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Assessment of recycling process induced damage sensitivity of recycled concrete aggregates

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Abstract

This paper evaluates the complex nature of recycled concrete aggregates that are susceptible to damage due to recycling. The study was carried out by microstructural assessment techniques beyond the standard testing methods normally specified for aggregates. The laboratory produced recycled concrete aggregates were investigated using fluorescent microscopy and image analysis. Contrary to common opinion, microstructural studies showed that adhered mortar (AM) is not always the primary parameter determining the quality of the recycled coarse aggregate. Sandstone coarse aggregate originally had defects in the form of voids and cracks. Further processing of the recycled coarse aggregate changed the microstructural profile of the material and enhanced their properties. The unusual results of the performance tests carried out on the recycled aggregate concretes could be explained with the findings of microscopic level investigations.

Keywords: Recycled coarse aggregate; Recycling process; Damage sensitivity; Microcracking; Mechanical properties

1. Introduction

In evaluation of the recycled aggregate characteristics, it should be kept in mind that each recycled aggregate particle is still a piece of concrete composed of the original coarse aggregate (OCA) and the adhered mortar (AM). The recombined form of these concrete particles with a new matrix is called recycled aggregate concrete. For a clear understanding of the recycled aggregate and to predict its possible effects on concrete, the constituents of these composite particles must be identified separately [1].

In most of the previous studies on recycled aggregate concretes, the recycling technology used was not considered and the recycling process was limited to only single-stage crushing. There is inadequate research focusing on the characteristics of the recycled aggregates produced by further processing technology that can improve the quality of the product. A more reliable approach to determine the expected enhanced performance of the recycled aggregate concrete can only be done by clarifying the possible microstructural changes brought about by the recycling process on each constituent of the recycled concrete aggregate [2].

2. Experimental

2.1. Production of the source concretes

Three laboratory-produced air-entrained concretes with low (0.35), medium (0.45) and high (0.63) water–cement ratios (W/C) were prepared as the source of the recycled aggregates. The materials used in the mixtures were an ordinary Portland cement, crushed sandstone as coarse aggregate and a fine aggregate from the Sagami River. A standard-type air-entraining and water-reducing agent (AEWR) or an air-entraining and high-range water reducing agent (AEHRWR) was included in the production of the source concretes. The properties of the original aggregates and mixture proportions of the source con-

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Table 1
Properties of the original aggregates

Fraction	Origin	Code	Density SSD (g/cm^3)	Water absorption (%)	Powder content (%)	Soundness loss (%)	Unit weight (kg/m^3)	FM
Coarse	Sandstone	OCA	2.65	0.94	0.05	9.1	1700	6.48
Fine	River sand	NS	2.64	2.63	1.64	2.6	1570	2.87

cretes are presented in Tables 1 and 2. Some important characteristics of the concretes are shown in Table 3.

The concretes were cast into $300 \times 300 \times 300$-mm moulds. After a 28-day water curing, the original concrete blocks were demolded. From demolding to the crushing age of 1 year, the concrete blocks were stored in the production plant and exposed to outdoor condition.

2.2. Recycling process and properties of the recycled coarse aggregates

The recycling technology of this project consists of crushing the source concrete with a combination of jaw crusher and impact crusher and processing the crushed material twice with a mechanical grinding equipment to minimize the AM. The flow of the production with representative data of the output material obtained in three levels of the recycling process is illustrated in Fig. 1.

During the different stages of the process, a large number of recycled products were obtained as coarse and fine aggregates. This research was conducted with only "Level 1" and "Level 3" recycled coarse aggregates having the highest and the lowest AM contents for each type of source concrete. In the experimental studies, each recycled coarse aggregate was labeled according to a coding system as shown in Table 4 where A, B and C denote the W/C of the source concretes from lower to higher, and 1, 2 and 3 indicate the level of process at which the aggregate was obtained (or AM content from higher to lower). The AM content of the recycled coarse aggregates was determined by the hydrochloric acid dissolution method. The basic properties of the recycled coarse aggregates are summarized in Table 5.

