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Investigating the effect of improving the low grade recycled aggregate by carbonation

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ABSTRACT A potential solution for both sustainability in demolition and increased service life is repurposing concrete that is taken out of service as recycled concrete aggregate (RCA). This material allows for a more economical aggregate source for towns that are located far from any virgin aggregate sources. Recycling existing concrete for use as aggregate in new construction has gained consideration in recent years because of high costs of disposal of waste concrete and shortage of natural aggregate. In Japan, insufficient of natural aggregate has become more concerned for construction companies. Furthermore, the deterioration of concrete structures that lead to a large amount of concrete waste from demolition is also of great concern. Recycle concrete aggregate is one of the efficacious ways to solve the problems. However, the application of recycled concrete aggregate in the construction field is still finite due to quality and cost-related problems. In Japan recycled aggregate are classified into three categories namely; high, medium and low recycled aggregate symbolized by H, M and L. The classification is based on absolute dry density and water absorption rate. High cost of H class of RCA and the low quality of M and L classes of RCA has limited the utilization of RCA in concrete structure. In this research, studies were carried out to investigate the effect of using carbonation technology in improving the low classes of RCA produced from concrete of different water cement ratio. Concrete of different water-cement (30%, 50%, 70% and 35% 45%, 55%, 65%) were cast and RCA were produced and carbonated. 18 types of RCA were used in this study. The Recycled aggregate concrete is evaluated according to compressive strength, tensile strength and drying shrinkage. Additionally, the double mix method of RCA for improving strength is evaluated. It was found that carbonation of RCA can increase the density and decrease the water absorption of RCA. the results showed that the strengths of the recycled aggregate concrete(RAC) has a direct relation to the water-cement ratio of the original concrete and carbonation of RCA can increase the strengths of RAC. It was also found that by exposing recycled aggregates to carbon dioxides decreases drying shrinkage of RAC.

1 INTRODUCTION

In decades, the construction industry has been developed rapidly especially in most developed counties like Japan, Canada, Europe and United State of America where there is significantly decrease in the availability of natural aggregate and substantial amount of construction and demolition waste is generated. According to an investigation carried out in 2012 by the Ministry of land, Infrastructure and transportation of Japan (MLIT), the amount of construction waste generated in Japan is approximately 31 million tons annually. In Canada, about 11 million tons of landfill waste per year can be attributed to construction activities alone, of which 21% (2,310,000 tons) of the waste is from concrete rubbl (1). There is close to 100 million tons of demolished concrete produced annually in the United States and European countries combine (2). Based on predicted utilizations data, the aggregate industry in the world may confront a scarcity of high-qualit natural aggregate reserves within close proximity to major urban centers (3). To ensure a sustainable adequate long-term of high quality aggregate supply for construction industry, alternative source of aggregate will therefore need to be considered. The utilization of recycled concrete aggregate (RCA) in construction company has been considered as an efficacious way to reuse construction and demolition waste. Recycled concrete aggregate developed by crushing concrete from obliterated concrete structures may serve as a feasible aggregate alternative and assist to abate or alleviate the natural aggregate shortage while redirecting appreciable amounts of construction waste from landfills. Many researchers have investigated the application of RCA in new concrete, this investigation adduced that the mechanical properties of concrete made with RCA, including the tensile strength, compressive strength, and elastic modulus etc. are inferior to that of conventional concrete when the water-cement ratio (W/C) is similar. This is one of the rational motive for limited application of RCA for non-structural concrete. On the application of RCA, some technologies have been developed to improve the mechanical properties of Recycled Aggregate Concrete (RAC). Two methods have been proposed by Elhaka (4) to improve mechanical properties of RAC. The first, is the self-healing methods by soaking the RCA in water for 30 days which enhanced the properties of RCA because of reaction of the un-hydrated cement particles in the adhered mortar with water again. The second is the addition of the silica fume as an additive which can enhanced the interfacial transition zone and the RCA itself as well. Poon and Ko (5) also reported that polyvinyl alcohol (PVA) solution could be used to enhance the properties of RCA which translate to an increase in the strength and durability of RAC.

