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Mechanical characteristics and recoverability of low-quality crushed coarse aggregate by surface modification and microwave heating

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Abstract: This paper presents a quantitative review of the mechanical performance, as well as the separation from the matrix and the recovery performance of surface-modified coarse aggregate manufactured from low-quality crushed coarse aggregate (LCCA) coated in an inorganic powder. The results of the experiments showed that reinforcing the interfacial transition zone, a vulnerable area in concrete, by coating the surface of the LCCA with a surface modification material, can help reduce micro-cracking and improve the structural integrity of the aggregate. Therefore, the use of coated LCCAs resulted in concrete of improved strength and durability. Further, it was demonstrated that the dielectric material (Fe_2O_3) present in the inorganic coating layer (surface modification coarse paste) could be heated effectively by microwaves. The results can be explained by an increase in void volume, along with a weakening of the hydrated cement paste, promoting the efficient recovery rate of surface-modified LCCAs.

Keywords: recycling, low-quality crushed coarse aggregate, surface modification, interfacial transition zone, microwave, recovery, durability.

1. Introduction

Concrete is one of the most prominent building materials used in society, and aggregates, which account for 70-80% of its total volume, have a significant impact on its quality. Thus, in order to manufacture high-quality concrete, there is a need to use quality aggregates with stable physical and chemical properties that satisfy the strength and standard particle size requirements and are free from foreign matters, including salt and impurities. In case of Japan, the supply of aggregates has declined between 1990 and 2011, as shown in Fig. 1 [1]. In addition, the total demand for crushed coarse aggregates in 2010 was shared between concrete manufacture (65%) and road construction (35%), and these percentages have remained nearly constant over the years [2]. Also, the amount of natural gravel used has decreased substantially since 1998 with the sharp decline in the use of aggregates in general, and this has consequently resulted in a growing reliance on crushed coarse aggregates. Due to these factors, in addition to environmental issues, there has been an emphasis on the importance of recycling aggregates, which is the major component of concrete, by volume [3,4]. Moreover, the decrease in road construction work is expected to lead to less demand for sub-base coarse material for roads [5-9], and from a long-term perspective, this signals a need to expand and diversify the use of recycled concrete waste and to use recycled aggregates for concrete manufacture. For this reason, research on recycled aggregates has been conducted from various angles worldwide, and the Japanese Industrial Standards (JIS) for recycled aggregates have been revised. However, problems still remain relating to the production of high-quality recycled aggregates such as high energy consumption and the generation of large amounts of fine powder during crushing. On the other hand, there is a dilemma of using low-quality recycled aggregates as they can reduce the performance of the concrete. In addition, because fresh aggregate resources are scarce,

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there is a need to develop a technology that can completely recycle aggregates through a closed process. This would allow high-quality crushed coarse aggregate with properties closest to those of the original to be recovered from concrete waste.

2. Complete recovery of coarse aggregates using microwave heating

Under the aforementioned circumstances, improving the quality of low-quality crushed coarse aggregates (LCCA) with low densities and large water absorption ratios can lead to the manufacture of concrete that conforms to the strength and modulus of elasticity requirements. Also, it is anticipated that such concrete will have improved durability and resistance against deterioration resulting from drying shrinkage and carbonation. To achieve this goal, as shown in Fig. 2, modification materials (pozzolanic materials, etc.) can be added that improve the chemical bonding and mechanical friction between the aggregate in the inorganic coating layer (surface modification coarse paste; SMCP) on the surface of the LCCA and the cement matrix [8,13]. The interfacial transition zone (ITZ), which is considered the weakest link in the overall structure of concrete, is improved, thus allowing LCCA to be used for manufacturing concrete, as shown in Fig. 3 [7-9]. Also, this technology involves coating iron oxide (Fe_2O_3), which has a high dielectric constant, onto the LCCA as a binder, and then selectively heating and weakening the aggregate interface with microwaves to manufacture recycled aggregates, following the dismantling of the constructed structure, as shown in Fig. 4 [7-9]. This technique allows the aggregates to be almost completely recycled by recovering the high-quality aggregates using inorganic coating materials, combined with a small amount of energy [8,13]. Therefore, the technique offers the possibility of a trade-off between improving concrete strength and maximizing the recovery ratio of aggregate obtained from LCCA. The resulting concrete consists of three main components, defined as follows: LCCA; coating material applied to the surface of the LCCA (SMCP); and surface-modified coarse aggregate (SMCA).

