# EFFECT OF WATER CEMENT RATIO OF CARBONATED RECYCLED CONCRETE AGGREGATE ON THE COMPRESSIVE STRENGTH AND AIR PERMEABILITY OF RECYCLED AGGREGATE CONCRETE

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## ABSTRACT

The utilization of Recycled concrete aggregate (RCA) has increased in recent years as a result of significant scientific researched. In recent year, it has been reported that the mechanical properties and durability of Recycled aggregate concrete (RAC) can be improved when using the carbonation technique to treat the RCA. The carbonation procedure is less expensive and more environmentally friendly when compared with other methods of improving RCA. The parental concrete of the RCA was made with different mix proportion (water-cement ratio and binder), the problem of insufficient information about the parental concrete of the RCA raised concern about the effectiveness of the carbonation technology. In this research, RCA was produced from concrete mixed of different water ratio (35%, 45%, 55%, and 65%) on Ordinary Portland cement and 50% Blast furnace slag and treated with carbonation technique. The effectiveness of the water-cement ratio of the parental concrete of RCA on the carbonation technology was measured on compressive strength and air permeability of RAC. It was found that the water-cement ratio of the parental concrete of RCA has a significant effect on the carbonation of RCA. The lower the water-cement ratio of the parental concrete of the RCA treated with carbonation the less improvement on the compressive strength and air permeability of RAC and the compressive strength and air permeability of RAC also depend on the water-cement ratio of the parental concrete of the RCA. Lower water-cement ratio of the parental concrete of the RCA increase the compressive strength and reduce the air permeability of RAC.

**Keywords:** *Water-cement ratio, RCA, Carbonation, RAC, compressive strength, Air permeability.*

## 1. INTRODUCTION

Due to depletion of natural aggregates in many parts of the world as a result of environmental exploitation and availability of concrete waste in large quantities which resulted from the demolition of old concrete structures that is made from different mixed proportion, the desire of many countries for sustainability in construction which require a very high quality aggregate, recycled concrete aggregate (RCA) could be used as an alternative for natural aggregate in concrete mixtures. However, structural designers are generally hesitant to use concrete made with RCA (recycled aggregate concrete (RAC)) ascribing to the lack of sufficient information about the old concrete that is converted into RCA and generally perception that recycled aggregate concrete may not possess the required structural strength (compressive strength) and durability (air ingression) as natural aggregate concrete (NAC).

In Japan, the application of RCA has gained significant relevant in construction industry as a result of fantastic research on the improvement of RCA that is almost the same quality as natural aggregate. In previous researched, some technologies have been proffered to enhanced the properties RAC. Outski (2003) reported that utilization of double mixing method could improve the properties of RAC, the reason is that during the mixing the RCA will be covered with mortar of a lower water cement ratio, which can lead to a stronger ITZ. Kou &Poon (2010) reported the improvement of RCA using polyvinyl alcohol (PVA) solution which increased the strength and the durability of RAC. In recent year, it has been reported that the mechanical properties and durability of RAC can be improved when using the carbonated RCA Iyoda (2014), because when the carbon dioxide react with calcium hydroxide that is present in the attached mortar to form calcium carbonate thereby densifying the attached mortar and reducing the pore in the attached mortar, due to these process, the properties of RCA improved. Furthermore, the carbonation procedure is less expensive and more environmentally friendly when compared with other method of improving RCA due to $CO_2$ utilization by RCA. The parental concrete of the RCA is made with different mix proportion (water-cement ratio and binders), the problem of insufficient information about the parental concrete of the RCA raises concern about the effectiveness of the carbonation technology In this study, RCA was produced from concrete mixed of different water ratio (35%, 45%, 55% 65%) on Ordinary Portland cement and 50% Blast furnace slag and the effect of water-cement of parental concrete of RCA with and without carbonation on the strength and air permeability of RAC were experimentally investigated.

