Study of Methods for Improving Strength and Durability of Low-Quality Recycled Aggregate Concrete

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Abstract. In recent years, the amount of concrete waste is increasing every year by demolishing and renewing of concrete structures in Japan. In addition, it is expected to continue to increase in the future. In addition, there is a concern about the decrease of disposal sites, so it is necessary to have an effective method to use concrete waste. As an effective method of using concrete waste, the use of recycled aggregate can be considered. In order to promote the use of recycled aggregate, it is necessary to promote the use of low-quality recycled aggregate that can be produced with low energy and low cost. However, the strength and durability of concrete using low-quality recycled aggregate are significantly lower than those using normal aggregate. In previous studies, we examined the improving methods of mortar using low-quality recycled fine aggregate and concrete using low-quality recycled coarse aggregate. It was found that accelerated carbonation of recycled aggregate was optimal for mortar using low-quality recycled fine aggregate, and addition of C-S-H type accelerator was optimal for concrete using low-quality recycled coarse aggregate. Therefore, in this study, we aimed to improve the strength and durability of concrete using both low-quality recycled fine and coarse aggregate, so we examined the improving methods and its mechanism. There are two methods to improve the strength and durability of concrete using low-quality recycled aggregate: accelerated carbonation of recycled aggregate and addition of C-S-H type accelerator. As a result, it was found that the combinations of accelerated carbonation of recycled fine aggregate and addition of C-S-H type accelerator had a high improving effect in concrete using both low-quality recycled fine and coarse aggregate.

Keywords: Recycled fine aggregate; Recycled coarse aggregate; Accelerated carbonation of recycled aggregate; C-S-H type accelerator

1. INTRODUCTION

In order to prevent global warming, it is effective to reduce the emission of greenhouse gases, especially carbon dioxide (CO_2). Also in Japan, the government has stated "Carbon Neutral by 2050" to reduce the emissions of greenhouse gases to zero by 2050, and has made efforts in various fields to contribute to creating decarbonized society. Also in concrete field, various technologies have been considered to create a decarbonized society, such as reducing the use of Ordinary Portland cement by using admixtures of blast furnace slag powder and fly ash to significantly reduce CO_2 emissions from concrete materials, and developing carbon-recycled concrete using calcium carbonate produced from collected CO_2. In addition, in "Carbon Dioxide Utilization (CO2U)-ICEF ROADMAP1.0" presented at the ICEF international conference held in 2016, it was shown that CO_2 capture and storage in concrete and concrete aggregates has a great potential for effective utilization of CO_2 on a global scale in the near future. By taking strategic actions, there is a potential to reduce 3.6 billion tons of CO_2 on a global scale by 2030 through CO_2 capture and storage in concrete aggregate. On the other hand, in recent years, the amount of concrete waste is increasing every year by demolishing and renewing of concrete structures in Japan. In addition it is expected to continue to increase in the future. In addition, there is a concern about the decrease of disposal sites, so it is considered necessary to have an effective method to use concrete waste. As an effective method of using concrete waste, the use of recycled aggregate can be considered. In order to promote the use of recycled aggregate, it is necessary to promote the use of low-quality recycled aggregate that can be produced with low energy and low cost. However, the strength and durability of concrete using low-quality recycled aggregate are significantly lower than those using normal aggregate. In previous studies, we examined the improving methods of mortar using low-quality recycled fine aggregate and concrete using low-quality recycled coarse aggregate. It was found that accelerated carbonation of recycled aggregate was optimal for mortar using low-quality recycled fine aggregate, and addition of C-S-H type accelerator was optimal for concrete using low-quality recycled coarse aggregate. Therefore, in this study, we aimed to improve the strength and durability of concrete using both low-quality recycled fine and coarse aggregate, so we examined the improving methods and its mechanism. Two methods were used to improve the strength and durability of low-quality recycled aggregate concrete: accelerated carbonization of recycled aggregate and addition of C-S-H type accelerator.