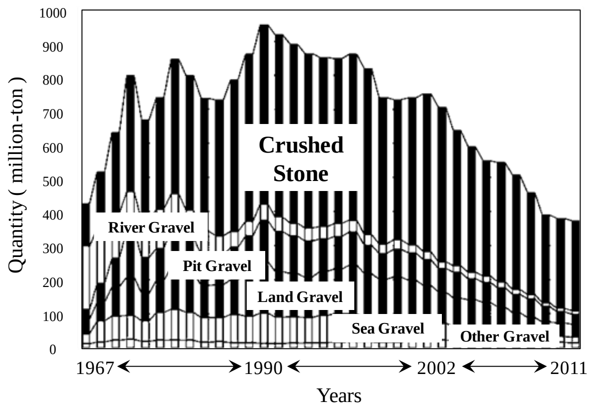


Fig. 1 – Changes in the aggregate supply in Japan [1]

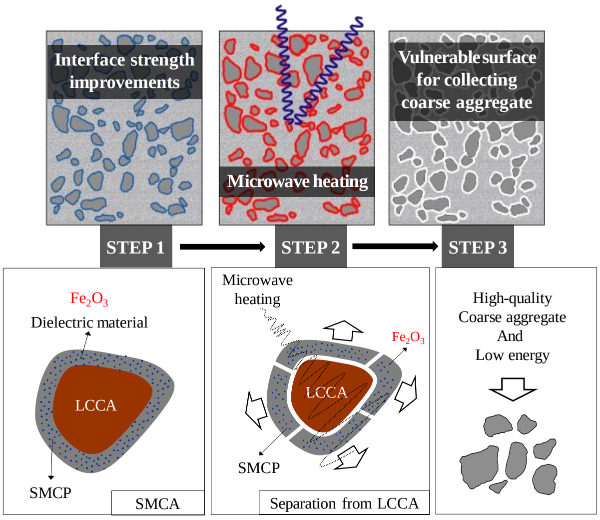
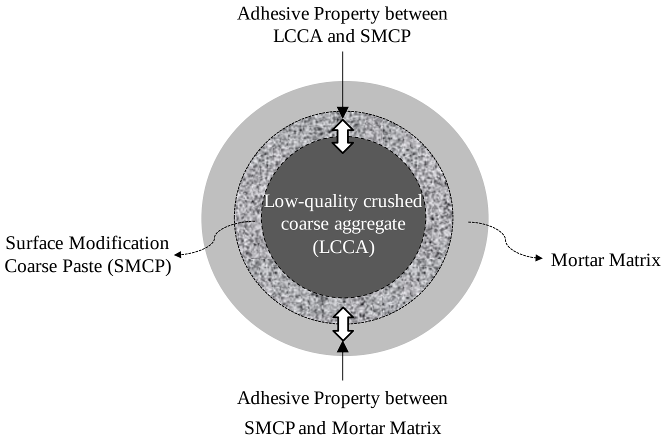


Fig. 2 – Improvement of concrete strength by modification and recovery by microwave heating [8,13]