## 2. MATERIALS AND EXPERIMENTAL PROGRAM

### 2.1 Materials

JIS Ordinary Portland cement (N) and Blast furnace slag (BFS) was used. The fine aggregate was mountain sand. The RCA was obtained by crushing 8 batches of concrete of which the mixture proportion is given in Table 1. The 28 days' compressive strength of the original concrete is shown in Figure 1. After curing in water for 28 days, the original concrete was crushed in cycling plant. Then, the crushed concrete was sieved into several fractions with different sizes. In this research, the sizes of 5 mm –20 mm were used as RCA to produce the RAC.

### 2.2 Carbonation Procedure

Carbonation of recycled concrete aggregate(RCA) is the process in which carbon dioxide ($CO_2$) infiltrate into the attached mortar of RCA thereby reacting with calcium hydroxide (CH) and forming calcium carbonate that act as an inert feeling to the pore in the attached mortar thereby densifying the attached mortar. To investigate the effect of water-cement ratio of carbonated RCA on the RAC. Some portion of attached RCA was carbonated with an accelerated carbonation method. The carbonation device includes carbonation chamber, $CO_2$ storage cylindrical tank. The RCA was put into a carbonation chamber at the temperature of 20°C and the relative humidity of 60%., the chamber was vacuumed at 1 bar of environmental pressure. $CO_2$ was injected into the chamber and the pressure of the chamber was kept at a constant level. RCA was carbonated for 7 days in the chamber with a $CO_2$ concentration about 5%. The RCA sample was mixed at 2 days' interval to enable the circulation of $CO_2$ around the attached mortar of the RCA. The properties of RCA and carbonated RCA produced from different water- cement and binding materials of parental concrete are shown in

**Table 1.** Mix proportion of the original concrete for making RCA.

| W/C (%) | s/a (%) | Units weight ($kg/m^3$) | | | | |
|---|---|---|---|---|---|---|
| | | W | C | BFS | S | G |
| 35 | 45 | 165 | 471 | | 756 | 952 |
| 45 | 47 | | 367 | | 830 | 964 |
| 55 | 49 | | 300 | | 892 | 957 |
| 65 | 51 | | 254 | | 948 | 939 |
| 35 | 45 | 165 | 236 | 236 | 756 | 942 |
| 45 | 47 | | 183 | 183 | 830 | 957 |
| 55 | 49 | | 150 | 150 | 892 | 951 |
| 65 | 51 | | 127 | 127 | 894 | 934 |

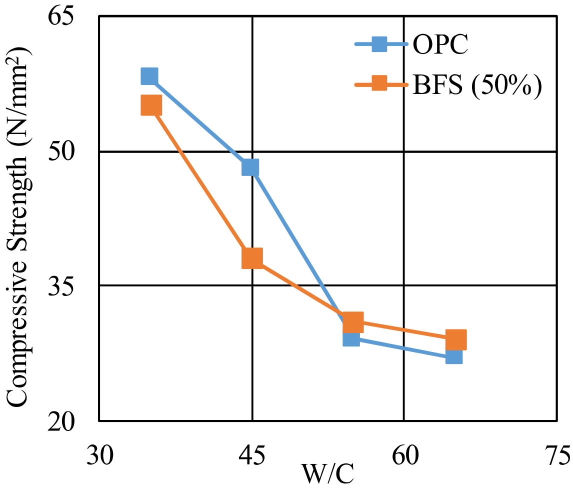


**Figure 1.** Compressive strength of the original concrete

**Table 2.** Physical properties of RCA and Carbonated RCA.

| Recycle aggregate | 100% OPC | | |
|---|---|---|---|
| | density ($g/cm^3$) | water absorption (%) | porosity (%) |
| R35 | 2.34 | 4.72 | 11.08 |
| R45 | 2.36 | 4.74 | 11.16 |
| R55 | 2.29 | 5.03 | 11.52 |
| R65 | 2.33 | 4.91 | 11.45 |
| R35C | 2.37 | 4.21 | 9.98 |
| R45C | 2.4 | 4.04 | 9.68 |
| R55C | 2.33 | 4.26 | 9.97 |
| R65C | 2.38 | 4.25 | 10.12 |

Note: R means RCA from OPC without carbonation at different W/C and RC RCA from OPC with carbonation at different W/C

Table 2 and table 3. The results revealed that, the properties such as porosity, water absorption, and density of RCA were improved by carbonation, which concurred with the Previous research. Iyoda (2014). The density and water absorption of Carbonated RCA has significantly improved as shown in Figure 2 and Figure 3 in the case of RCA made of OPC and BFS at different water cement ratio respectively. The formation of $CaCO_3$ as a result of carbonation in the attached mortar of carbonated RCA has reduce the porosity of the carbonated RCA thereby reducing the water absorption and increasing the density of the carbonated RCA.