2. LOCATION OF THE POROSITY AND IMPROVING METHODS FOR RECYCLED AGGREGATE CONCRETE

2.1. Location of the porosity in recycled aggregate concrete

It is thought that the cause of the decrease in strength and durability of low quality recycled aggregate concrete is the large amount of porosity. In previous studies, it has been reported that there are many porosity in attached mortar and interfacial transition zone (ITZ) of the recycled aggregate concrete. Figure 1 shows location of porosity in recycled aggregate concrete. There are five locations of porosity in recycled aggregate concrete: (1) cement paste, (2) attached paste of recycled fine aggregate, (3) ITZ of recycled fine aggregate, (4) attached mortar of recycled coarse aggregate, and (5) ITZ of recycled coarse aggregate. It is thought that the strength and durability of low-quality recycled aggregate concrete will be improved by improving these porosities. In fact, it is thought that porosity also exists in the old ITZ between the attached mortar and the aggregate. This porosity was difficult to study and was not indicated.

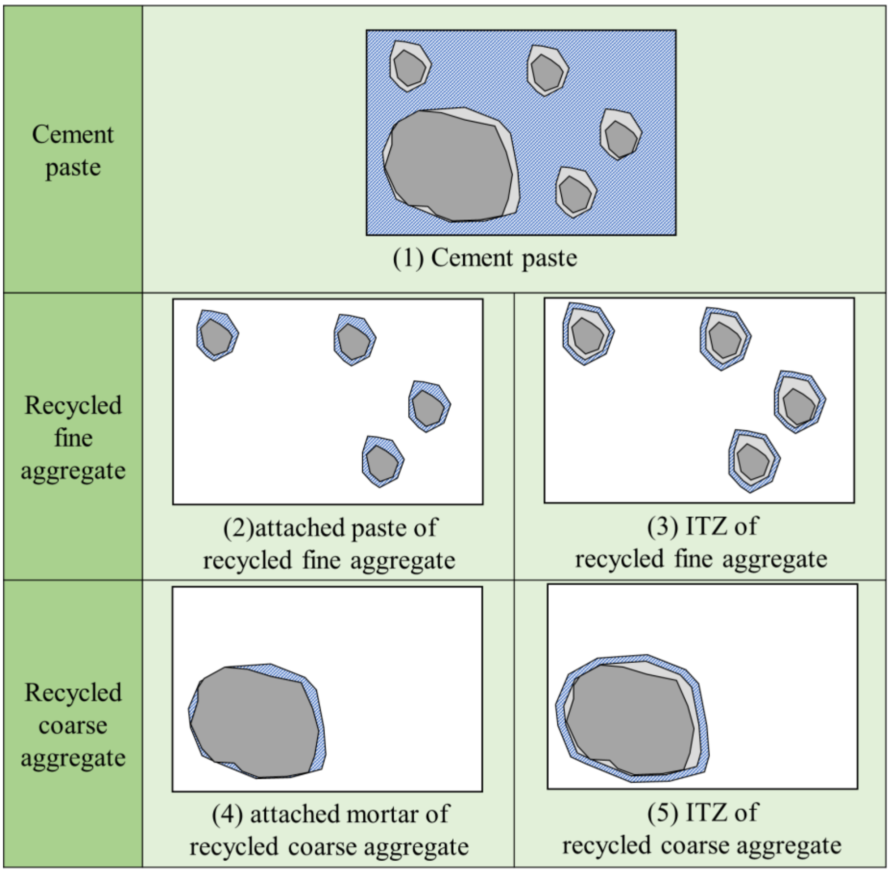

Figure 1 Location of the porosity in recycled aggregate concrete

2.2. Improving methods of recycled aggregate concrete

2.2.1 Accelerated carbonation of recycled aggregate

Carbonation of concrete is considered to cause corrosion of the reinforcing bars in reinforced concrete. But focusing only on concrete, it is known that calcium hydroxide changes to calcium carbonate, and strength of concrete increases as porosity is densified by carbonation. Therefore, if the attached mortar of recycled aggregate can be densified by carbonated, recycled aggregate can be improved, and the strength and durability of concrete can be improved. In this study, recycled aggregate was carbonated for 1 week in accelerated carbonation chamber at a temperature of 20°C, a relative humidity of 60% and a carbon dioxide concentration of 5%.

