Study of environmentally friendly concrete combining recycled aggregate with blast furnace slag cement

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Abstract. The environmental issues need transition to promoting the formation of recycling-based Society as well as realization of carbon neutrality. In the concrete field, there is an attempt to use demolished concrete structures as recycled aggregate. It has not been widely used because of it is low quality compared to natural aggregate. However, since the water absorption and porosity can be modified by carbonation technology, it has recently been focus as a CCU material.
In this study, we aimed to achieve carbon neutrality by using a combination of carbonated recycled aggregate with blast furnace slag cement, which emits less CO_2 emissions than ordinary Portland cement. As a result, the CO_2 balance approached zero when ground granulated blast furnace slag replacement ratio was high and carbonated recycled aggregate was used. However, strength of these concrete was lower than that using recycled aggregate. It could be attributed to the increased porosity of the new mortar section. As a solution to this problem, the addition of a C-S-H type accelerator which promotes hydration resulted in improved strength.

Keywords: recycled aggregate, carbonation technology, ground granulated blast furnace slag, CO_2 balance, C-S-H type accelerator

1 Introduction

Starting with the adoption of the Sustainable Development Goals (SDGs) and the Paris Agreement at the UN Summit in 2015, there has been a call for a shift to production processes that take into account environmental load reduction and resource recycling in order to realize a sustainable society. In particular, the reduction of carbon dioxide emission that is the factor in global warming is universally recognized as a pressing issue. In the concrete sector, in order to reduce CO_2 emissions during manufacturing, concrete development is being promoted using low-CO_2 emitting clinker and cement with high admixture replacement. However, just combining them is not enough to achieve Carbon Neutral (CN). Therefore, one method being considered is to aim for a total net-zero emissions by combining technologies to absorb CO_2 in the concrete. On the other hand, there is an attempt to use dismantled concrete blocks as recycled aggregate as an approach that takes resource recycling into consideration. This recycled aggregate has not been widely used because of it is low quality compared to natural aggregate. However, it has been reported that the water absorption and porosity can be modified by carbonation. Therefore, if recycled aggregate can be successfully utilized as a Carbon Capture Utilization (CCU) material, it can contribute to both CN and resource recycling.

In this study, we focused on ground granulated blast furnace slag (GGBS) which can replace a large amount of Ordinary Portland cement, and low-quality recycled aggregate which has more adhesive paste and higher potential of CO_2 absorption. We evaluated the properties of concrete made with these materials.

2 Effect of GGBS replacement rates on recycled aggregate concrete

2.1 Aggregates

Table 1. shows the physical properties of the aggregates used in this study. The recycled aggregates were low-quality recycled fine aggregate (RS) and recycled coarse aggregate (RG) which original aggregate were limestone aggregates. And ordinary aggregate (OS; mixed sand, OG; limestone) was also used for comparison. Physical properties of aggregate were measured according to JIS A 5021 and JIS A 5023.

The carbonated recycled aggregates (CRS and CRG) were carbonated for one week in an accelerated carbonation (temperature 20°C, relative humidity 60%, CO_2 concentration 5%), referring to previous studies. The samples were stirred once a day to ensure that CO_2 was distributed throughout the aggregate.

Table 1. Physical properties of fine and coarse aggregate

Symbol	Type of aggregate	density (g/cm^3)		Water absorption rate (%)	Amount of pore (%)
		Surface dry	Absolute dry		
OS	Ordinary fine aggregate	2.60	2.55	1.92	5.01
RS	Recycled fine aggregate	2.19	1.94	13.03	25.33
CRS	Recycled carbonated fine aggregate	2.25	2.03	10.79	21.94
OG	Ordinary coarse aggregate	2.70	2.69	0.32	1.00
RG	Recycled coarse aggregate	2.40	2.25	6.77	15.23
CRG	Recycled coarse carbonated coarse aggregate	2.41	2.29	5.58	12.92