**2.3 mixing procedure**

Sixteen different types of recycled aggregate were used in the mix proportioning (RAC and carbonated RAC samples) with water cement ratio of 50% as shown in Table 4. In this research, the RCA and carbonated RCA were pre-soaked for 24 hours and surface dried to enable homogenous mixing of the attached mortar to the new mortar. Pre-soaked RCA could improve the behaviour of recycled concrete by preventing the transfer of water between the RCA and the cement paste. This would reduce the amount of water required to achieve greater strength and lower water absorption. For both RAC and carbonated RAC, a series of cylindrical specimens with the dimension of ϕ100mm by 200mm height and ϕ100mm by 50mm height were cast in plastic moulds for both strengths test and air permeability test respectively. After curing in the laboratory for 24 hours, the specimens were demolded and cured in a water tank with the temperature at 20 ± 3 ° C. for 28 days.

**2.4 Test procedure**

***2.4.1 Measurement of compressive strength***

After 28 days of curing the specimen inside water at a temperature of **20** ±3 ° C, the compressive strength was determined using 100-200mm cylindrical specimen. Three specimen were used in each case of the experiment which was in compliance with JIS A1108:2006.

***2.4.2 Measurement of Air permeability***

Air permeability tests were carried out using ϕ100 x 50 mm size specimens. The specimens were dried at 40 ° C in a drying oven until the weight of the specimen becomes constant. Measurement was carried out in an air permeability testing equipment. The air flow rate Q ($cm^3/s$) was measured in steady-state conditions. The air permeability coefficient, K ($cm^4/Ns$) was calculated according to the Hagen-Poiseuille shown in equation (1) for a laminar flow of a compressible fluid through a porous material:

$$K = \frac{2LP_a}{(P_1^2 - P_a^2)}\frac{Q}{A} \quad (1)$$

**Table 3.** Physical properties of RCA and Carbonated RCA.

| Recycle aggregate | 50% BFS | | |
|---|---|---|---|
| | density ($g/cm^3$) | water absorption (%) | porosity (%) |
| R35B | 2.33 | 5 | 11.63 |
| R45B | 2.34 | 4.87 | 11.41 |
| R55B | 2.39 | 5.07 | 11.62 |
| R65B | 2.33 | 5.14 | 12 |
| R35BC | 2.35 | 4.5 | 9.98 |
| R45BC | 2.35 | 3.87 | 9.64 |
| R55BC | 2.38 | 4.05 | 8.74 |
| R65BC | 2.38 | 4.19 | 10.58 |

Note: RB means RCA from 50%BFS without carbonation at different W/C and RBC RCA from 50%BFS with carbonation at different W/C