2.2.2 Addition of C-S-H type accelerator

C-S-H type accelerator is an admixture based on Calcium Silicate Hydrate (C-S-H). It has been explained that C-S-H nanoparticles works as seed of crystal growth in cement hydration process, then setting and strength development in early age are enhanced by this nanoparticles in this accelerator. In this study, the addition rate was set at 10% of the unit water content.

3. OUTLINE OF EXPERIMENT

Table 1 shows the physical properties of fine and coarse aggregate used in this study. In this study, Class L recycled fine and coarse aggregate were used, also normal fine and coarse aggregate were used. Figure 2 and 3 show the improving effect on dry density and water absorption rate of recycled aggregate by accelerated carbonation. Before mixing concrete, both recycled fine and coarse aggregate were pre-wetted for 24 hours before mixing to be used in the surface dry state. In addition, in this study, Ordinary Portland cement was used in all mix propotions. Table 2 shows the mix proportion of concrete. The mix proportion was set at a constant water-cement ratio of 50% and s/a of 48%. The mix proportions were as follows: one without accelerated carbonation of both fine and coarse aggregate, one with acceleted carbonation of only fine aggregate, one with accelerated carbonation of both fine and coarse aggregate, and C-S-H type accelerator added at 10% of unit water content. In this study, the names of mix proprtion are indicated by fine aggregate type and coarse aggregate type, and those with C-S-H type accelerator are indicated by fine aggregate type and coarse aggregate type-ACX.

Table 1 Physical properties of fine and coarse aggregate

Sample name	Surface dry density (g/cm³)	Absolute dry density (g/cm³)	Water absorption rate (%)	Amount of fine particles (%)
NS	2.60	2.55	1.92	2.00
LS	2.24	2.00	12.01	8.60
LSC	2.31	2.13	8.47	
NG	2.70	2.69	0.32	0.80
LG	2.51	2.37	5.90	1.00
LGC	2.55	2.45	4.35	

NS is normal fine aggregate, LS is recycled fine aggregate and LSC is carbonated of LS. NG is normal coarse aggregate, LG is recycled coarse aggregate and LGC is carbonated of LG.

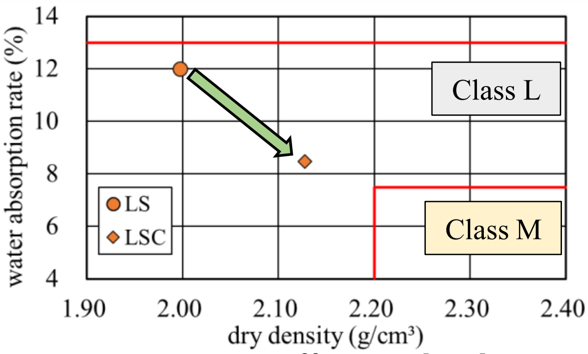

Figure 2 Improving effect on dry density and water absorption rate of recycled fine aggregate

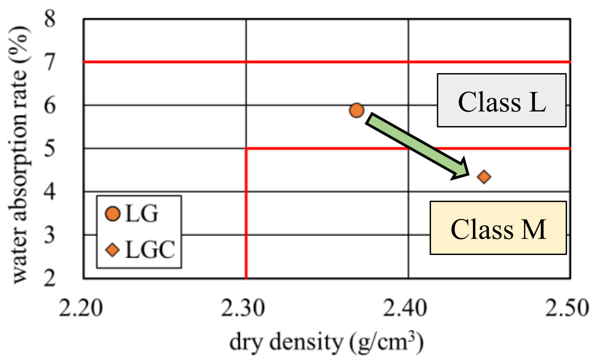

Figure 3 Improving effect on dry density and water absorption rate of recycled aggregate