2.2 *Mix proportion*

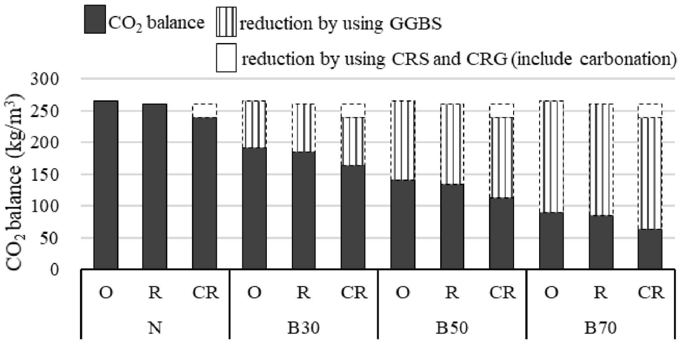
The mix proportion of binder was 4 kinds, only using Ordinary Portland cement (OPC) was N, 30% replacement of GGBS is B30, 50% replacement of GGBS is B50, 70% replacement of GGBS is B70. Table 2. shows mix proportion conditions. All kinds of concrete were kept constant as W/B: 50 weight % and s/a: 48 weight %. Chemical admixture that has effect of air entraining and high performance water-reducing was used due to control air content at 4.5 ±1.5 volume % and slump at 18 ±2.5 cm.

Table 2. Mix proportion conditions

	Mix proportion (weight %)				Type of using aggregate ; Symbol (fine aggregate, coarse aggregate)
	Binder mix proportion		W/B	s/a	
	OPC	GGBS			
N	100	0	50	48	O (OS, OG), R (RS, RG), CR (CRS, CRG)
B30	70	30			
B50	50	50			
B70	30	70			

2.3 *CO_2 balance in materials*

Fig. 1. shows the CO_2 balance calculated from the CO_2 emissions derived from the materials and the CO_2 reductions achieved by absorption of CO_2 in the recycled aggregate. The amount of CO_2 emissions was calculated from multiplied amount of CO_2 (kg/t) by used weight (t/m^3) of each binder and aggregate. The CO_2 emissions from the transportation and production of recycle aggregate were not included in the scope of this study, because the business model has not yet been developed.
The amount of CO_2 absorption in the recycled aggregate was calculated from the difference in decarbonation ratio of before and after carbonation at 550 to 800 degree Celsius using TG-DTA. It was found that carbonated recycled aggregate and high substitution of blast furnace slag fine powder can significantly reduce CO_2.



CO_2 emission (kg/t)

OPC	764.3
GGBS	26.5
OS	2.9
OG	3.7

CO_2 absorption(kg/t)

CRS	26.69
CRG	2.03

Fig. 1. CO_2 balance of concrete

2.4 *Outline of experiment*

(1) Compressive strength test

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

(2) Porosity test by Archimedes' method

After curing a φ100*200 mm cylindrical specimen in water for 28 days, both ends were cut off by about 25 mm, and the remaining 150 mm specimen was cut into three pieces by about 50 mm. Immediately after cutting, the specimens were placed in a container filled with water and saturated with water under vacuum conditions, and the saturated mass and mass in water were measured. The specimens were then placed in a drying oven at 40°C until the mass loss became constant, the dry mass was measured, and the porosity was calculated by Archimedes' method.

2.5 *Results and discussion*

(1) Compressive strength

Fig. 2. shows the results of compressive strength. For all binder types using recycled aggregate (R) were lower than using ordinary aggregate (O). It is presumably caused by the difference in aggregate density.

Focusing on the effect of carbonation on recycled aggregate, different binder types showed different trends. CRN showed higher strength than NR, it is similar to previous studies. However, CRB30 and CRB50 showed almost the same strength using R. Furthermore, CRB70 showed lower strength than RB70.

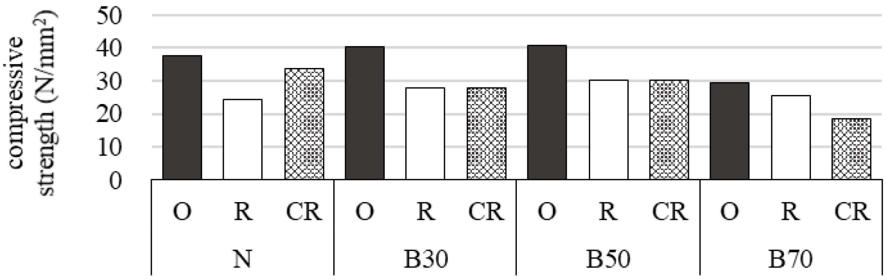


Fig. 2. Compressive strength

(2) Porosity

Fig. 3. shows the results of porosity. The study was conducted by classifying the amount of pore for each location where pore exist; cement paste which containing Interfacial Transition Zone (CP+ITZ), coarse aggregate (G), and fine aggregate (S), since the pore of the recycled aggregate is very higher than normal aggregate. It is reported that the ITZ in concrete with recycled aggregates has loose and porous product layer due to moisture movement and chemical reactions from the higher porosity and absorption capacity, and it appeared to be an important factor in governing strength.

