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Proposed Mix Proportion Method for Modified Low Quality Aggregate Concrete

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ABSTRACT

A long period of time has passed since the JIS proposed recycled aggregate concrete. However, the use of recycled aggregate concrete has not progressed in Japan. The reason is that it is more difficult to ensure the quality of recycled aggregate concrete when the quality of the aggregate is poor, and a mix proportion method has not been established. On the other hand, carbonation of recycled aggregate is being promoted worldwide from the perspective of using CCU materials to reduce CO_2 emissions toward a carbon-neutral society. We have also explored the carbonation of low-quality recycled aggregate and its modification effect. Carbonation can improve the strength and durability of concrete. On the other hand, it was also found that the properties of concrete made with different cements are different. It was found that the properties of the modified recycled aggregate concrete were like those of the unmodified recycled aggregate concrete, especially when high content of blast furnace slag was used. Based on these results, we were able to propose a mix proportion method based on the strength development of the three cement types. In addition, CO_2 emission was calculated by using CCU materials, and the environmental benefits were also mentioned.

1. INTRODUCTION

Toward the year 2050, various industries in Japan are working to achieve a carbon-neutral society. In the construction industry, it is well known that CO_2 emissions from the production of steel and cement, the main materials used in concrete, are extremely large, and there is a need to reduce CO_2 emissions. For concrete, it is essential to use cement with a large amount of ground granulated blast furnace slag in order to reduce the use of clinker.

On the other hand, there are many structures in Japan and worldwide that are reaching the end of their service life, resulting in the disposal of large quantities of concrete. In the past, the recycling rate has been high in Japan, as concrete was reused as roadbed material; however, as road construction is also downsizing, it is becoming increasingly difficult to recycle this material. Therefore, the use of recycled aggregate as concrete aggregate is strongly desired in a recycling-oriented society. In Japan, recycled aggregate and recycled aggregate concrete were certified by JIS at an early stage, but the reality is that the use of recycled aggregate has not become widespread. This is due to the low quality of the aggregate and the lack of a design method for mixing the aggregate.

In addition, concrete is expected to absorb carbon dioxide for the realization of a carbon neutral society. It is known that structures can also fix carbon dioxide over a long period of time. If carbon dioxide can be fixed in recycled aggregate made from dismantled concrete structures, it will lead to a reduction in the amount of carbon dioxide. In this study, we carbonated the concrete block to absorb carbon dioxide and quantified the amount of carbon dioxide absorbed by the recycled aggregate, taking into account its production and storage. In addition, we aimed to understand the strength properties of concrete using recycled aggregate whose quality was improved by carbonation, and to present a mix proportion method using this type of aggregate. In addition, the carbon dioxide emissions of concrete were calculated, and mixes that could significantly reduce emissions were studied. This allows us to propose a mix design that considers the carbon dioxide emissions at the same strength level.

2. MODIFICATION OF RECYCLED AGGREGATE – CARBONATION TECHNOLOGY

The authors have reported that accelerated carbonation of recycled aggregate improves the quality of the aggregate. The authors have reported that the carbonation of low-quality aggregates in particular contributes significantly to the improvement of density and water absorption, since the remaining pores in the adhered mortar are filled with calcium carbonate. In this study, we attempted to improve the quality of the recycled aggregate used for concrete production by using low quality aggregate and applying accelerated carbonation. Table-1 lists the aggregates used in this study. Normal crushed stone was also used for comparison. It can be seen that the physical properties of the coarse and fine recycled aggregates were also improved. In this study, concrete was produced using these aggregates.

Table-1 Physical properties for using aggregate in this study

Name	Kinds of Agg.	Carbonated	Drying Density(g/cm^3)	Water absorption ratio (%)
O_S	Normal fine aggregate	-	2.60	1.21
R_S	Low-quality Recycled fine aggregate	None	2.00	11.59
RC_S		Done	2.04	10.29
O_G	Normal coarse aggregate	-	2.67	0.51
R_G	Low-quality Recycled coarse aggregate	None	2.22	7.25
RC_G		Done	2.28	5.92

3. PRODUCTION OF RECYCLED AGGREGATE CONCRETE

Table-2 shows the mix proportions of the recycled aggregate concrete produced in this study. Concrete with varying water-cement ratios was produced here to establish a mix design methodology.