In Japan, Japanese Industrial Standard (JIS) categorized RCA into three classifications which are High-quality (H) RCA (JIS A 5021:2011), Medium-quality (M) RCA (JIS A 5022:2012), and Low-quality (L) RCA (JIS A 5023:2012), the classification is based on absolute dry density and water absorption. The H class of RCA has density above 2.5 g/cm^3 and water absorption of 3% and below. The M class of RCA has density of over 2.3 g/cm and water absorption 5% and below. The L class of RCA has density bellow 2.3 g/cm^3 and water absorption below 7%. The High-quality (H) RCA could be used as natural aggregate in concrete, yet the high cost and high energy required in manufacturing of H class of RCA has limited its utilization in concrete. On the contrary, the M and L class of RCA have relatively significant volume of adhered mortar and they could be manufactured with low cost and also required less energy.

The large volume of mortar adhered to the natural aggregate in the low type of RCA is very porous which increase the water absorption of RCA that could affect the properties of RAC. The low quality type of RCA has restricted their application despite the low cost of these classes of RCA. Therefore, the problem of the high cost of H type of RCA and the poor quality of M and L type of RCA has restricted the utilization of RCA concrete structure. This study aimed at investigatin the effect of using accelerated carbonation technology in improving the low classes of RCA produced from concrete of different water cement ratio (30%, 50%, 70% and 35% 45%, 55%, 65%) and the performance of the RCA in the RAC with respect to compressive strength, tensile strength and drying shrinkage.

2 EXPERIMENTAL PROGRAM AND MATERIAL

2.1 *Mechanism of carbonation technology*

Calcium carbonate is produced when calcium hydroxide reacts with carbon dioxide. In the field of concrete, calcium hydroxide is one of the product of hydration and concrete is capable of being permeated by carbon dioxide from atmosphere because of the pores nature of concrete, this implies that concrete has the capacity to absorb carbon dioxide from the atmosphere. This phenomenon is called carbonation. This carbonation does not apply to reinforced concrete structure because in the case of reinforced concrete structure there exist an alkaline thin oxide film surrounding the reinforcement, if carbonation occur as a result of carbon dioxide infiltration of concrete, the alkalinity of concrete would gradually shift to neutral and this process is called neutralization. As the neutralization continue the thin oxide film is destroyed round the reinforcement in the concrete and also corroded due to the infiltration of water and oxygen into the concrete. However,in consideration of the constituent of the mortar adhering to the surface of RCA, the low quality of RCA can be improving through accelerated carbonation because the calcium hydroxide, which is the one of the main cement hydration product in the mortar adhering to the surface of RCA, can react with carbon dioxide accompanied by an increases in the solid volume of calcium carbonate, which is formulated by the following reaction: $Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$. The other products of hydration, such as calcium silicate hydrate gel (CSH) also converted to calcium carbonate, water and a modified CSH gel with a higher degree of polymerized silica gel. (6–11) Carbonation of RCA can densify the mortar adhered on the RCA. After the carbonation of RCA there was a significant reduction in water absorption and porosity of the RCA. This would improve the quality of RCA. Carbonation of RCA would increase the strength and the permeability resistance of RAC and other mechanical properties of RAC.

2.2 *Experimental program*

The experimental program was carried out consistently by first producing concrete with different water-cement ratio 30%, 50%, and 70%) and recycled. There after the properties of RCA were tested and the compressive and tensile strength were examined. Secondly, a concrete with different water-cement ratio (35%, 45%, 55% and 65%) was produced and also recycled.

The recycled aggregate properties were tested (carbonated and un-carbonated). Finally, concrete was made at water cement ratio of 50% and recycled in accordance with JIS classification of M and L. The density, water absorption of the RCA was examined and the compressive strength, the tensile strength and the drying shrinkage of RACs were also examined.