The classification of pore was based on the following.
Total pore: measured from Archimedes method
From aggregate: “amount of aggregate pore (Table1)” × “volume of using”
From CP+ITZ: “Total pore” - “From aggregate”

In the same binder type, the amount of pore in the cement paste should be the same because the mix proportions of the cement paste are the same. However, CRB70 has more pore at cement paste than OB70 and RB70.The one of possibility is that some component of the recycled aggregate affected the hydration reaction of the cement paste. On the other hand, if the hydration of the cement paste was not affected, this difference can be attributed to the ITZ.

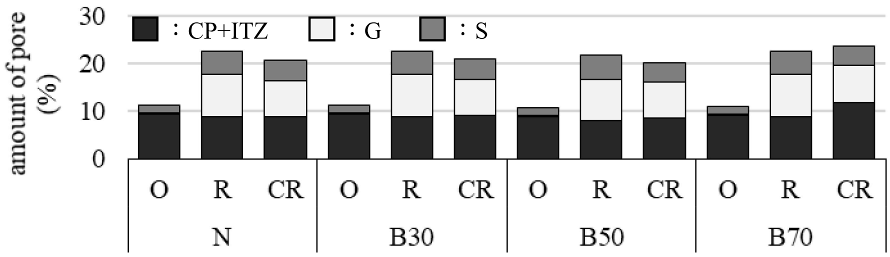


Fig. 3. The amount of pore

3 Study of Combination using C-S-H type accelerator

3.1 Materials Used and mix proportion Conditions

C-S-H type accelerator (ACX) is a chemical admixture that main constituent is C-S-H nanoparticles. The mechanism of ACX is that introduced into the liquid phase of the concrete, after that, it acts as seed crystals and accelerate hydration without waiting for the formation of C-S-H from the cement. Therefore, it is expected to effectively promote hydration in not only cement paste but also like ITZ where cement particles are less present.

Table 3 shows the symbol of mix proportion. The results using O, R, CR are same date at Section 2. In the case of using CR, it was also performed that ACX was added at 1.0% of the water weight (CR-X). Other condition of mix proportion was based on table 2.

Table 3. Symbol of mix proportion

	Symbol			
	O	R	CR	CR-X
N	Same date at section 2			Using CR and adding ACX at 1.0 % (of the water weight)
B30				
B50				
B70				

3.2 Outline of experiment

Compressive strength test was performed as in chapter 2. In addition, air permeability tests and pore size distribution were measured due to examine how to ACX contributes to the pore structure.

(1) Air permeability test

The porosity was measured using φ100*200 mm cylindrical specimen which were after curing in water for 28 days. It was cut to 50 mm thickness as Porosity test in chapter 2 and dried at 40-degree Celsius until constant volume. Air was allowed to permeate through the specimens at a pressure of 0.1 MPa, and the amount of air permeation was measured using a female cylinder. The air permeability coefficient was calculated from equation (1) using the water displacement method.

$$K= 2LP_1/(P_1^2-P_2^2)*Q/A \quad (1)$$

K: Air permeability coefficient ($cm^4/(N*s)$), L: Specimen thickness (cm), P1: Loading pressure (N/mm^2), P2: Outflow side pressure (N/cm^2), Q: Amount of permeated air (cm^3/s), A: permeable area (cm^2)

(2) Measured pore size distribution

The case of using N or B70 were measured pore size distribution by the Mercury Intrusion Porosimetry (MIP). The specimen was cut at about 5*5*5 mm without coarse aggregate as possible. The measurement device used Quantachrome Poremaster 33.

3.3 Results and discussion

(1) Effect of ACX addition on compressive strength

Fig.5. shows the ratio of compressive strength to using O aggregate. In the graph, the vertical axis of 1.0 is same strength using O. In all binder types, the addition of ACX improved the strength.