Table 2 Mix proportion of concrete

Symbol name	Improving method		Aggregate		W/C (%)	s/a (%)	air (%)
	carbonated	ACX	fine	coarse			
NSNG	-	-	NS	NG	50	48	4.5
LSLG	-	-	LS	LG			
LSLG-ACX	-	○					
LSCLG	S carbonated	-	LSC	LG			
LSCLG-ACX	S carbonated	○					
LSCLGC	S,G carbonated	-	LSC	LGC			
LSCLGC-ACX	S,G carbonated	○					

3.1 Compressive Strength Test

Compressive strength test was carried out in 28days, according to JIS A 1108. All specimens were cured in 20°C tap water.

3.2 Air Permeability Test

The specimens were dried at 40 °C in a drying oven until the weight loss became constant. Measurement was carried out in an air permeability testing equipment. The air permeability coefficient was calculated using Equation (1). All specimens were cured for 28days in 20°C tap water.

$$K = \frac{2LP_1}{(P_1{}^2 - P_2{}^2)} \cdot \frac{Q}{A} \quad (1)$$

K: Air permeability coefficient ($cm^4/(N \times s)$), L: Specimen thickness (cm), P_1: Loading pressure (N/mm^2), P_2: Outflow side pressure (N/cm^2), Q: Amount of permeated air (cm^3/s), A: permeable area (cm^2)

3.3 Drying Shrinkage Test

Drying shrinkage test was carried out, 1, 2, 4, 8, 13 weeks after cured period according to JIS A 1129-3. All specimens were cured for 28days in 20°C tap water.

3.4 Porosity Test

The porosity was calculated by Archimedes method. After 28 days of curing, the specimens for the air permeability test were immediately saturated in a vaccuum state, and the saturated mass and the mass in water were measured. After that, It was the specimens were dried at 40 °C in a drying oven until the weight loss became constant and measured the mass in an absolutely dry state. The porosity was calculated by the Archimedes method using these values.

4. RESULTS AND DISCUSSION

4.1 Compressive Strength Test

Figure 4 shows compressive strength. Compressive strength of LSLG was about 50% of compressive strength of NSNG. Comparing compressive strength of LSLG with that of LSCLG and LSCLGC, it can be seen that compressive strength was improved by accelerated carbonation of recycled aggregate. On the other hand, in the previous studies, compressive strength was not improved by accelerated carbonation of only recycled coarse aggregate. Therefore, compressive strength is most improved by accelerated carbonation of both recycled fine and coarse aggregate, but the improving effect of accelerated carbonation of recycled fine aggregate was higher than that of accelerated carbonation of recycled coarse aggregate. In addition, compressive strength of LSLG-ACX, LSCLG-ACX, and LSCLGC-ACX was also greatly improved compared to no addition of C-S-H type accelerator (LSLG, LSCLG, and LSCLGC). Also, compressive strength of LSCLGC-ACX was improved to 90% of compressive strength of NSNG, while compressive strength of LSCLG-ACX was also greatly improved to 85% of compressive strength of NSNG.