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Table-2 Mix proportions for this study

Aggregate	Cement	W/C (%)	s/a (%)	Air (%)	Unit water (kg/m^3)
O: Normal Aggregate **R: Low-quality Recycled aggregate** **RC:** Improve**d Recycled aggregate**	OPC BB(Blast furnace slag cement Type B) BC(Blast furnace slag cement Type C)	40 50 60	48	4.5	175

Figure-1 shows the compressive strength test results of each concrete on 50% water cement ratio. As shown in the authors' previous study, the strength of recycled aggregate concrete is lower than that of concrete made with regular aggregate. This is presumably due to the reduction in aggregate strength caused by adhered mortar and mortar lumps. On the other hand, the proposed modified recycled aggregate concrete has higher strength than the concrete using unmodified recycled aggregate, although it is not as strong as the ordinary aggregate concrete with the same water-cement ratio. This clearly shows the usefulness of the modified recycled aggregate.

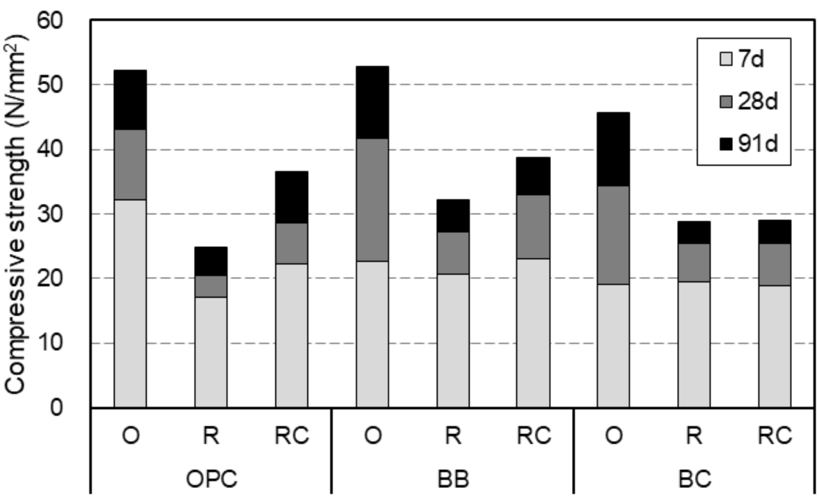

Figure-1 Results of compressive strength on each concrete (W/C 50%)

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4. CALCULATION OF CO_2 EMISSION AND ABSORPTION CONSIDERED AS CCU MATERIALS

With improved recycled aggregate, not only improvement of aggregate properties but also CO_2 absorption and fixation can be expected. Therefore, the following method of quantifying the amount of CO_2 absorbed and fixed was conducted for the amount of CO_2 absorption by the recycled aggregate.

Differential thermogravimetric analysis (TG-DTA) was used with reference to the existing literature. In the measurement procedure, recycled fine aggregate and recycled coarse aggregate were divided into smaller pieces, and at least 500 g of each piece was taken as a representative sample. Next, all samples were pulverized to less than 150 µm using a sieve. The pulverized samples were immersed in acetone for 4 hours to prevent CO_2 fixation before measurement. After immersion in acetone, the samples were vacuum-dried for at least 24 hours. During the measurement, nitrogen gas flowed in at 150-200 mL/min, the temperature increase rate was 20°C/min, and the maximum temperature of 1000°C was measured. In this study, the temperature range of mass loss in the calcination reaction was assumed to be 550-850°C, and the ratio of mass loss to sample mass was used as the CO_2 content; the amount of CO_2 fixed was obtained by subtracting the CO_2 content before and after the carbonation treatment as in Equation (1) and expressed as the amount of CO_2 fixed per 1 ton of recycled aggregate (kg-CO_2 /t) per ton of recycled aggregate. The measured values were averaged over three measurements, and the number of measurements was increased for those that varied.

$$RACO_2=(Ra-Rb)/100\times1000 \quad (1)$$

where $RACO_2$(kg-CO_2/t): CO_2 fixed amount of recycled aggregate, Ra (%): CO_2 content after carbonation treatment, Rb (%): CO_2 content before carbonation treatment

4.1 Recycled Aggregate Manufacturing Process

(1) CO_2 emissions during production

The CO_2 emissions associated with the manufacture of recycled aggregate were calculated from the electricity consumption of the recycled aggregate manufacturing plants. Table-3 shows an overview of the aggregate manufacturing plants, where L represents three plants and M and H represent one plant each. The number of data was influenced by the small number of aggregate manufacturing plants, which were selected from the members of ACRAC (Association for the Promotion of Recycled Aggregate Concrete). The electricity emission factor was used as 0.441 kg-CO_2/t. The CO_2 emissions were calculated from Equation (2).