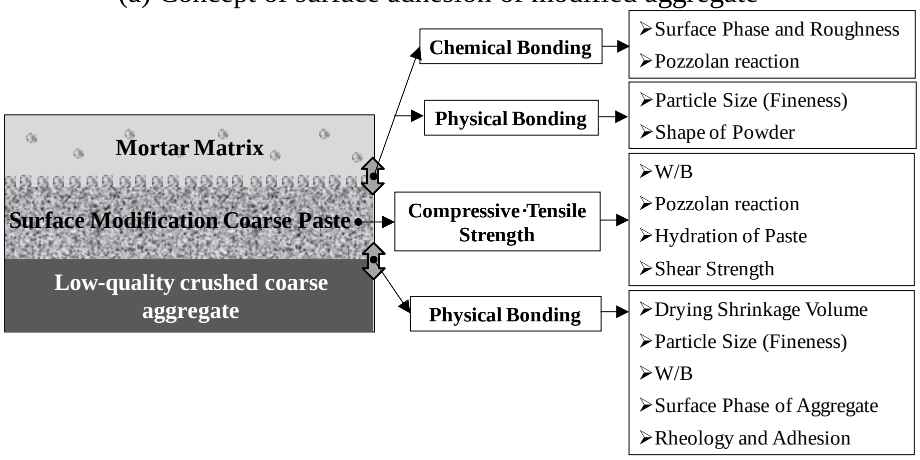
3. Performance of SMCA concrete

3.1 Overview and method of experiment

Concrete generally consists of cement, water, and fine/coarse aggregates. In SMCA concrete, the surface of the original aggregate is coated with cement paste, which requires that the SMCP is reflected in the mix design [9]. The modified aggregates used in this experiment were produced by the surface of the LCCA with SMCP (cement, cement + fly ash), containing the dielectric material (Fe_2O_3), while retaining its initial status (natural coarse aggregate) in such a way to maintain the regular thickness. Next, they were cured in the air for about seven days at a temperature of 20°C and a relative humidity of 60% until the SMCP had hardened completely. An LCCA concrete specimen with a water-cement (W/C) ratio of 55% was used as a control. The W/C ratio of the SMCA concrete and the quantity of chemical admixture were adjusted as shown in Table 1, in order to match the properties of the control specimen. Also, the same amount of cement was applied to the mix design for the LCCA and SMCA [9]. In this experiment, the conditions in which the aggregate standards for concrete manufacture were not met were set forth as: "an absolute drying density of 2.5g/cm^3 and below and a water absorption ratio of 3% and above." Under these conditions, coarse aggregate was defined as "low-quality coarse aggregate (LCCA)" and coarse

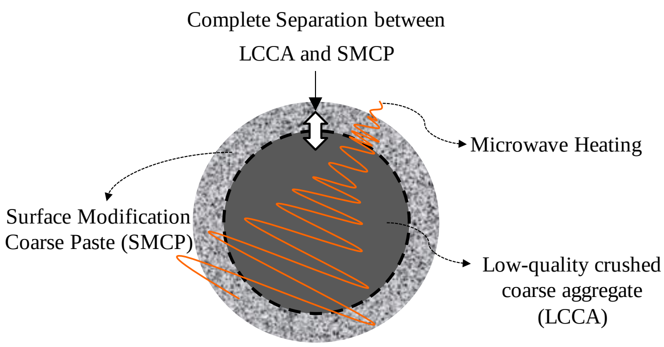


(a) Concept of surface adhesion of modified aggregate

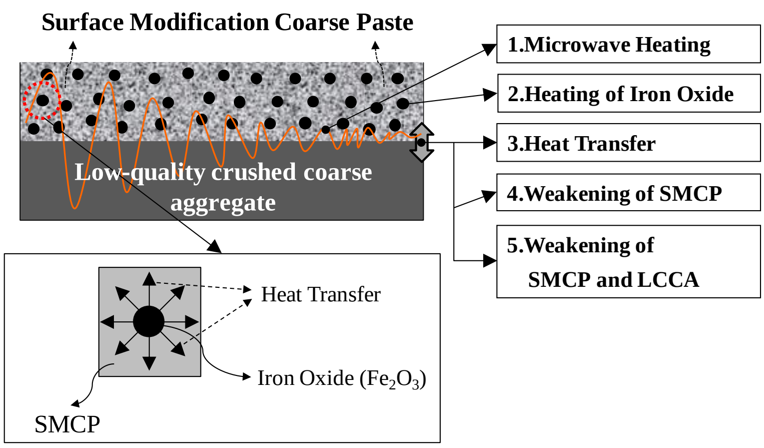


(b) Control factor of surface adhesion of modified aggregate

Fig. 3 – Mechanism of adhesion between modified aggregate and interface [7,8]



(a) Concept of surface separation between LCCA and SMCP



(b) Control factor of surface separation of modification aggregate

Fig. 4 – Mechanism of weakening between LCCA and SMCP [7-9]

aggregate with a modified surface as "surface modified coarse aggregate (SMCA)." Experimental factors and conditions for each of these aggregates are shown in Table 2. Also, the mixing ratio of the surface modification material is shown in Table 3. Cement and cement substitutes, made of pozzolanic materials (fly ash) with Fe_2O_3, were used as a binder for the surface modification material. In order to assess the mechanical properties and the durability between the coarse aggregate and concrete using this technique, density, water absorption ratio, compressive and splitting tensile strengths, drying shrinkage, and carbonation tests were conducted. Also, for the purpose of assessing the aggregate recovery characteristics, the temperature characteristics as a function of microwave heating (frequency of 2.45 GHz and power output of 1800 W) for 0, 60, 120, or 180 s and the recovery ratio of recycled coarse aggregates (RCA) were measured [9,11]. Temperatures were measured via thermography both before and after microwave heating and the temperature characteristics under each condition were assessed.