The recycled coarse aggregate properties clearly demonstrate that processing level and quality of the source concrete played a very important role in the characteristics of the recycled aggregates. Further processing and higher quality source concrete resulted in better quality aggregates. As Fig. 2 shows, the reclamation ratios of the recycled coarse and fine aggregate noticeably change depending on the processing level. By using only jaw and impact crushers (Level 1) without continuing further process, the reclamation ratio of recycled coarse aggregate became 60%, which means an output of 400 kg crushed concrete fines per 1 ton of the source concrete. While the further processing offered high-quality recycled coarse aggregates with a minimized AM content, the reclamation ratio of the coarse fraction decreased up to 35%. The recent trends in Japanese industry are to develop a closed-loop recycling system to handle the large amount of crushed concrete fines and powder generated during the recycling process for producing recycled cement.

2.3. Test program and procedure

2.3.1. Optical microscopy and image analysis

A microscopic level study that included image analysis was carried out to monitor the changes in microstructure of the aggregates at different stages of the recycling process. The particles sampled from each recycled aggregate population between 15 and 20 mm in size were embedded into epoxy in the plastic moulds. In this way, three samples were produced for each type of coarse aggregate. A number of sandstone coarse aggregate particles were also prepared for visual inspection by optical microscopy. After hardening of the epoxy resin, the specimen was cut to obtain plain aggregate surface with a thin blade diamond saw and then polished.

In order to determine the net effect of the recycling process on the microstructure of the recycled aggregates, the reference core samples with a diameter of 25 mm representing the microstructural characteristics of the source concretes just before the recycling process were produced by drilling the source concrete blocks prior to crushing. Then, several slices were taken from the core samples and polished sections were prepared. The next stages of the plane section preparation procedure are similar to "fluorescent liquid replacement technique (FLR)," which was developed by Gran [3].

Table 2
Mixture proportions of the source concretes

Code	W/C (%)	S/A (%)	Mixture composition (kg/m^3)						D_{max} (mm)
			Water	OPC	Coarse aggregate	Sand	Admixture		
							AEWR	AEHRWR	
A	35	41	170	486	986	679	–	4.37	20
B	45	43	170	378	1004	749	–	3.40	20
C	63	47	167	267	988	867	0.668	–	20

Table 3
Properties of the source concretes

Code	Slump (mm)	Air (%)	Compressive strength (N/mm^2)				
			Standard curing		Kept on site		
			7 days	28 days	7 days	40 days	1 year
A	200	4.4	48.8	60.7	47.1	56.1	60.1
B	100	4.0	37.9	49.0	33.8	40.5	41.7
C	75	4.5	19.3	28.3	18.1	24.4	25.5

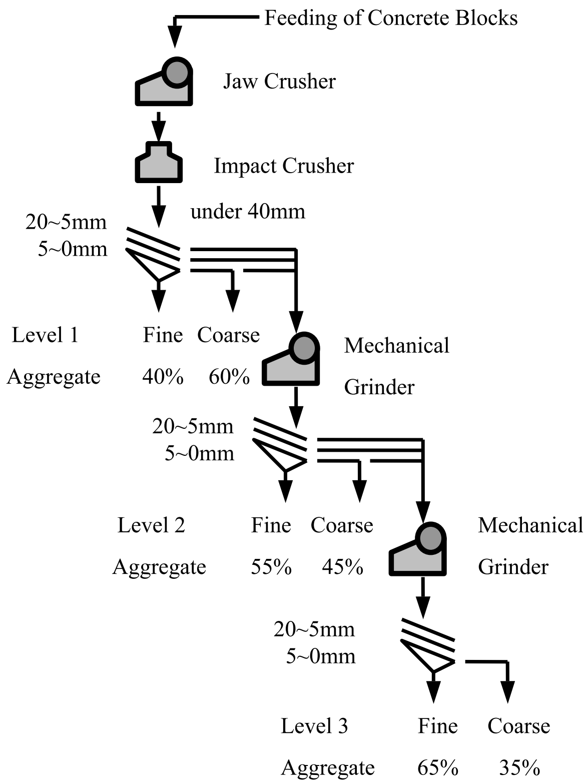

Fig. 1. Flow of the recycling process.