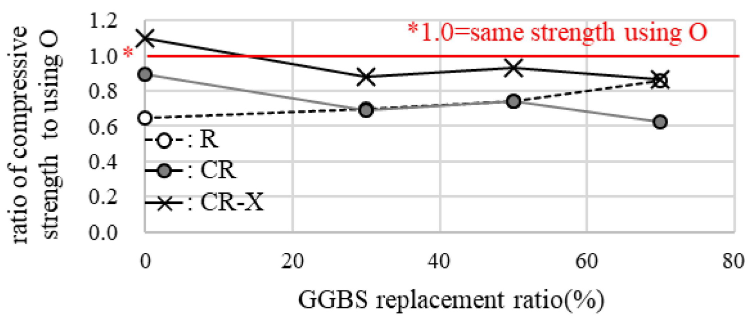


Fig. 5. The ratio of compressive strength to using O aggregate

(2) Effect of ACX addition on air permeability

Fig. 6. shows the relationship between air permeability and compressive strength. In all binder types, the addition of ACX decreased air permeability and increased compressive strength.
Especially in B70, the addition of ACX significantly improves the air permeability. The air permeability test measures the amount of air that passed through the concrete. It means that the more continuous the voids are formed, it made the air permeability higher. Therefore, it is assumed that B70 was reduced the pore in the cement paste and also reduce pore continuity due to the addition of ACX.

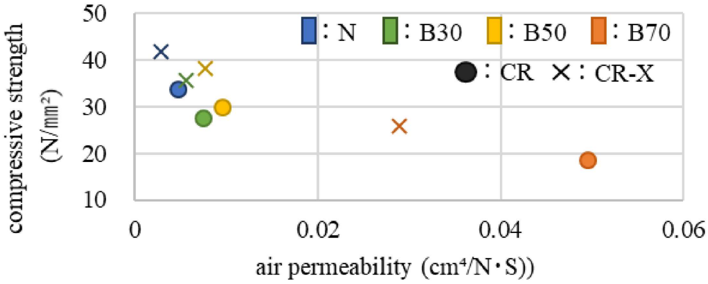


Fig. 6. The relationship between compressive strength and permeability

(3) Effect of ACX addition on pore size distribution

Fig. 7. shows the pore size distribution. Compared with the case of using O, a lot of large diameter pores (larger than 50 nm) were observed in the case of using CR. However, there was a tendency to shift smaller diameters using CR-X. Also, the total pore size up to 20 μm was smaller in RC-X than in RC. In general, it is said that cement paste has mostly pore of 50 nm or less, and voids of 50 nm or more are considered to exist mostly in the ITZ. Therefore, it is considered that the ITZ could be densified by the addition of ACX. However, it is likely to also include the impact of densified CP since there is no strict classification of pore. It is necessary to confirm the observation of ITZ by SEM and the change in Vickers hardness in the future.

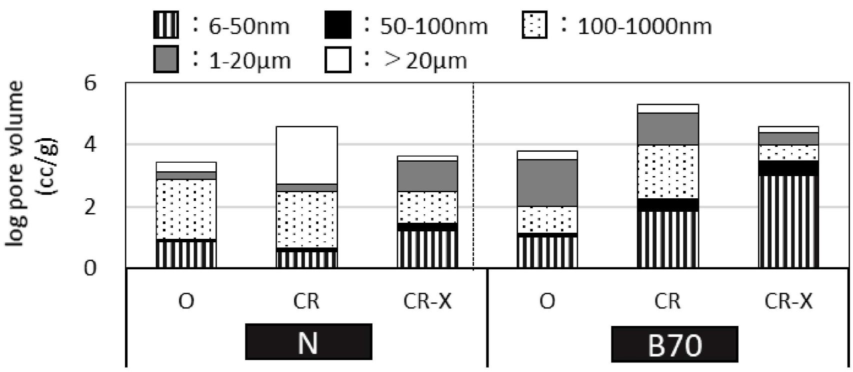


Fig. 7. The pore size distribution measured by MIP

4 Conclusion

The following conclusions were obtained from the study.

(1) The recycled aggregate with carbonation reduced the amount of pore and improved the aggregate properties like density and amount of pore. The use of recycled aggregate can also contribute to the reduction of CO_2 emissions by absorption of CO_2.

(2) The compressive strength of the recycled aggregate was lower than that of the ordinary aggregate.

(3) In case of using OPC, the concrete using recycled aggregate with carbonation showed higher strength and less pore than using recycled aggregate. However, in case of using GGBS used in large amounts as OPC substitute was not.

(4) The combination of CR aggregate and C-S-H accelerator improved air permeability and compressive strength for all binder types. And all so, the pore size distribution tended to shift to smaller diameter with the addition of ACX.

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Acknowledgments

This paper is based on results of “Development of Materials, Manufacturing Methods and Quality Control System on Innovative Carbon Negative Concrete”, JPNP21014, commissioned by the New Energy and Industrial Technology Development Organization (NEDO).