3.2 Characteristics of density and water absorption ratio

The parent materials of the LCCA used in this study, quarried from mountain rock, were crushed using a jaw crusher and filtered by size, ranging from 5 mm to 20 mm. The particle size distribution

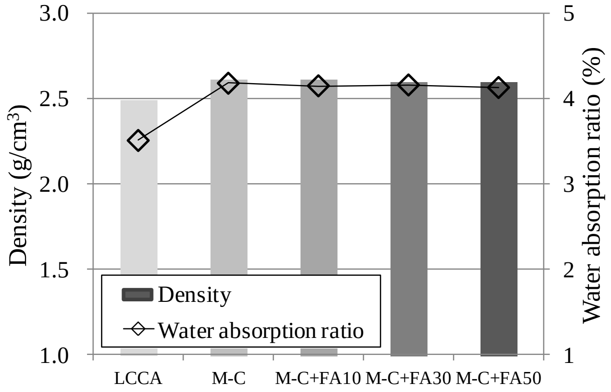


Fig. 5 – Density and water absorption ratio of each coarse aggregate

was then adjusted to satisfy the standard gradation prescribed by JIS A 1102 (standards for aggregate sieve testing), followed by measuring the density and water absorption ratios of each specimen in accordance with JIS A 1110 (standards for coarse aggregate density and water absorption test). The experimental results showed that the density of SMCAs as 2.5 g/cm^3 or more was higher than those that received no surface modification treatment by 4 to 5%, as shown in Fig. 5. This is thought to be due to the SMCP coating, causing the ITZ to become more compact. However, there was also an increase in the water absorption ratio (Fig. 5). This is deemed to be a consequence of the cement paste

Table 1 – Mix proportion of concrete

Type	W/C (%)	Slump (mm)	Air (%)	G_{max} (mm)	Unit weight (kg/m^3)				Admixture (%)
					W	C	S	G	
LCCA concrete (L)	55	180±25	4.5±1.5	20	175	318	805	913	C×0.5(a*)
SMCA concrete (M)					175	312	805	935	C×0.6(a*)

Note: W – water; C – cement; S – fine aggregate; G – coarse aggregate; L – LCCA concrete; M – SMCA concrete; a* – plasticizer.

Table 2 – Experimental factors and conditions

Experimental factors		Conditions	
LCCA		Standard density: 2.49g/cm^3, Water absorption ratio: 3.51%	
SMCP	W/C	30%	
	Modification materials	Cement, Fly ash (F/A)	
	Replace ratio of modification materials (%)	M-C	Cement =100
		M-C+FA10	Cement + Fly-ash = 90:10
		M-C+FA30	Cement + Fly-ash = 70:30
		M-C+FA50	Cement + Fly-ash = 50:50
Cement matrix		Normal strength W/C =55%	

Note: LCCA – low-quality crushed coarse aggregate; SMCP – surface modification coarse paste; M – surface-modified coarse aggregate; C – cement; C+FA – cement+fly ash; 10, 30, 50% replacement of fly ash to cement in SMCP.

Table 3 – Mix proportions of SMCP [9]

W/B (%)	Water (g)	Binder (g)	Fe_2O_3 (g)	Superplasticizer (g)	Table flow (mm)
30	21	70	B×100 %	B× (1.3-1.9) %	300

Note: L – based on 1 kg of low-quality crushed coarse aggregate; density of each material (unit: g/cm^3); B – amount of binder; cement 3.16; fly ash 2.22

acting as a lacquer on the LCCA surface, resulting in water absorption by the LCCA and SMCP. Nevertheless, the LCCA and SMCA in these experiments satisfied the JIS A 5022 criteria (standards for concrete using recycled aggregate Grade M) for recycled coarse aggregate Grade M that can be used in pile foundation and foundation concrete. Thus, with respect to the water absorption ratio, no potential problems are expected according to JIS A 5022.