$$Rce=(Mo\times Ec)/MC \quad (2)$$

where Rce(kg-CO_2/t): CO_2 emissions from recycled aggregate production, Mo(kW): rated output of the production facility, Ec(kg-CO_2/t): electricity emission factor, Mc(t/h): production capacity of recycled aggregate

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The CO_2 emissions of recycled fine and coarse aggregate M and H are shown as an average of the plant's measured values using the inventory data (MSD* and HSD*) presented in the previous literature, since the data for each of these materials are for one plant. For recycled aggregate L, the data is the average of the three plants. Table-3 shows the CO_2 emissions related to the production of recycled aggregate, which were higher for fine aggregate than for coarse aggregate. This is due to the lower hourly production capacity of fine aggregate compared to coarse aggregate. The results also showed that the order of L < M < H was larger. It was clear that the higher the quality, the higher the manufacturing energy.

Table-3 CO_2 emissions on different kinds of aggregate from different plants

Kinds of Agg.	Quality	Plant	Manufacturing methods	CO_2 emissions (kg-CO_2/t)	
Recycled coarse aggregate	L	LA	Dry Breaking	1.7	2.1
		LB	Dry Breaking	2.1	
		LC	Dry Breaking	3.4	
	M	MA	Dry Breaking + Wet milling	9.3	6.9
		MSD*		4.6	
	H	HA	Dry Breaking + Wet milling	27.9	25.4
		HSD*		22.9	
Recycled fine aggregate	L	LA	Dry Breaking	1.7	2.2
		LB	Dry Breaking	1.2	
		LC	Dry Breaking	3.6	
	M	MA	Dry Breaking + Wet milling	13.9	8.6
		MSD*		3.3	
	H	HA	Dry Breaking + Wet milling	41.9	42.7
		HSD*		43.6	

(2) CO_2 absorption during manufacturing

Two types of raw concrete were used to quantify the CO_2 fixed during the manufacturing process of recycled aggregate L and the CO_2 fixed during storage. The raw concrete was demolished concrete (Raw Concrete A) and returned concrete (Raw Concrete B). The original concrete A was demolition debris from a building completed in 1974. Based on JASS 5 at that time, we estimated that the cement was OPC and the nominal strength was 24 N/mm^2. The composition of the raw concrete B was 24-12-20 BB. Recycled aggregate L was manufactured by dry crushing using a jaw crusher, impact crusher, and vibrating sieve machine.

The method for quantifying the CO_2 immobilized in the manufacturing process of recycled aggregate was determined by using the returned concrete, raw concrete B, to quantify the CO_2

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content of the recycled aggregate immediately after production and subtracting the CO_2 content in the material used for the raw concrete. It was found that 7.1 kg-CO_2/t was fixed in the production process of the recycled coarse aggregate and 12.7 kg-CO_2/t in the production process of the recycled fine aggregate. This is because new fracture surfaces were exposed during the two crushing processes, and that the smaller particle size and larger surface area resulted in the fixation of CO_2. This value was used for the inventory data in this study, although further data construction and quantification methods will be needed in the future. In addition, this value was also applied to the inventory data for H and M because it is considered that the manufacturing process for recycled aggregates H and M also involves crushing followed by grinding and other special processes.

4.2 Recycled Aggregate Storage Process

The determination of the amount of CO_2 immobilized during storage of the recycled aggregate, the recycled aggregate was exposed for 28 days outdoors with a roof installed as a test. The surface of the aggregate was sprayed with a mist once a day to moisten the surface of the aggregate, and CO_2 in the air was immobilized. The determination method was based on the difference between the CO_2 content immediately after the recycled aggregate was produced and the CO_2 content after 28 days of storage. The amount of CO_2 fixed during storage was examined for recycled aggregate produced from raw concrete A and B. The amount of CO_2 fixed was 5.6 kg-CO_2/t for the recycled coarse aggregate produced from raw concrete A and 19.9 kg-CO_2/t for the recycled fine aggregate. The amount of fixed of CO_2 was confirmed to be 4.0 kg-CO_2/t for the recycled coarse aggregate and 16.4 kg-CO_2/t for the recycled fine aggregate produced from the raw concrete B. Therefore, the average value of each was calculated here and set as 4.8 kg-CO_2/t for coarse aggregate and 18.1 kg-CO_2/t for fine aggregate.