Microscopical examination of the concrete sections through image analysis has been successfully performed by several researchers in the Nordic countries [4–8]. In this investigation, the examination of the plane sections was done by using a fluorescent optical microscope (Olympus PMG3) equipped with an image analyzer. A Japanese image processing software (Himawari) was used in the analysis. The original microscope images were transmitted to the image processor by a color camera. The images processed in the analyzer were converted into binary form as white features in front of the black background. The binary images were filtered to reduce as much as possible the other features captured together with the target crack images. Then, a final retouching was performed on the crack images to eliminate the remaining undesirable features and defects by using a painting software. In this stage, enhanced images were ready for quantitative analysis. Kukko [4] developed a procedure for systematic collection of the image analysis data by dividing the total observation area into squares. Following a similar procedure, a transparent grid was attached on each plane section before the analysis. The horizontal and vertical dimensions of one observation area were 1.64 and 1.74 mm, respectively.

The possible cracking patterns within the recycled coarse aggregate particles were classified under three categories: OCA cracks, AM cracks and interface (ITZ) cracks between OCA and AM. The constituents of a recycled coarse aggregate particle analyzed in the microscopic studies and an example of an enhanced crack image within the zone of OCA are illustrated in Fig. 3.

Two microstructural damage parameters were defined in assessment of the cracking patterns: crack density (Δ_{cr}) for OCA or AM and cracking ratio (ITZ_{cr}) for interfacial transition zone, where:

$$\Delta_{cr} = \frac{\text{total crack area}}{\text{total observation area}} \times 100(\%) \quad (1)$$

$$ITZ_{cr} = \frac{\text{total crack length in ITZ}}{\text{total length of ITZ}} \times 100(\%) \quad (2)$$

Due to the uncertainty of the specific area occupied by the ITZ, the ratio of cracked length to total interface length around coarse aggregate (ITZ_{cr}) was taken into account instead of Δ_{cr} in evaluation of the cracks developed through the interfacial transition zone. The cracks around the fine aggregate particles were included with the AM cracks due to the practical difficulties in classification of the images. In microscopic investigations, the images of 45 observation areas from each constituent of recycled coarse aggregate were collected and analyzed by image processor.

2.3.2. Performance tests on recycled aggregate concretes

In order to correlate the effects of recycling process induced microstructural changes within the recycled aggregates with the mechanical performance of the concretes incorporating identical aggregates, the concrete mixtures with a W/C of 0.55 were designed. The natural aggregates of the control mixture were the same sandstone and river sand used in the production of the source concretes. Mixture proportions and some fresh properties of the concretes are summarized in Table 6. The performance tests were carried out after a 28-day water curing of the specimens. Compressive and splitting tensile strength and total permeable porosity were determined as the performance parameters. Compressive strength was determined on three 100 × 200 mm cylinder specimens. Splitting tensile strength of four 100 mm cubes were tested according to BS 1881:Part 117. The volume of total permeable voids of the concretes were

Table 4
Codes of the recycled aggregates

Quality of source concrete	Aggregate codes AM content		
	High	Medium *	Low
High (W/C = 0.35)	A1	A2	A3
Medium (W/C = 0.45)	B1	B2	B3
Low (W/C = 0.63)	C1	C2	C3

* Those were not used within the scope of this study.

Table 5
Properties of the recycled coarse aggregates

Source concrete	Process level	Code	AM content (%)	Density SSD (g/cm^3)	Water absorption (%)	Soundness loss (%)	100 kN crushing value (%)	FM
A	1	A1	52.3	2.42	4.88	29.7	3.83	6.67
	3	A3	30.2	2.51	3.14	8.10	1.53	6.51
B	1	B1	55.0	2.41	5.58	48.3	5.19	6.57
	3	B3	32.4	2.50	3.19	18.4	1.73	6.39
C	1	C1	52.3	2.37	6.27	49.1	6.30	6.59
	3	C3	32.3	2.48	3.76	22.5	2.28	6.69

measured on four 100 × 100 × 30-mm concrete slices as described in ASTM C 642-97.