3.3 Strength Characteristics

Compressive and splitting tensile strength tests, based on JIS A 1108 and JIS A 1113, were performed and, with respect to the mechanical properties, the compressive and splitting tensile strengths of each SMCA concrete specimen (M-C) were higher than those of the LCCA concrete (L) specimens by 5%-9% at 7, 14, and 28 days of curing, as shown in Fig. 6. The improved strength of the modified aggregate concrete was due to the reinforced physical and chemical bonding between the modified paste and cement matrices, which was caused by the increased mechanical friction resulting from the size and shape of the iron oxide particles and the SMCP coating effect on the ITZ [11]. In particular, the SMCA concrete using fly ash as a pozzolanic material (M-C+FA10, M-C+FA30) showed an increase in strength of approximately 12% after 7, 14, and 28 days of curing compared to the LCCA concrete. When pozzolanic materials such as fly ash were added to the SMCP, the micro-filler effect and pozzolanic reaction densified the ITZ structure. Also, the splitting tensile strength increased by approximately 12% after 7, 14, and 28 days of curing (Fig. 6). However, in the case of SMCA concrete (M-C+FA50), the compressive and splitting tensile strength decreased by approximately 2-7% at 7, 14 and 28 days of curing, as compared to the LCCA concrete. For this reason, because M-C+FA50 contained a larger quantity of fly ash than M-C+FA10 and M-C+FA30, it is believed that a hydration reaction did not occur.

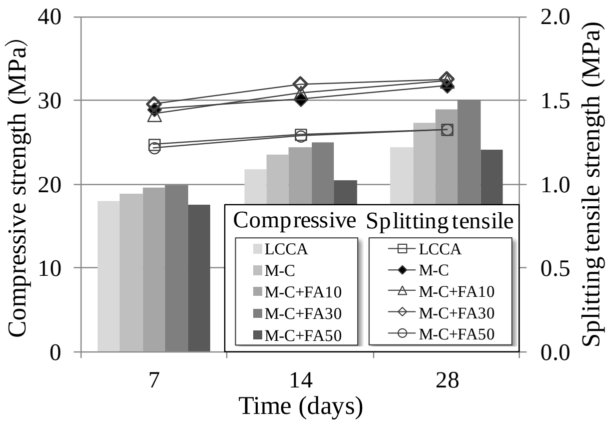


Fig. 6 – Strength comparison

3.4 Durability

In general, drying shrinkage of concrete is very complex since it is related both to the internal elements of concrete and external factors. In this experiment, it was confirmed that the water absorption ratio of SMCA was slightly higher than that of LCCA in section 3.2. Therefore, SMCA concrete has the potential for high drying shrinkage, due to the evaporation of moisture from the coarse aggregates during the curing process. In this experiment, the characteristics of drying shrinkage between LCCA concrete and SMCA concrete were evaluated. Figure 7 shows drying shrinkage of the specimens measured using the dial gauge method, JIS A 1129.

As a result of the drying shrinkage, the length change of the SMCA concrete was equivalent to or slightly lower than that of the LCCA concrete (L) up to 120 days. In particular, in case of SMCA concrete using fly ash as a pozzolanic material (M-C+FA30, M-C+FA50), the length change ratio tended to decrease by approximately 2-5% up to 120 days, as compared to the LCCA concrete, as shown in Fig. 7. From this result, we believe that evaporation of moisture from the coarse aggregates was suppressed somewhat, due to the same mechanisms described in section 3.3, which led to the densification of the ITZ structure. Therefore, it is difficult to argue that there is a substantial difference in terms of drying shrinkage resistance and that the quality of SMCA concrete is sufficient with respect to this particular property. Also, based on the proportional relationship between the water absorption ratio and the carbonation rate coefficient [12], it was speculated that modified aggregate, with a slightly higher water absorption ratio than LCCA, could exert a negative impact on the properties of concrete as it would facilitate the movement of substances within the concrete. Figure 8 shows carbonation resistance of the specimens measured using an accelerated carbonation test for concrete, JIS A 1153. As a result of carbonation depth, the carbonation resistance of SMCA concrete was either equivalent to or higher than that of LCCA concrete (L). In particular, with a trend similar to that observed for drying shrinkage, in case of SMCA concrete using fly ash as a pozzolanic material, the carbonation depth decreased by approximately 5-15% at 1, 4, 8, 12, and 16 weeks, as compared to the LCCA concrete. Based on this result, it is difficult to argue that there is a substantial difference in terms of carbonation resistance and that the quality of SMCA concrete is sufficient with respect to this particular property.