4.3 Production Process of Modified Recycled Aggregate (Accelerated Carbonation)

The authors summarized the data on CO_2 fixation by accelerated carbonation of recycled aggregate. The amount of CO_2 fixed by accelerated carbonation is shown as an average of measured and estimated values. Accelerated carbonation was performed for 7 days at a CO_2 concentration of 5%, a temperature of 20°C, and a humidity of 60%. Table-4 shows the amount of CO_2 fixed in the recycled aggregate by carbonation. Compared by aggregate type, the amount of fixation was higher for the recycled fine aggregate, and the amount of fixation was higher for the lower quality aggregate.

Table-4 CO_2 absorptions on recycled aggregate using accelerated carbonation

	Kinds	**Quality**	**Real or Estimate**	**Number of test sample**	**CO_2 absorption (kg-CO_2/t)**	
RLG	Recycled coarse agg.	L	Real	4	13.1	12.4
			Estimate	10	11.6	
RMG		M	Real	2	6.2	6.0
			Estimate	3	5.9	

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RHG		H	Real	1	1.7	1.7
RLS	Recycled fine agg.	L	Real	6	27.7	26.1
			Estimate	3	24.5	
RMS		M	Real	3	11.5	11.5
RHS		H	Real	1	10.0	10.0

4.4 Creating Inventory Data

Table-5 and Figure-2 shows the CO_2 balance of recycled aggregate. CO_2 emissions related to the production of crushed stone (G) and crushed sand (S) are also shown for reference. The amount of CO_2 emitted from the manufacture of recycled aggregate L is lower than that of crushed stone and crushed sand, while the amount of CO_2 fixed by carbonation is much higher. From these results, we were able to construct inventory data for carbonated recycled aggregate. Table-6 shows the inventory data for the various materials.

Table-5 Calculated total CO_2 balance of Recycled aggregate

Name	Kinds	Quality	CO_2 Emissions（kg-CO_2/t）	Absorbed CO_2（kg-CO_2/t）			Inventory data（kg-CO_2/t）
				Manufacture	Storage	carbonated	
G	Coarse	Normal	2.9	―	―	―	2.9
RLG		L	2.1	7.1	4.8	12.4	-22.2
RMG		M	6.9		―	6	-6.2
RHG		H	25.4		―	1.7	16.6
S	Fine	Normal	3.7	―	―	―	3.7
RLS		L	2.2	12.7	18.1	26.1	-54.7
RMS		M	8.6		―	11.5	-15.6
RHS		H	42.7		―	10	20

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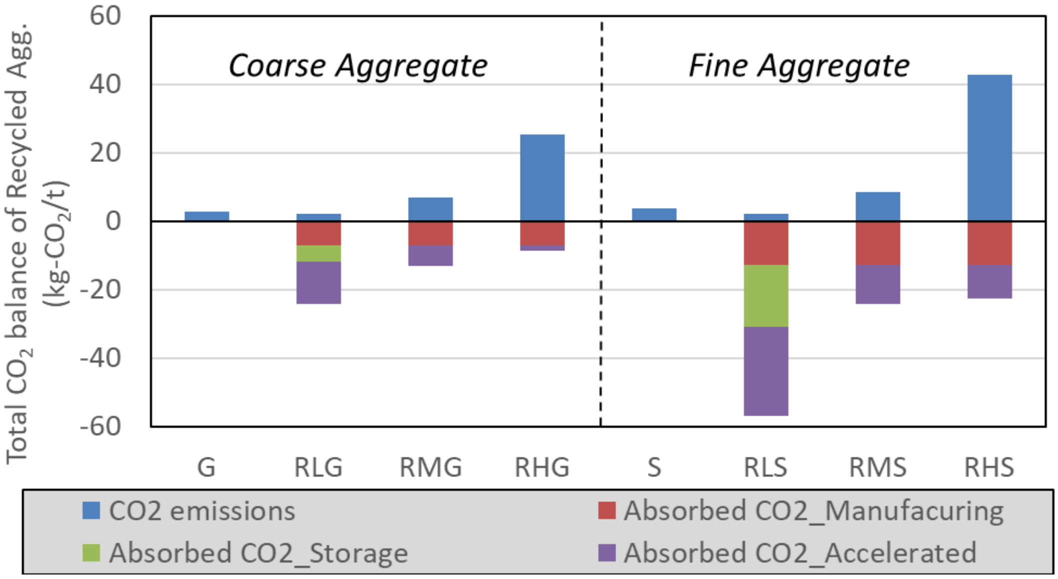