3. Results and discussion

3.1. Visual microscopy findings on sandstone coarse aggregate

Optical visual microscopy of the sandstone sections under fluorescent light provided useful information. Sandstone particles originally had segmented fine fissures with a thickness up to 30 μm. In addition to these microdefects, some particles had independent coarse cavities larger than 50 μm in diameter that were mostly friable. The amount of the weak particles in the total aggregate population was about 8% by mass. Their physical properties were also inferior with a high water absorption value (2,4%) compared to that of the regular particles (0.9%).

3.2. Crack potential of recycled coarse aggregates in relation to recycling process

In assessment of the cracking tendency of the recycled coarse aggregate due to the recycling process, microstructural findings belonging to the core samples representing the initial state of the recycled coarse aggregate were compared with the data showing crack patterns developed at different stages of the recycling process in each constituent of the recycled coarse aggregate. The changes in microcracking profile of the OCA and AM belonging to the recycled coarse aggregates with different origins are illustrated in Fig. 4a–c in terms of crack density (Δ_{cr}). Fig. 5 also employs the second damage assessment parameter (ITZ_{cr}) showing the crack potential of the interfacial transition zone between OCA and AM for the recycled coarse aggregates produced from different quality source concretes.

The results clearly demonstrate that the source of the cracks in the original concretes prior to recycling process was mainly the sandstone coarse aggregate. Except almost invisible and negligible amount of shrinkage cracks, no mortar or ITZ crack could be detected on the plane sections belonging to the source concrete cores. The sandstone coarse aggregate was the most susceptible constituent of the recycled coarse aggregate in terms of the microstructural stability. After the source concretes were recycled, reorientation of the cracks in the crushed concrete gave the most of the answers to the questions. One of the interesting point observed was a tremendous decrease in the cracks belonging to OCA particle as a constituent of the recycled coarse aggregate after double crushing stage (Level 1). While the reduction in the original aggregate cracks in high-quality recycled coarse aggregate (A1) was about 58%, a further decrease was observed (69%) in the particles belonging to a low-quality one (C1). Separation of the cracked OCA particles is not so easy if those are surrounded by a high-strength mortar. The results imply

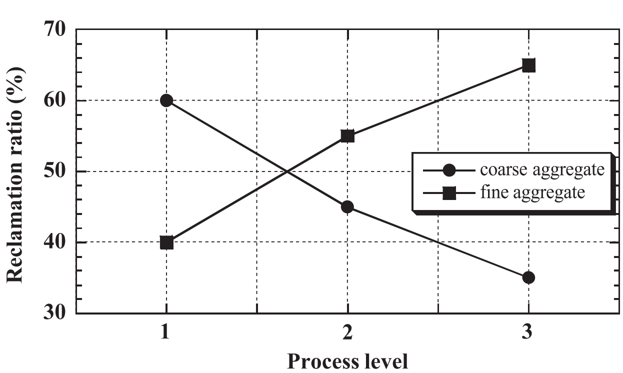

Fig. 2. Variation in the reclamation ratio depending on the crushing level.

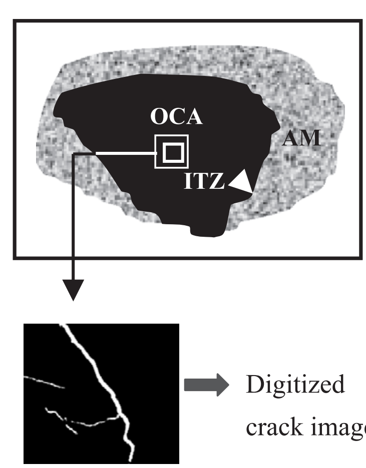

Fig. 3. Illustration of the zones within the recycled coarse aggregate and an example of a crack belonging to the OCA.

Table 6
Mixture proportions and fresh properties of the concretes

Mixture	W/C	Materials (kg/m^3)						Air content (%)	Slump (mm)
		Water	Cement	Aggregate		Admixture			
				Fine	Coarse	WR-AE	AE		
OCA-NS	0.55	165	300	813	1039	0.94	0.72	4.3	90
A1-NS		160	291	819	959	0.91	0.47	4.5	90
A3-NS		157	285	825	1002	0.89	0.46	4.0	65
B1-NS		160	291	819	955	0.91	0.47	4.1	80
B3-NS		157	285	825	998	0.89	0.46	3.8	65
C1-NS		160	291	822	940	0.91	0.47	4.5	65
C3-NS		158	287	826	988	0.90	0.46	4.7	75

that during crushing operation, the fracture path follows the weakest zones such as cracked or porous OCA particles. After double crushing, the damage to AM and ITZ between OCA and AM was negligible. This result also indicated that Level 1 crushing did not affect the integrity of the recycled coarse aggregate.