2.3 *Materials*

The original concrete was produced by utilizing an ordinary Portland cement and natural aggregates, the fine aggregate was land sand with dry density of 2.69 g/cm^3 and water absorption of 0.99% and fine modulus of 2.9. The coarse aggregate was crushed aggregate with relative density of 2.72 g/cm^3 and water abortion of 0.54% and fine modulus of 6.6. Blast furnace cement was used to reduce the environmental impact and also to curtail the possibility of Alkali silica reaction. The original concrete was produced at different water-cement ratio as outlined in section 2.2 and the comprehensive strengths were obtained. The original concrete was fist crushed by a jaw crusher and impact crusher to produce RCA of a grain size 20-5 mm. The produced recycled aggregates were categorized into three parts and labeled according to water/cement ratio of the original concrete. The first category is the recycled aggregate from the cement/water ratio of 30%, 50% and 70% which was labeled as R30, R50 and R70 respectively. This was not carbonated and the performance of RCA of different water-cement ratio in RAC without carbonation with respect to compressive strength and tensile strength was checked. The second category is the recycled aggregate from the concrete produced with water-cement ratio of 35%, 45%, 55% and 65% and labeled as R35, R45, R55 and R65 respectively. This was divided into carbonated and un-carbonated RCA. The density and water absorption of the both carbonated and un-carbonated was examined. The final category the RCA, concrete was produced with water/cement ratio of 50% and recycled into M and L classification of JIS (JIS A 5022 and JIS A 5023) of RCA. M and L was carbonated as MC and LC respectively. The performance of M, L, MC and LC in RAC with respect to compressive strength, tensile strength and the shrinkage was also examined. All the recycled aggregates had almost the same maximum particle size of 5 mm–20 mm although, their shape and surface texture were almost similar because all the RCA were produced from the same source. The RCA particles are all more angular in shape as correlated to the natural source.

Table 1. The compressive strength of the original concrete.

W/C	Compressive Test (N/mm^2) 28 days
30%	76.6
50%	66.9
70%	29.3

2.4 *Accelerated carbonation method*

To improve the quality RCA that could influence and improve the mechanical properties of RCA. A proportion of RCA was carbonated with an accelerated carbonation method. The RCA was put into a carbonation test chamber at a temperature of 20 ± 2°C, the relative humidity of 60% and CO_2 concentration of 5%. The aggregates were stirred once in every two days so that carbon dioxide could circulate the aggregate and filed pore and also densified the RCA.

3 THE EFFECT OF DIFFERENT WATER CEMENT RATIO OF THE ORIGINAL CONCRETE OF RCA WITHOUT CARBONATION

3.1 *Preparation of recycled aggregate*

The effect of different water cement ratio of the parental concrete of the RCA on the properties of RCA and strengths of RAC was examined. Firstly, concrete with water/cement ratio of30%, 50%, and 70% was cast. The targeted slump was 10 ± 2.5 cm and the targeted air volume was 4.5 ± 1.5%. The concrete was cured in water for 28 days. The compressive strength was determined after the 28 days of curing in water as shown in table 1. Thereafter, the concrete was recycled into RCA as explained in section 2.3. The properties of the recycled aggregate are shown in Table 2.

3.2 *Density and water absorption rate*

According to JIS, the quality of RCA is classified base on the relative density and water absorption rate. The relative density, and water absorption capacity of the natural coarse aggregates and RCA were carried out in accordance with the test procedure given in the (JIS A 1110). The R30 was found to have the highest relative density proceeded by R50. R70 has the least relative density. The density of RCA is relying on the adhered mortar content, the density of the adhered mortar itself, and the density of the original aggregate.

Water absorption rates are important to consider when making concrete mixture proportions that include RCAs. The water absorption rate of R30 is less than that of R50 and R70. R70 has the highest water absorption. Since, the quality of the recycles aggregate is classified on the basis of relative density and water absorption. The classification of R30 which

Table 2. Properties of recycled concrete aggregate without carbonation.

	Aggregate type	Symbole	Density (g/cm^3)	Water absorbtion (%)	Fine modulus	Class
Fine aggregate	Land sand	S	2.69	0.99	2.91	–
Coarse aggregate	Crushed stone	N	2.72	0.54	6.6	–
RCA	W/C (30%)	R30	2.39	6.15	6.68	L
	W/C (50%)	R50	2.34	6.55	6.79	L
	W/C (70%)	R70	2.24	6.64	6.66	L

shows that R30 is of low quality recycled aggregate. R50 and R70 show no significant classification, as illustrated in figure 1.