Figure-2 Total CO_2 balance of recycled aggregate

Table-6 CO_2 emissions Inventory data

Materials	CO_2 emissions (kg-CO_2/t)
Ordinary Portland cement	766.6
Blast furnace slag type B (BB)	458.7
Ground granulated Blast furnace slag	26.5
Normal coarse aggregate	2.9
Normal fine aggregate	3.9
Low-quality Recycled coarse aggregate	2.1
Low-quality Recycled fine aggregate	2.2
Improved recycled coarse aggregate	-22.2
Improved recycled fine aggregate	-54.7

5. METHODOLOGY FOR MIX PROPORTION OF RECYCLED AGGREGATE CONCRETE

5.1 Relationship between C/W and compressive strength

Figure-3 shows the relationship between C/W and compressive strength. It was confirmed that the relationship between C/W and compressive strength of the modified recycled aggregate concrete showed a positive correlation for all mixes. In OPC, the compressive strength improvement effect of the modified recycled aggregate was confirmed, but the effect became smaller as the mixing ratio of BB, BC, and ground granulated blast furnace slag increased. Therefore, the C/W equation for BB and BC with low-quality recycled aggregate was corrected for the intercept so that the strength result of W/C:50% with low-quality recycled aggregate was on the line with the C/W equation for modified recycled aggregate, and the

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equation was shifted in parallel without changing the slope. The above mix proportion design was performed and a quantitative evaluation of the CO_2 reduction effect.

5.2 CO_2 emissions on same strength

The CO_2 reduction effect was evaluated by designing mix proportion corresponding to the same strength based on the C/W equation obtained in 5.1. All mixes were designed to have a unit water volume of 175 kg/m^3, s/a of 48%, and air volume of 4.5%, a coefficient of variation of 10%, and a mix strength of 1.73σ. The CO_2 emissions of the concrete for each strength, calculated using the inventory data for each material shown in Table 3, are shown in Figure-4. The CO_2 emissions of the OPC mix were significantly higher than those of the ordinary aggregate with low-quality recycled aggregate, but the use of modified recycled aggregate reduced the CO_2 emissions. In the case of the BB and BC blends, the CO_2 emissions of the low-quality recycled aggregate were similar to those of the regular aggregate. In the BB and BC blends, CO_2 emissions of low-quality recycled aggregate were similar to those of ordinary aggregate. In particular, the CO_2 emissions on BC blend with low nominal strength were close to zero, suggesting the possibility of carbon neutrality.

6. CONCLUSIONS

The following findings were obtained within this study

(1) Recycled aggregate can absorb CO_2 during the manufacturing process and after 28 days of storage.

(2) The CO_2 immobilized after storage can be combined with the CO_2 from accelerated carbonation. In addition, the accelerated carbonation of $Ca(OH)_2$ after storage is a new method to increase CO_2 absorptions.

(3) Recycled aggregate L has low CO_2 emissions related to aggregate production, while CO_2 absorption by carbonation is very high, indicating that the CO_2 balance can be greatly reduced.

(4) The CO_2 reduction effect of the improved recycled aggregate concrete was highest in the OPC mix, suggesting that carbon neutrality can be achieved in the poor mix in the BC mix, and the reduction of CO_2 emissions was quantitatively demonstrated.