When the recycling process was extended to Level 3, OCA particles regained some part of the cracks. A small increase in the ITZ cracks was also observed in the recycled coarse aggregate originated from the low-quality source concrete (C3), but the amount of the cracks was still very low. At the end of Level 3 process, no microstructural change was observed in AM in terms of the crack density (Δ_{cr}). In short, prior to use in concrete, recycled coarse aggregates mostly had cracks belonging to the OCA.

Crushing value test results of the aggregates also coincide with the findings of the microstructural studies (Table 5). When the recycling process was extended up to Level 3 following double crushing, the OCA particles mostly lost their porous features, crack openings and excessive adhering mortar. This level of refinement significantly increased the mechanical performance of the recycled aggregate particles in crushing value test. All Level 3 recycled coarse aggregates could give lower crushing values than virgin sandstone aggregate regardless of the quality of the source concrete. Consequently, further recycling did not worsen the integrity of the recycled coarse aggregate. The stable behavior of the AM and the good ITZ bond in the OCA provided resistance against microcracking, which was the most important reason for maintenance of the high integrity of the recycled concrete aggregate.

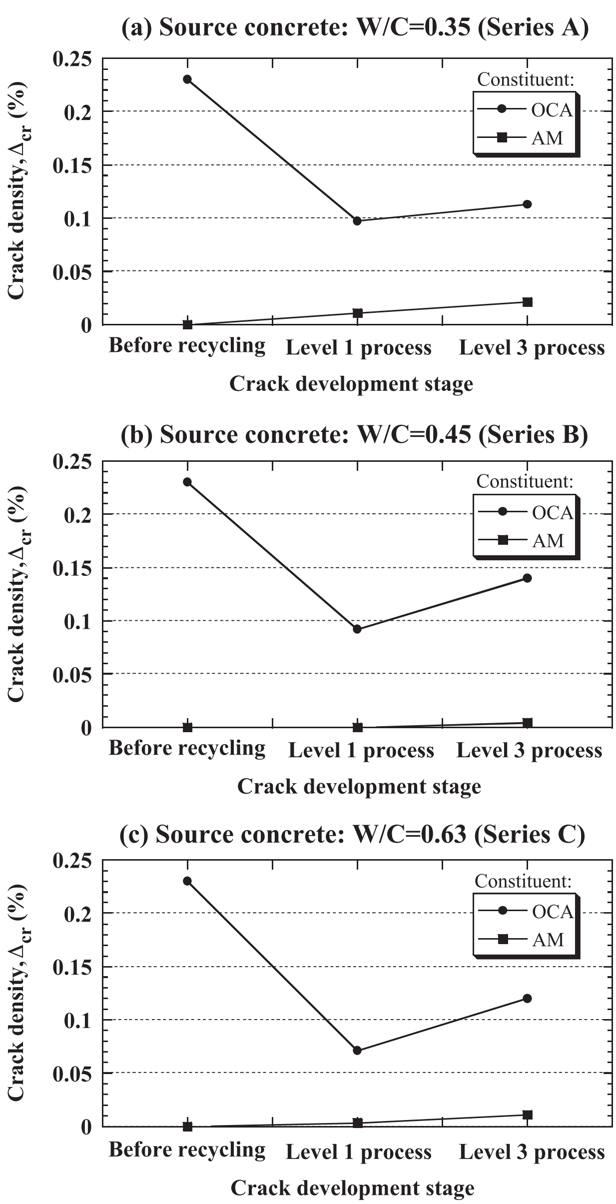

Fig. 4. Microcracking profile of the recycled coarse aggregate constituents.