3.3 *Concrete mixture proportioning*

Six batches of concrete were developed as part of this research to investigate the effect of the RCA of different water-cement ratio on the strength of recycled aggregate concrete. The mix proportion is shown in Table 3. The targeted slump was 10 ± 2.5 cm and the targeted air volume was 4.5 ± 1.5%.

Water cement ratio was (50%) and sand–total aggregate ratio was 50%.

3.4 *Compressive strength*

The compressive strength values reported are averages of three cylinders with dimensions 100 mm by 200 mm and were determined in compliance with JIS A1108:2006. All compressive strength specimens were cured in water for 28days at temperature of 20°C.The compressive strengths after 28 days of curing of the RAC (R30, R50 and R70) are shown in table 4. The change in the compressive strengths of the original concrete and the RAC are shown in Figure 2. This shows that the higher the water cement ratio of the parent concrete of the RCA, the lower the strength of the RAC. The R30 develop the maximum compressive strength, it decreases by 47% of the compressive strength of its parental concrete and it was the RCA of the low water-cement ratio of parental concrete and also has lowest water absorption rate. The R50 and R70 have almost 13% decrease in the compressive strength as compared to their parental concrete compressive strength. This also indicate that the lesser the water absorption rate of RCA the higher the strength of the RAC and there is a positive correlation among the RA's strengths because of the same water cement ratio. The partial replacement of the recycled aggregate of R30 and R70 were examined as indicted in the mix proportion in the Table 3 and the result of the compressive strength is show in figure 3. The 50% replacement of the R30 and R70 develop the maximum compressive strength, followed by 70% of R30 and 30% of R70. The 30% of R30 and 70% of R70 developed the minimum compressive test. This implies that at 50% replacement of R30 and R70 the compressive strength increase.

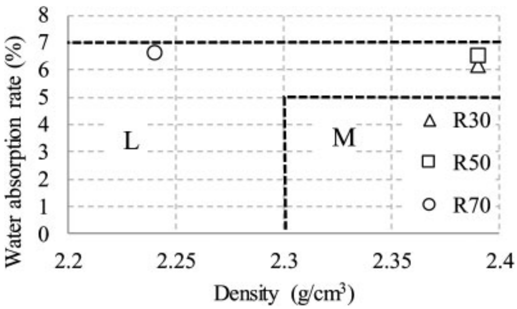

Figure 1. Absolute dry density and water abortion ratio of un-carbonated RCA.

Table 4. The compressive strength of RCA.

RCA	Compressive Test (N/mm^2) 28 days
R30	35.91
R50	32.06
R70	27.45
R30-R70(7:5)	30.97
R30-R70(5:5)	32.48
R30-R70(3:7)	28.19

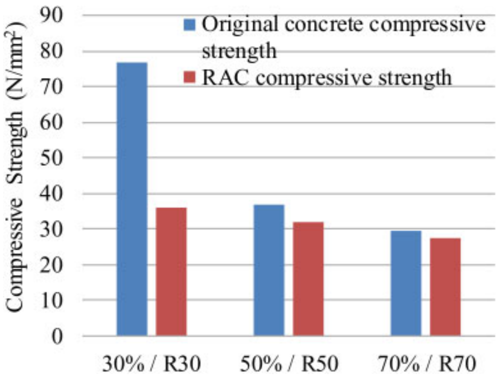

Figure 2. The compressive strength of original concrete and RCA.

Table 3. The mix proportions of the RCA concrete.

Aggregate Type	W/C (%)	s/a (%)	Units weight (kg/m^3) W	C	BFS	S	R30	R50	R70
R30							801	–	–
R50	50	50	172	189	155	888	–	784	–
R70							–	–	750
R30-R70(7:5)							560	–	225
R30-R70(5:5)							400	–	375
R30-R70(3:7)							240	–	525

3.5 *Splitting tensile strength*

Splitting tensile strength was measured using 100 mm by 200 mm long cylindrical specimens and following the testing methods outlined in JIS A 1113:2006. All the specimens of each concrete types were tested after 28 days of cured in water. The results for the splitting tensile strength of the recycled concrete are presented in figure 4. R30 develop the maximum splitting tensile strength. There is no significant variation of splitting tensile strength among the RCA and the replacement of the R30 and R70.