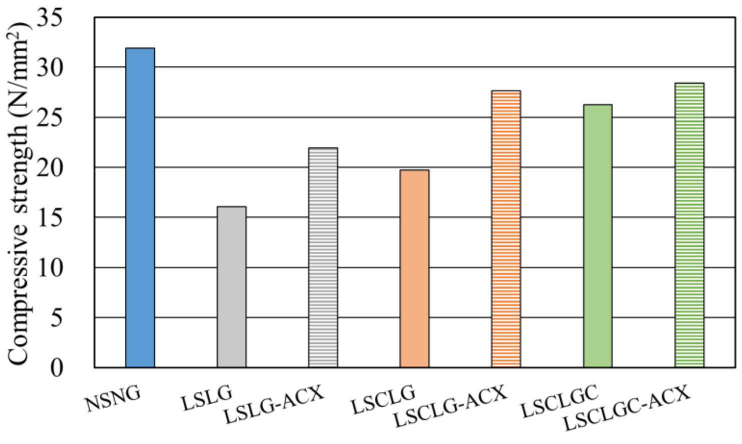

Figure 4 Compressive strength

4.2 Air Permeability Test

Figure 5 shows air permeability coefficient. Air permeability coefficient of LSLG is significantly larger than that of NSNG. Comparing air permeability coefficient of LSLG with that of LSCLG and LSCLGC, it can be seen that air permeability coefficient was improved by accelerated carbonation of recycled aggregate. On the other hand, in the previous studies, air permeability coefficient was not improved by accelerated carbonation of only recycled coarse aggregate. Therefore, as in the case of compressive strength, air permeability coefficient was most improved by accelerated carbonation of both recycled fine and coarse aggregate, but the improving effect of accelerated carbonation of recycled fine aggregate was higher than that of accelerated carbonation of recycled coarse aggregate. In addition, air permeability coefficient of LSLG-ACX, LSCLG-ACX, and LSCLGC-ACX was also greatly improved compared to that of no addition of C-S-H type accelerator (LSLG, LSCLG, and LSCLGC). Also, the air permeability coefficient of LSCLGC-ACX was the most improved, while the air permeability coefficient of LSCLG-ACX was also greatly improved.

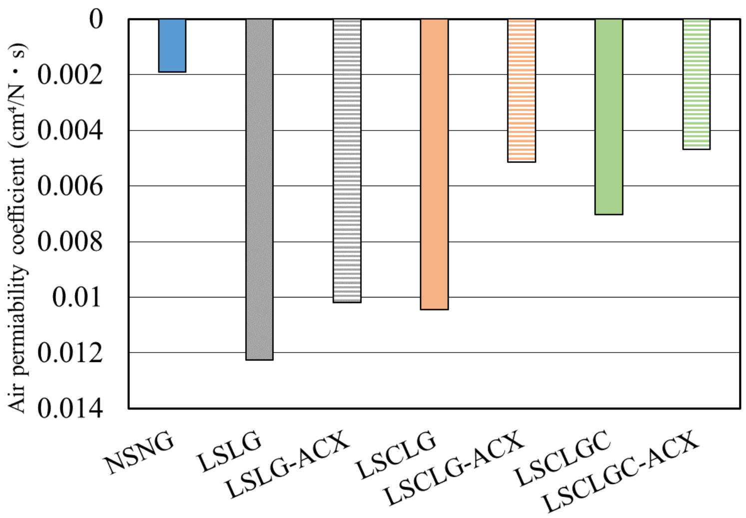

Figure 5 Air permeability coefficient

4.3 Drying Shrinkage Test

Figure 6 shows length change rate and Figure 7 shows mass change rate. The length change rate at the 13th week after the end of curing was about -1100×10^{-6} in case of LSLG while it was about -500×10^{-6} in case of NSNG. Drying shrinkage of concrete can be suppressed if the water content of concrete at the end of curing is reduced. In other words, if the porosity can be made dense, the excess water content at the end of curing will decrease and drying shrinkage can be suppressed. In the case of the forced carbonation of aggregate, the water absorption rate of the aggregate was reduced, therefore, the porosity of the adhered mortar was made dense, and the water content of the aggregate was reduced by pre-wetting, thus, the drying shrinkage was suppressed. Comparing drying shrinkage of LSLG, LSCLG, and LSCLGC, it can be seen that drying shrinkage of LSCLGC was most suppressed, but the gap between LSLG and LSCLG was larger than that between LSCLG and LSCLGC. This may be due to the fact that the water absorption rate of recycled fine aggregate is higher than that of recycled coarse aggregate, and the improving effect of water absorption rate by accelerated carbonation is greater. In addition, drying shrinkage of LSLG-ACX, LSCLG-ACX, and LSCLGC-ACX was also suppressed compared to that of LSLG, LSCLG, and LSCLGC. It is thought that porosity of cement paste and ITZ of coarse aggregate was densified by addition of the C-S-H type accelerator and reduced the excess water content of specimen at the end of curing, thus drying shrinkage was suppressed. In addition, from Figure 7, it can be seen that mass change rate is smaller for mix proportions in which drying shrinkage is suppressed. Thus, it is considered to be important to reduce the excess water content, in other words, porosity of concrete at the end of curing.

