgin concrete.
4) The strength of concrete expressed some increase with a reduction of the porosity of bond mortar. When the porosity ratio of new mortar was under 15%, the strength of recycled aggregate concrete greatly increased. Therefore, it is suggested that the quality of recycled aggregate influences not only the pore structures of concrete, but also its strength.

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