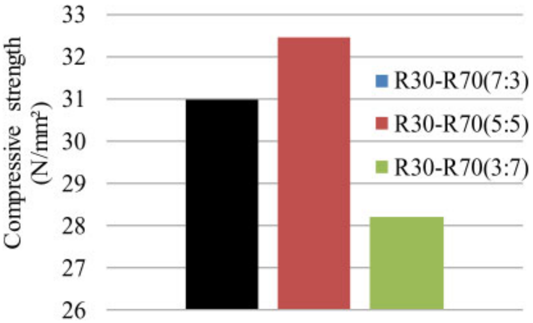

Figure 3. The compressive strength of the partial replacement of RCA (R30 & R70).

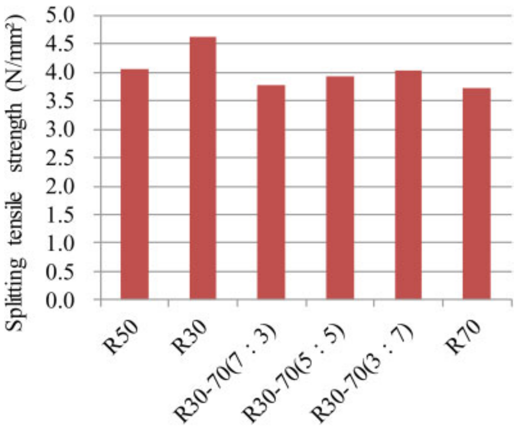

Figure 4. The splitting tensile strength of RAC and partial replacement of R30 & R70.

4 THE EFFECT OF DIFFERENT WATER-CEMENT RATIO OF THE ORIGINAL CONCRETE OF RCA WITH CARBONATION

4.1 *Preparation of recycled aggregate*

The effect of different original concrete mix proportions on the properties of recycled concrete aggregate was examined. Concrete with water-cement ratio of 35%, 45%, 55%, and 65% were cast. The concrete was cured in water for 28 days. After the 28 days of curing in water, the concrete was recycled into RCA (R35, R45, R55 and R65). Some portion of RCA were carbonated (R35C, R45C, R55C and R65C) as explained in section 2.3. The physical properties of the Recycled aggregate are shown in table 5.

4.2 *Density and water absorption*

The absolute density, and absorption capacity of the RCAs were carried out in accordance with the test procedures outlined in JIS A 1110 200. The R5C was discovered to have the highest density and low water absorption influenced by the size of the pore in the adhered mortar as shown in figure 5. The R55 showed the highest water absorption (see Table 8). This suggests that the adhered mortar on the 55% has a higher water absorption and thus, a lower density.

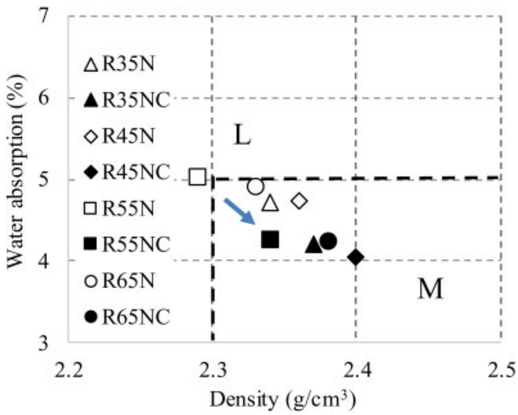

Figure 5. Absolute dry density and water absorption ratio of un-carbonated and carbonated RCA.

Table 5. Properties of recycled concrete aggregate.

	W/C (%)	Symbol	Density (g/cm^3)	Water absorbtion (%)	Class
Recycled Concrete Aggregate	35%	R35	2.34	4.72	M
	35% (CO2)	R35C	2.37	4.21	M
	45%	R45	2.36	4.74	M
	45% (CO2)	R45C	2.4	4.04	M
	55%	R55	2.29	5.03	L
	55% (CO2)	R55C	2.34	4.26	M
	65%	R65	2.33	4.91	M
	65% (CO2)	R65C	2.38	4.25	M

After carbonation, the 55% improved to class M type of RCA as shown in figure 6. All the carbonated RCAs increase in density almost at the same rate, this shows that by injecting carbon dioxide in RCA can increase the density and decrease the water absorption of RCA which can significantly enhanced the quality of the RCA.