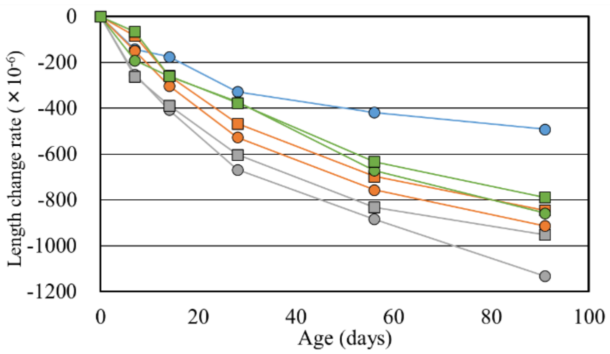

Figure 6 Length change rate

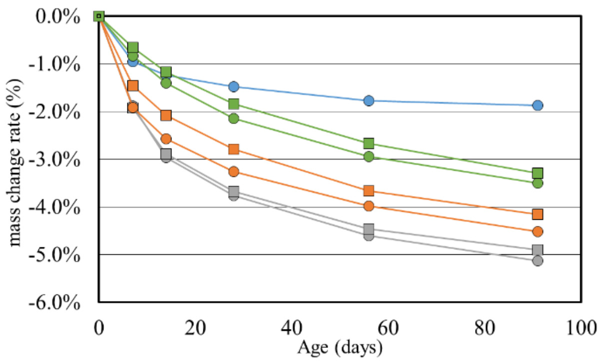

Figure 7 Mass change rate

4.4 Relationship between porosity and each physical property

Figure 8 shows the relationship between porosity and compressive strength and Figure 9 shows the relationship between porosity and air permeability coefficient. It can be seen that compressive strength and air permeability coefficient improved as porosity decreased. In addition, improving effect of LSLG-ACX and LSCLG was small. On the other hand, it can be seen that LSCLGC-ACX which carried out three improving methods was the most efficient, but LSCLG-ACX, which carried out two improving methods, was also greatly improved. In addition, porosity of atached mortar, in (2) and (4) in Figure 1, is considered to be improved by accelerated carbonation of recycled aggregate. However, in porosity test by Archimedes method, porosity is calculated by summing up porosity of the five pores which are shown in Figure 1. Therefore, it is difficult to specify the degree of improving each porosity other than (2) and (4). Since both strength and air permeability coefficient of concrete are greatly affected by ITZ, so investigated to what degree porosity at ITZ of recycled coarse aggregate, was improved by each improving method. In this study, in order to investigate the mechanism of porosity improvement by each improvement method, Vickers hardness was mesured.