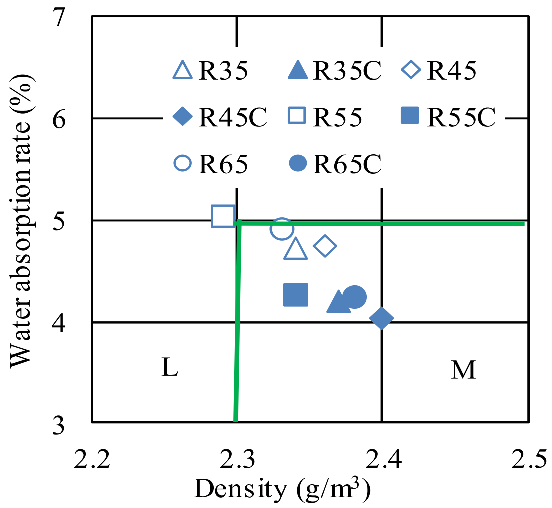


**Figure 2.** density and water absorption ratio of carbonated and un-carbonated RCA

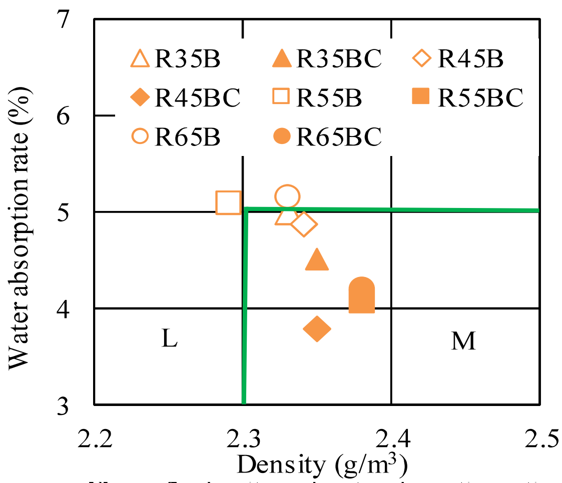


**Figure 3.** density and water absorption ratio of carbonated and un-carbonated RCA

Where,

K = air permeability coefficient, ($cm^4/Ns$)
Q = volume flow rate of the fluid ($cm^3/s$)
A = cross-sectional area of the specimen ($cm^2$)
L = thickness of the specimen in the direction of flow (cm)
$P_1$= the inlet pressures, $P_1$, ($N/cm^2$)
$P_a$= outlet pressure, assumed in this test to be equal to atmospheric pressure ($N/cm^2$)

## 3. RESULT AND DICUSSION

### 3.1 Compressive strength

Figure 4, shows the compressive strength of the RAC made with RCA (different water cement ratio of parental concrete with OPC) treated with and without carbonation. As it is well known that the compressive strength of Concrete decrease with high water cement ratio as indicated in figure 1. The trend continues in the RAC because RCA possess some features of its parental concrete. Low water cement ratio of the parental concrete of RCA would enable a high dense and low pore of attached mortar of the RCA. Also High water cement ratio of the parental concrete of RCA would enable low dense and high pore of attached mortar of the RCA. These shows that, the water cement ratio of the parental concrete is also a factor in determining the compressive strength of the RAC. The lower the water cement ratio of the parental concrete the higher the compressive strength of the RAC. In contrary, the carbonation of RCA made of low water cement ratio of parental concrete has no significant effect on the strength improvement of the RAC, as shown in figure 4, the carbonated RCA made of 35% water cement ratio of the parental concrete has no significant improvement on the compressive strength of RAC when compared with the high water cement ratio of the parental concrete. The reason is that in the case of 35% water cement ratio of the parental concrete of the RCA, the pore in the attached mortar is very small and large amount of $Ca(OH)_2$ formation due to OPC and the penetration of carbon dioxide that would initiate the process of carbonation in the attached mortar would be hindered to some extent because of the small pore in the attached mortar. But in the case of the high water cement ratio of the parental concrete of RCA, carbonation treatment of RCA is very effective on the improvement of compressive strength of RAC. The carbonation treatment of RCA made of high water cement ratio has significantly improved the compressive strength of RAC. The other possible reason of the compressive strength of RAC made RCA of 35% water cement ratio not improving is that the attached mortar of the RCA is higher in strength than the new mortar.

Figure 5, the compressive strength of the RAC made with RCA (different water cement ratio of parental concrete with 50%BSF) treated with and without carbonation. It shows that the compressive strength of

**Table 4.** Mix proportion of the RAC.

| specimen | W/C (%) | s/a (%) | Units weight (kg/m³) W | C | BFS(50)% | S | G |
|---|---|---|---|---|---|---|---|
| R35 | 50 | 45 | 160 | 160 | 160 | 813 | 887 |
| R45 | | | | | | | 895 |
| R55 | | | | | | | 866 |
| R65 | | | | | | | 883 |
| R35C | 50 | 45 | 160 | 160 | 160 | 813 | 889 |
| R45C | | | | | | | 910 |
| R55C | | | | | | | 887 |
| R65C | | | | | | | 903 |
| R35B | 50 | 45 | 160 | 160 | 160 | 813 | 883 |
| R45B | | | | | | | 887 |
| R55B | | | | | | | 868 |
| R65B | | | | | | | 886 |
| R35BC | 50 | 45 | 160 | 160 | 160 | 813 | 891 |
| R45BC | | | | | | | 891 |
| R55BC | | | | | | | 902 |
| R65BC | | | | | | | 902 |