5 IMPROVEMENT OF LOW QUALITY TYPE OF RCA BY CARBONATION

5.1 *Preparation of recycled concrete aggregate*

The RCA was obtained by crushing a batch of concrete of which the mixture proportion is given in Table 6. After 28 days' compressive strength of the original concrete. The original concrete was recycled to produce M and L type of RCA. Thereafter, the recycled concrete was sieved into several fractions with different sizes. In this research, the crushed fractions with sizes of 5–20 mm were selected as M and L RCA to produce the RAC. some portion were carbonated as explained in section 2.3.

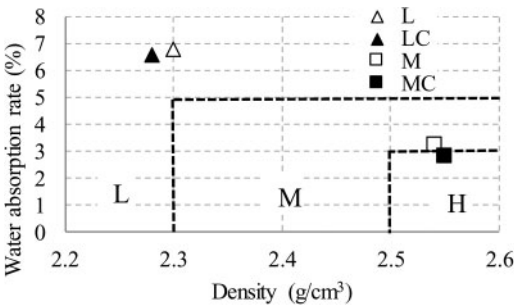

Figure 6. Absolute dry density and water abortion ratio of carbonated and un-carbonated RCA.

5.2 *Concrete mixture proportioning*

Four batches of concrete were developed as part of this research to test the improvement of mechanical properties of recycled aggregate concrete. Compressive strength and splitting tensile test are the mechanical properties of RAC tested and the properties of RCA were also examined. The mix proportion is shown in Table 6 The targeted slump was 10 ± 2.5 cm and the targeted air volume was $4.5 \pm 1.5\%$. Water cement ratio is 50% and sand – total aggregate ratio is 50%. Natural aggregate was used as control.

5.3 *Density and water absorption rate*

The absorption capacity and density of RCA are affected by adhered mortar. The absorption ability is one of the important which differentiate RCA from natural aggregate (N), which can invariably influence both the fresh and harden properties of concrete as a result of the porous nature of the adhered mortar. The relative density, and water absorption capacity before carbonation and after carbonation of both the natural coarse aggregates and RCA were carried out in accordance with the test method given in the JIS (JIS A 1110:006). The natural aggregate was found to have the highest density proceeded by carbonated MC. (Table 7). L has the lowest relative density. The density of carbonated of RCA is higher than the un-carbonated RCA. The water absorption rate of Carbonated M and L type of RCA is less than the un-carbonated. As a result of carbonation, the M type of recycled aggregate has improved to H type of recycled aggregate as illustrated in figure 6.

Table 6. Mix proportions of RAC.

				Units weight (kg/m^3)			
Aggregate Type	W/C (%)	s/a (%)	W	C	BFS	S	G
N	50	50	172	189	155	888	911
L							770
L(CO_2)							764
M							861
M(CO_2)							854

Table 7. Properties of aggregates.

	Aggregate type	Symbole	Density(g/cm^3)	water absorbtion (%)	Fine modulus	Standard
Fine aggregate	S and	S	2.69	0.99	2.91	–
Coarse	Crushed	N	2.72	0.54	6.6	–
Recycled	L	L	2.3	6.82	6.81	L
Concrete	L(CO_2)	LC	2.28	6.62	–	L
Aggregate	M	M	2.54	3.28	6.73	M
	M(CO_2)	MC	2.55	2.84	–	H

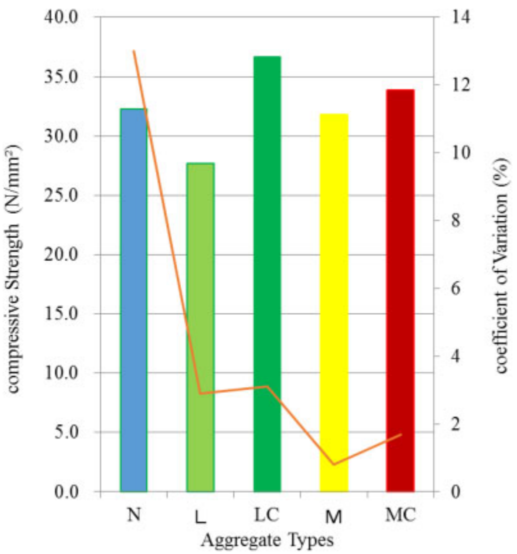

Figure 7. Compressive strength of RAC.