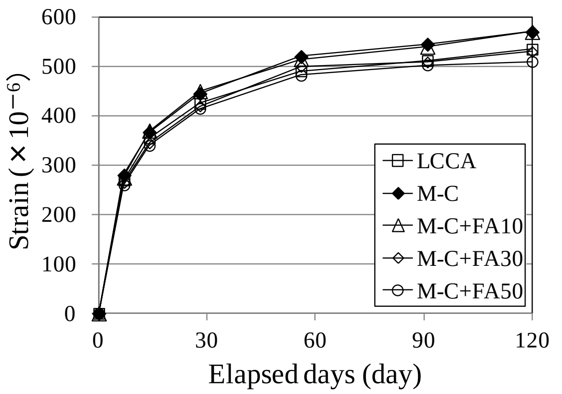


Fig. 7 – Drying shrinkage

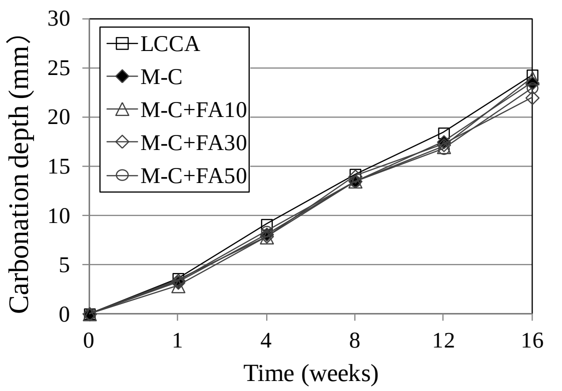


Fig. 8 – Carbonation depth

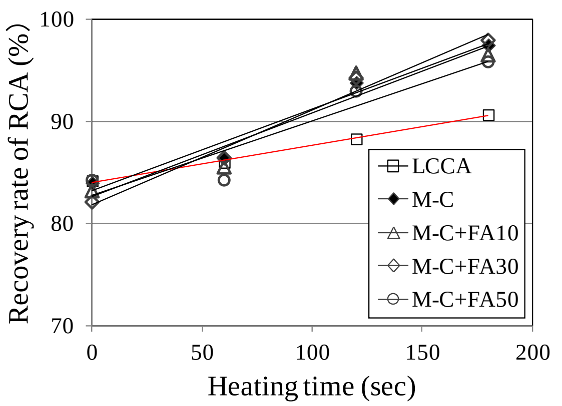


Fig. 9 – Recovery rate of RCA

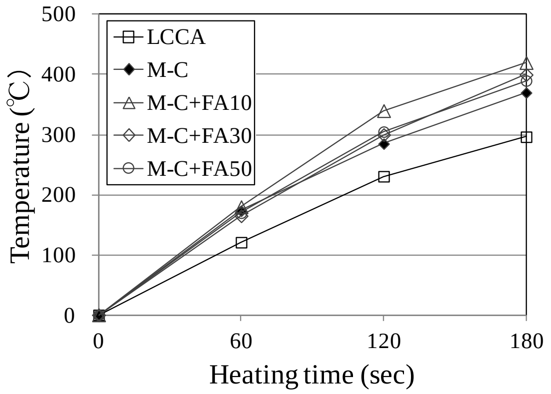


Fig. 10 – Comparison of temperature by microwaves

3.5 Recovery performance

In this study, the recovery ratio of recycled aggregate is as defined in Eqs. (1) and (2) [9]:

$$R = \alpha + \beta + \gamma \quad (1)$$

where, R denotes RCA, α denotes the LCCA, β denotes the original fine aggregate, and γ denotes cement paste. Also

$$r = M_{LCCA}/M_{RCA} \quad (2)$$

where, r denotes the recovery ratio of the RCA, M_{LCCA} is the mass of the LCCA, and M_{RCA} is the mass of the RCA.

As shown in Figs. 9 and 10, when the microwave heating time was set to 0 s and 60 s, the recovery ratio of the RCA for the SMCA was equivalent to or slightly lower than that of the LCCA. This is speculated to be due to the enhanced bonding caused by the SMCP coating between the LCCA and the cement matrices. On the other hand, when the microwave heating time was set to 120 s and 180 s, the recovery ratio of the RCA for the SMCA concrete became substantially higher than that of the LCCA concrete (L), as shown in Fig. 9. When the heating time was set to 120 s, the temperature reached 300˚C, which is the weakening temperature of the cement paste [9,11], and this is deemed to be the point at which the recovery ratio difference of the RCA began to occur, as shown in Fig. 10. In particular, when the heating time was set to 180 s, the recovery ratio of the RCA reached nearly 100%, based on which it was determined that the microwave energy effectively heated the dielectric material (Fe_2O_3) present in the SMCP. In addition, the surface weakening mechanism between the modified paste and LCCA due to microwave heating is under consideration.