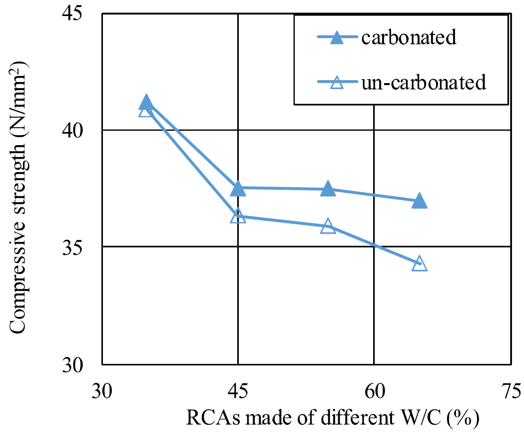


**Figure 4.** Compressive strength of RAC against the RCA made of different W/C with OPC

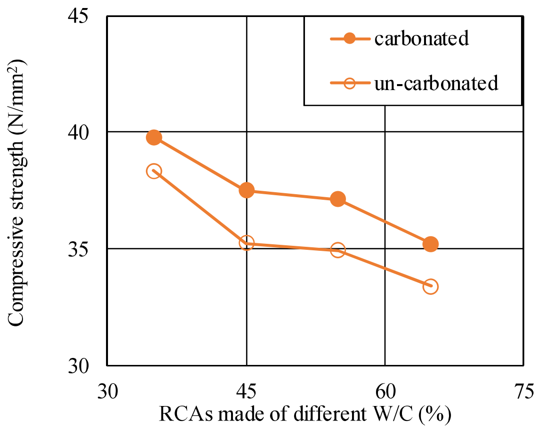


**Figure 5.** Compressive strength of RAC against the RCA made of different W/C with 50%BFS

RAC increase as the water cement ratio of the parental concrete of the RCA decrease. The carbonation of RCA increases the compressive strength almost at the uniform rate in all of the water cement ratio of the parental concrete, this is because BFS contents is generally prone to rapid carbonation. An explanation for this phenomenon is the small amount of $Ca(OH)_2$ formation

### 3.2 Air permeability

It has been identified in precursory research that the water cement ratio has significant influence on the concrete permeability. Goto (1981), The reduction of permeability of concrete with reducing water cement ratio was reported in several research. Glanville (1926), Lawrence CD (1985). The Air permeability of the RAC made with RCA (different water cement ratio of parental concrete with OPC) treated with and without carbonation are given in Figure 6. The results indicated that as the water cement ratio of the parental concrete of RCA increases, the coefficient of air permeability of RAC increases in both carbonated and un-carbonated RCA. The carbonation of the RCA slightly reduces the air permeability of the RAC this is as a result of the densification of the attached mortar during the carbonation process. But the water-cement ratio of the parental concrete of the RCA has greater effect on the air permeability of RAC.

Figure 7 show the Air permeability of the RAC made with RCA (different water cement ratio of parental concrete with 50%BFS) treated with and without carbonation, the air permeability of RCA decrease as the water cement ratio of the parental concrete decrease. The carbonation effect on the reduction of air permeability RAC becomes visible in 55 % and 65% water cement ration of the parental concrete when BFS is used

### 3.3 Relationship between Air Permeability Coefficient and the Compressive strength of RAC

Figure 8 and 9 provides a relationship between compressive strength and air permeability coefficient for various series of RAC. It can be seen from the figures that as the RAC compressive strength increases, the air permeability coefficient will decrease. The Figures indicates that the RAC from carbonated RCA has the highest compressive strength with the lowest coefficient of air permeability.

### 4. CONCLUSIONS

With the aim of elucidating the effect water cement ratio of the carbonated RCA on RAC the author investigate the RCA made of different water cement ratio and treated in accelerated carbonation environment with a special focus on the compressive strength and Air permeability of RAC. The following conclusion were obtained.