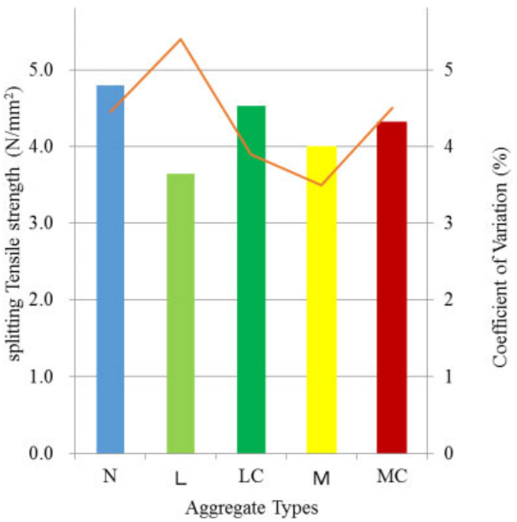

Figure 8. Splitting tensile strength of RAC.

5.4 *Strength test*

The compressive strengths for the natural aggregate (N), M and L RCA (carbonated and un-carbonated) are shown in figure 7. The compressive strength was carried out as described in section 3.4. The splitting test of the N, M and L (carbonated and un-carbonated) is shown in figure 8 and it was carried out as described in section 3.5.

5.5 *Discussion of strengths test result*

The compressive strength and the splitting tensile strength test result and the coefficient of variation is shown in Fig 7 and 8. Both LC and MC have an effect

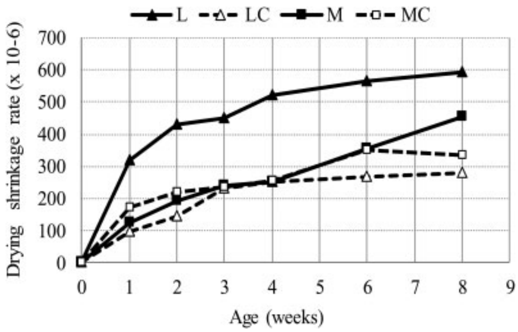

Figure 9. Drying shrinkage of RAC.

on the increase in the strength of the RAC. This implies that the carbonated portion of mortar adhere to the original aggregate had enhanced the quality of RCA thereby increasing the strength of RAC. The strengths of RAC made from carbonated recycled aggregate in accordance with JIS classification is high than the strengths of RAC made from un-carbonated recycled aggregate of the same water cement ratio without JIS classification. Usually, the coefficient of variation is 10% but in this research the coefficient of variation is about 5% which indicated small variation.

5.6 *Drying shrinkage test*

Figure 9 show the outcome of the result of length change (Drying Shrinkage) for a period of 8 weeks The drying shrinkage of L which has the highest water absorption rate is significantly large. There is no much difference between the drying shrinkage of M and MC. But LC show a tremendous improvement in reducing the drying shrinkage. This indicate that carbonation of low quality recycled aggregate can reduce the shrinkage of RAC.

6 CONCLUSIONS

An inclusive research program was conducted that included different concrete mixtures incorporating one natural aggregate and one RCA sources. The RCA concrete mixtures had different Mixture proportions (i.e. cement content, water–cement ratio, aggregate volume, etc.). A number of disparate RCA and RAC properties were evaluated. Some portion of the aggregate were carbonated. The research systematically enquired into the improvement of Low quality type of RCA by carbonation.

The following is the main finding of the research.

1. The compressive strength and the splinting strength of recycled aggregate concrete depend on the strength of the parental concrete of RAC.
2. the properties of low recycled aggregate can be enhanced by carbonation and water-cement ratio of the parental concrete of RCA does not have significant effect on the carbonation of RAC.
3. Carbonation of RCA can decrease the drying shrinkage of RAC.

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