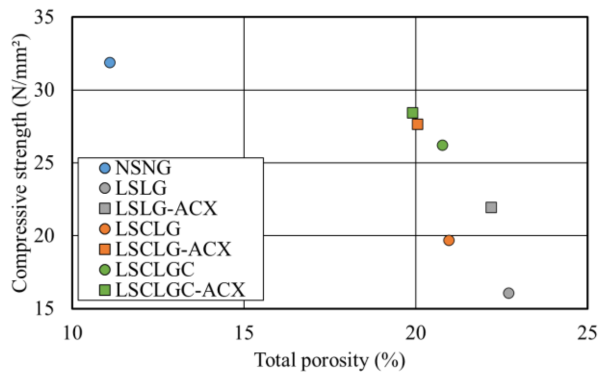

Figure 8 Relationship between porosity and compressive strength

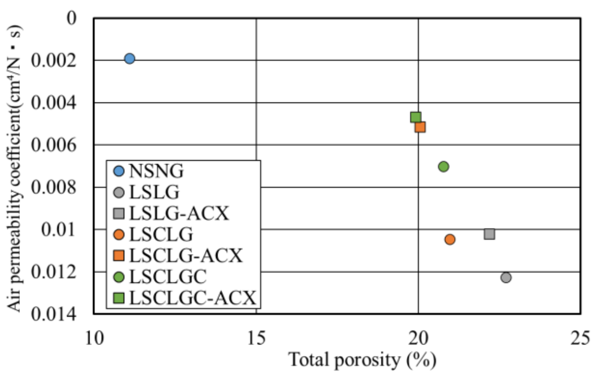

Figure 9 Relationship between porosity and air permeability coefficient

5. INVESTIGATION OF THE POROSITY IMPROVING MECHANISM BY EACH IMPROVING METHOD

5.1 Method of vickers hardness test

Vickers hardness test was carried out by making 30mm × 30mm × 10mm specimens from the specimens after air permeability test, and the specimen surfaces were mirror-finished on a turntable using abrasive paper #120-15000. Vickers hardness was measured using a micro hardness tester (load: 0.9807 N, test force: 10 μm/s). Two points were measured at 20 μm intervals from the edge of the coarse aggregate to 200 μm on a line orthogonal to the edge of the coarse aggregate, and the average value was calculated.

5.2 Vickers hardness

Figure 10 shows the Vickers hardness and Table 3 shows the thickness of ITZ. In all mix proportions, there is ITZ with low Vickers hardness a few tens μm from the edge of the aggregate. At a distance from the edge of the aggregate, there is a bulk area with the same degree of Vickers hardness that is not affected by aggregate. Since Vickers hardness of the bulk part is about 80-120 N/mm^2, if ITZ is defined as the part where Vickers hardness is less than 80 N/mm^2, the thickness of ITZ is about 40 μm in NSNG while it is about 120 μm in LSLG. This is because of the high water absorption rate of recycled aggregate, and the water inside recycled aggregate exuded to the aggregate interface when the hardening process was completed, resulting in the thickness of ITZ being expanded. On the other hand, it was found that the thickness of ITZ was reduced by accelerated carbonation of recycled aggregate and addition of C-S-H type accelerator. Comparing each improving method, the thickness of ITZ of LSLG-ACX is smaller than that of LSCLG and LSCLGC, it is considered that addition of C-S-H type accelerator has a greater effect on densifying porosity in ITZ than accelerated carbonation of recycled aggregate. In addition, Vickers hardness of the bulk part of LSLG-ACX, LSCLG-ACX and LSCLGC-ACX was slightly larger than that of LSLG, LSCLG and LSCLGC. Thus, it is considered that the addition of the C-S-H type accelerator may also improve the porosity of the cement paste (1). In addition, the thickness of ITZ of LSCLGC-ACX and LSCLG-ACX, which showed significant improving in strength and durability, was about 60 μm. It is considered that this is because densification of porosity of ITZ by addition of C-S-H type accelerator and reduction of water absorption rate and water exudation after hardening process by accelerated carbonation of recycled aggregate.

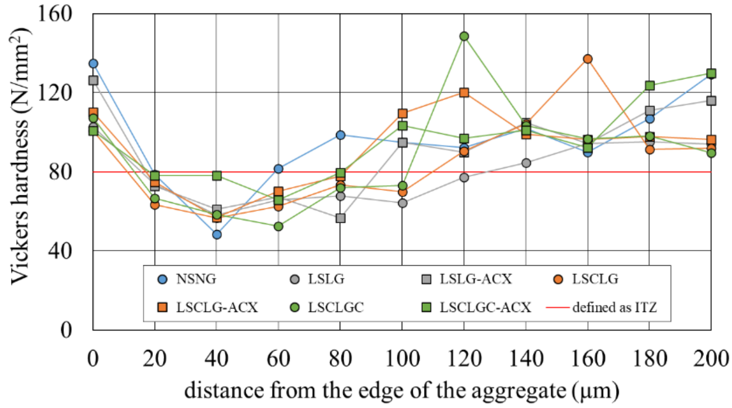

Figure 10 Vickers hardness

Table 3 Thickness of ITZ

Symbol name	Thickness of ITZ (μm)
NSNG	40
LSLG	120
LSLG-ACX	80
LSCLG	100
LSCLG-ACX	60
LSCLGC	80
LSCLGC-ACX	60