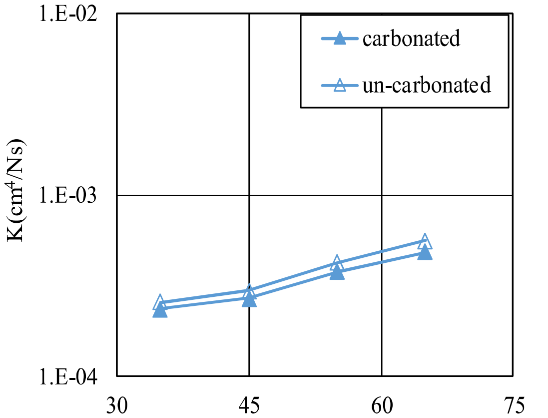


**Figure 6.** Air permeability coefficient of RAC against the RCA made of different W/C with OPC

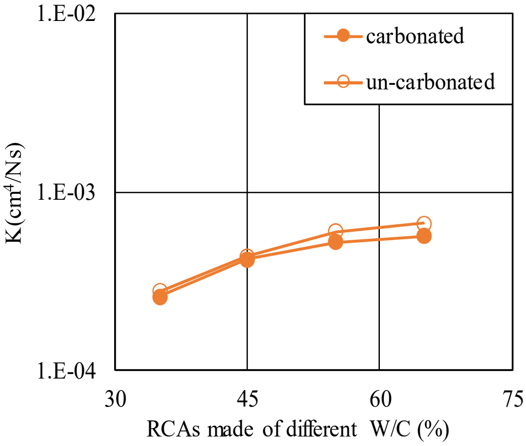


**Figure 7.** Air permeability coefficient of RAC against the RCA made of different W/C with 50%BFS

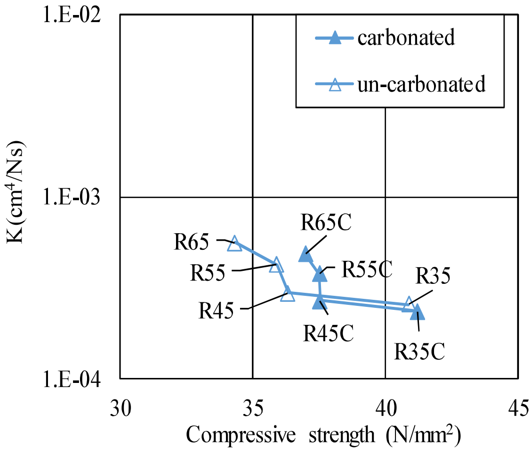


**Figure 8.** Relationship between Air permeability coefficient and the compressive strength of RAC

1. It was found that, the water cement ratio of the parental concrete of RCA affect the carbonation of RCA. The lower the water cement ratio of the parental concrete of the carbonated RCA the less improvement on the compressive strength and air permeability of RAC.
2. It was found that the compressive strength and air permeability of RAC also depend on the water cement ratio of the parental concrete of the RCA. The lower the water cement ratio of the parental concrete of the RCA higher the compressive strength and reduce the air permeability of RAC.

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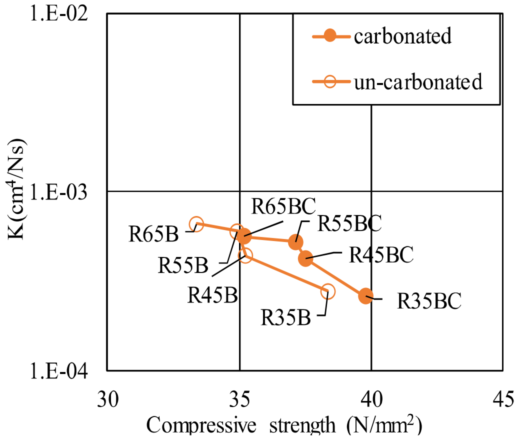


**Figure 9.** Relationship between Air permeability coefficient and the compressive strength of RAC

**PHOTOS AND INFORMATION**

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