4. Conclusion

In this study, the following conclusions were made based on the results of the experiments conducted to examine the effect of the surface modification treatment of LCCA on the mechanical properties and recovery performance of recycled concrete.

(1) When the W/C ratio was 55%, the improvements in the compressive strength and splitting tensile strength were confirmed to be due to the SMCP coating of the LCCA and the ITZ structure was densified by the admixtures (only cement and pozzolanic materials).

(2) When the SMCA concrete containing iron oxide (Fe_2O_3) was heated with microwaves the temperature increase was more significant than that of LCCA concrete. In particular, when the microwave heating time was 180 s, the maximum temperature was nearly 400˚C due to the microwaves effectively heating the iron oxide contained in the SMCP. Therefore, from the results of the recovery performance of SMCA with microwave heating, it was considered that recovered RCA is very similar to natural coarse aggregate. Thus the feasibility of high-quality RCA recovery has been demonstrated. However, to apply this technique in the field, there is a need for research to be conducted on the design of the quantitative mix and the cost effectiveness of SMCA concrete.

References

1. JAPAN Crushed Stone Association (JCSA). http://www.saiseki.or.jp/
2. Ministry of Economy (2011) "Trade and Industry," Yearbook of crushed stone statistics 2010. http://www.meti.go.jp/statistics/sei/saiseki/result/xls/agyear21.xls
3. Noguchi, T. and Tamura, M. (2001) "Concrete Design towards Complete Recycling," Structural Concrete, fib, 2, pp. 155-167.
4. Noguchi, T. (2008) "Resource Recycling in Concrete: Present and Future," Stock Management for Sustainable Urban Regeneration, 4, pp. 255-274.
5. Hendriks, Ch.F.; Janssen, G.M.T. (2001) "Construction and Demolition Waste. General Process," HERON, 46, pp. 79-88.
6. Shima, H.; Tateyashiki, H.; Matsuhashi, R.; and Yoshida, Y. (2005) "An Advanced Concrete Recycling Technology and its Applicability Assessment through Input-Output Analysis," Journal of Advanced Concrete Technology, 3, pp. 53-67. http://dx.doi.org/10.3151/jact.3.53
7. Tsujino, M.; Noguchi, T.; Tamura, M.; Kanematsu, M. and Maruyama, I. (2007) "Application of Conventionally Recycled Coarse Aggregate to Concrete Structure by Surface Modification Treatment," Journal of Advanced Concrete Technology, 5, pp. 13-25. http://dx.doi.org/10.3151/jact.5.13
8. Tsujino, M.; Noguchi, T.; Kitagaki, R.; and Nagai. (2010) "Completely recyclable concrete of aggregate-recovery type by a new technique using aggregate coating," Architectural Institute of Japan, 75(647), pp. 17-24. (*in Japanese*)
9. Choi, H.S.; Kitagaki, R.; and Noguchi, T. (2014) "Effective Recycling of Surface Modification Aggregate using Microwave Heating," Journal of Advanced Concrete Technology, 12, pp. 34-45. http://dx.doi.org/10.3151/jact.12.34
10. Tsujino, M.; Kitagaki, R.; Noguchi, T.; Nagai, H.; and Kunieda, Y. (2008) "Completely Recyclable Concrete of Aggregate-Recovery Type by Using Microwave Heating Technology," The 3rd ACF International Conference-ACF/VCA 2008, pp. 522-239.
11. Choi, H. et al. (2014) "Using Microwave Heating to Completely Recycle Concrete," Journal of Environmental Protection, 5, pp. 583-596. http://dx.doi.org/10.4236/jep.2014.57060
12. S. Nagataki; A. Gokce; and T. Saeki. (2000) "Effects of Recycled Aggregate Characteristics on Performance Parameters of Recycled Aggregate Concrete," American Concrete Institute. ACI Special Publication, 52, pp. 462-467.
13. Tsujino, M.; Noguchi, T; Kitagaki, R.; and Nagai. (2011) "Completely Recyclable Concrete of Aggregate-Recovery Type by Using Microwave Heating," Architectural Institute of Japan, 76, pp. 223-229. (*in Japanese*)