5.3 Investigation of the location of porosity improved by each improving method

Table 4 shows location of porosity improved by each improving method. Based on the test results in this study, it is discussed which porosity shown in Figure 1 was improved by the accelerated carbonation of aggregate and addition of C-S-H type accelerator. First, the addition of C-S-H type accelerator (LSLG-ACX) had little effect on the compressive strength and air permeability coefficient, but the thickness of ITZ was greatly reduced and Vickers hardness of the bulk part was slightly increased. This suggests that there is an effect on the porosity of (1) cement paste and (5) ITZ of coarse aggregate. Accelerated carbonation of recycled fine aggregate (LSCLG) had little effect on compressive strength, air permeability coefficient, and the thickness of ITZ. This is because the water absorption rate of the aggregate is greatly improved, and the water exuded to the fine aggregate interface is considered to be reduced. This suggests that there are effects on the porosity of (2) attached paste of recycled fine aggregate and (3) ITZ of recycled fine aggregate. In the case of accelerated carbonation of fine and coarse aggregate (LSCLGC), the results are similar, so it is considered that there are effects on the porosity of (2), (4) attached mortar of fine and coarse aggregate and (3), (5) ITZ of fine and coarse aggregate. The combination of accelerated carbonation of fine aggregate and addition of C-S-H type accelerator (LSCLG-ACX) had significant effect on compressive strength, air permeability coefficient and the thickness of ITZ. This suggests that there are effects on the porosity of (1) cement paste, (2) attached paste of fine aggregate, and (3), (5) ITZ of fine and coarse aggregate. In the case of the combination of accelerated carbonation of fine and coarse aggregate and addition of C-S-H type accelerator (LSCLGC-ACX), the results are similar, so the effects are considered to be on the porosity of (1) cement paste, and (2), (4) attached mortar of fine and coarse aggregate, and (3), (5) ITZ of fine and coarse aggregate. Therefore, it is important to improve the porosity of (5) ITZ of coarse aggregate.

Table 4 Location of porosity improved by each improving method

Sample name	(1) cement paste	(2) attached paste of recycled fine aggregate	(3) ITZ of recycled fine aggregate	(4) attached mortar of recycled coarse aggregate	(5) ITZ of recycled coarse aggregate
LSLG-ACX	○				◎
LSCLG		○	○		◎
LSCLG-ACX	○	○	○		
LSCLGC		○	○	○	○
LSCLGC-ACX	○	○	○	○	◎

6. CONCLUTION

The following was concluded about the improving effects on strength and durability of low quality recycled aggregate concrete caused by each improving methods.

(1) Accelerated carbonation of aggregate improves the porosity of attached mortar and ITZ of aggregate, and, thus, improves compressive strength, air permeability coefficient and drying shrinkage.

(2) Addition of C-S-H type accelerator improves the porosity of cement paste and ITZ of coarse aggregate, but improving effects on compressive strength, air permeability coefficient and drying shrinkage is small.

(3) The combination of accelerated carbonation of aggregate and addition of C-S-H type accelerator greatly improves the porosity of cement paste and attached mortar of aggregate, especially ITZ of coarse aggregate, as well as compressive strength, air permeability coefficient, and drying shrinkage. In particular, looking at strength, the strength of recycled aggregate concrete (LSLG) was 50% of that of normal concrete (NSNG), but the combination of accelerated carbonation of aggregate and addition of C-S-H type accelerator (LSCLGC-ACX) improved the strength to about 90%.

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