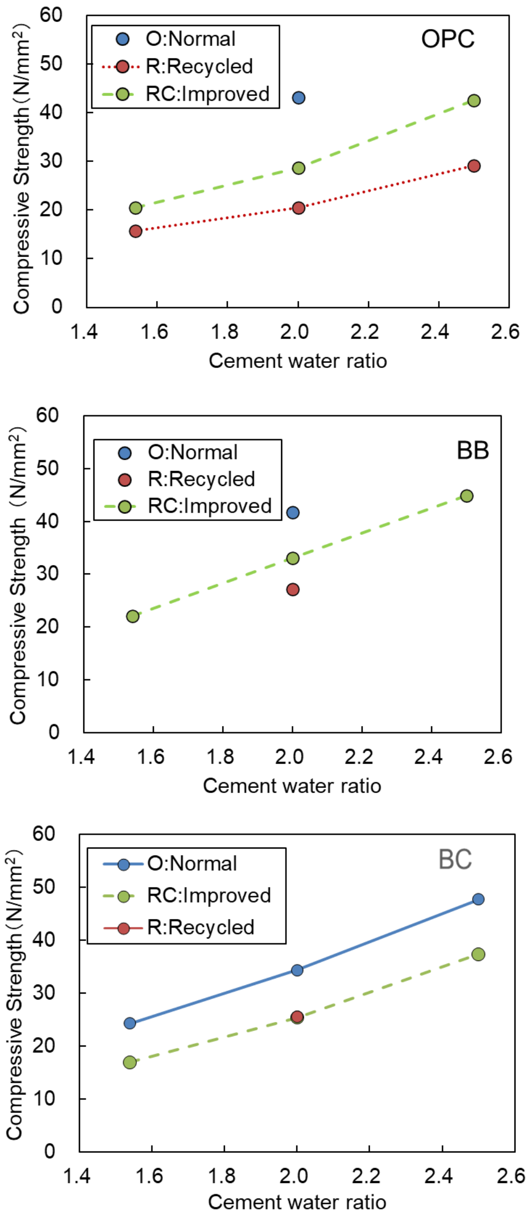

Figure-3 Relationship C/W and Strength

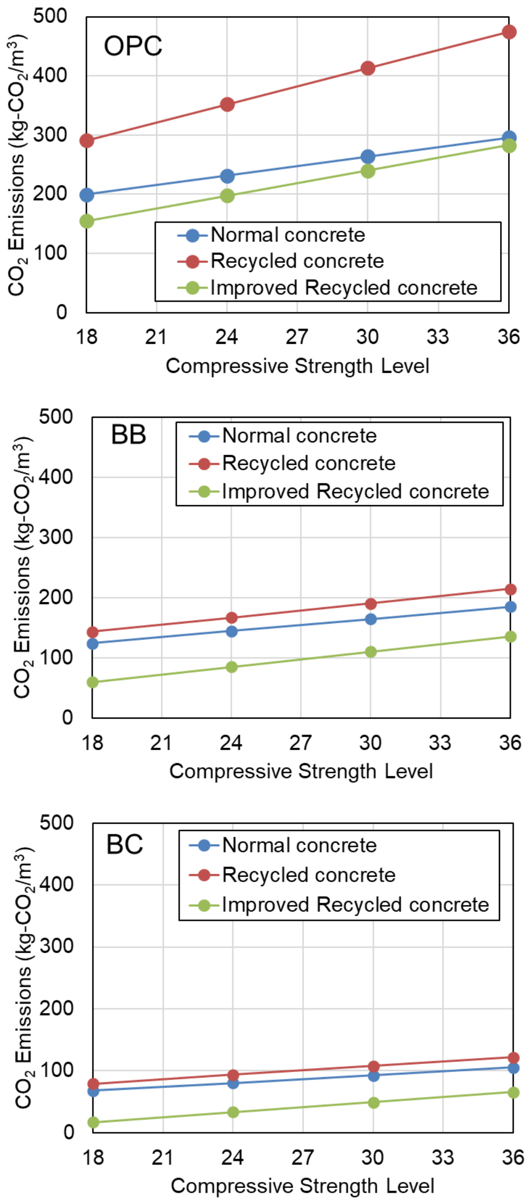

Figure-4 CO_2 Emissions on each concrete

REFERENCES

N. Matsuda, T. Iyoda (2023), "Influence of different coarse aggregate types on porosity and various properties in concrete", Proceedings of the Eighth International Symposium on Life-Cycle Civil Engineering, pp.3500-3507

Yota Takeiri, Nobuhiro Matsuda and Takeshi Iyoda (2024), "Study of Properties on High

ISSN: 3082-3714 (P), 3082-3722 (O)

GGBS Concrete with Improved Low Quality Recycled Aggregate", Proceedings of the 18th East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-18)

Erika ISHIKAWA, Takeshi IYODA, Daijirou TSUJI, and Kohei EGUCHI (2024), "Study of environmentally friendly concrete combining recycled aggregate blast furnace slag", Proceedings of the 4th fib International Conference on Concrete Sustainability (ICCS24)

R.Yuya, N. Matsuda, M. Kojima, T. Iyoda (2022), "Study of Methods for Improving Strength and Durability of Low-Quality Recycled Aggregate Concrete" Proceedings of The 17th East Asia-Pacific Conference on Structural Engineering & Construction

NOBUHIRO MATSUDA, TAKESHI IYODA (2020), "EFFECT OF CARBONATION TECHNOLOGY OF RECYCLED AGGREGATE ON CONCRETE AND RECYCLING RATE OF CONCRETE WASTE", Proceedings of Sixth International Conference on Construction Materials: Performance, Innovations, and Structural Implications Sustainability, ConMat'20, pp712-721

Japan Concrete Institute (2024), "Report of the Study Committee on Environmental Impact Assessment of Cement and Concrete (JCI-TC221A)"