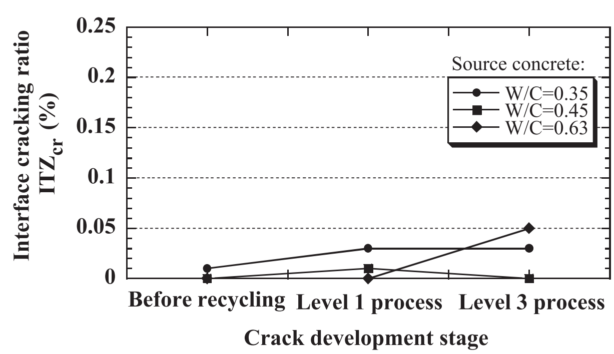

Fig. 5. Microcracking profile of the ITZ between OCA and AM.

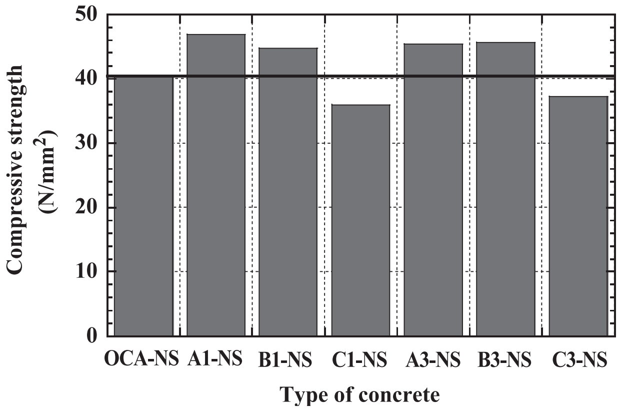

Fig. 6. Compressive strength of the concretes incorporating various coarse aggregates.

3.3. Relationship between crack potential of the coarse aggregate and mechanical performance of concrete

The mechanical performance of the concretes incorporating the coarse aggregates discussed in the previous section can be evaluated in Figs. 6 and 7 with respect to compressive strength and splitting tensile strength. The compressive strength of the concretes made with the recycled coarse aggregates originated from high- and medium-quality source concretes gave noticeably higher compressive strength values than that of the original aggregate concrete. However, extending the recycling process to Level 3 did not result in a significant change in compressive strength. The concretes made with low-quality recycled coarse aggregates gave the lowest compressive strength results. For those, reducing the AM content up to Level 3 could only make little improvement effect on the compressive strength. Remaining mortar adhering to OCA was enough to cause almost the same degree loss of compressive strength.

Similarly, recycled aggregate concretes gave quite comparable results in splitting tensile strength test. The concretes incorporating high- and medium-quality recycled coarse aggregates with minimum AM content (A3 and B3) could perform better than the reference concrete made with original aggregates.

As another important performance criteria, the total volume of the permeable pores of the concretes produced with the recycled coarse aggregates under discussion increased 20–52% compared with the porosity of the control concrete (Fig. 8). However, the majority of the recycled aggregate concretes with large porosity values give better mechanical performance than reference concrete incorporating natural aggregates. This paradoxical result can be easily interpreted from the microstructural profile of the coarse aggregates as discussed above. Elimination of the friable and porous aggregate particles during recycling process created almost microdefect-free recycled coarse aggregates with a high level of integrity. As a result, the mechanical performance of the recycled aggregate concretes was positively influenced by the refinement of the sandstone aggregate.

The reduced size and concentration of the sandstone aggregate particles after recycling are the other important effects contributing to enhanced mechanical performance. The smaller the OCA size, the lower the stress concentration at the zone between aggregate and surrounding mortar. The lower concentration of the sandstone aggregate in new concrete also suppresses its negative effects on the mechanical behavior due to the presence of the remaining weak particles.

On the other hand, there is one more important aspect of the mechanical behavior of the system including recycled coarse aggregate. As Neville [9] pointed out, the smaller difference between the modulus of elasticity of the hardened cement and the modulus of elasticity of the aggregate, the better response to bond stresses and a more monolithic concrete results. Similarly, Bremner and Holm [10] stated that elastically matched constituents would result in lower levels of the stress at the ITZ and less early microcracking. Recycled concrete aggregate is also a well-matched material with surrounding cement paste. A good elastic compatibility between the constituents of the recycled aggregate concrete is a big advantage for the system in terms of the mechanical performance.

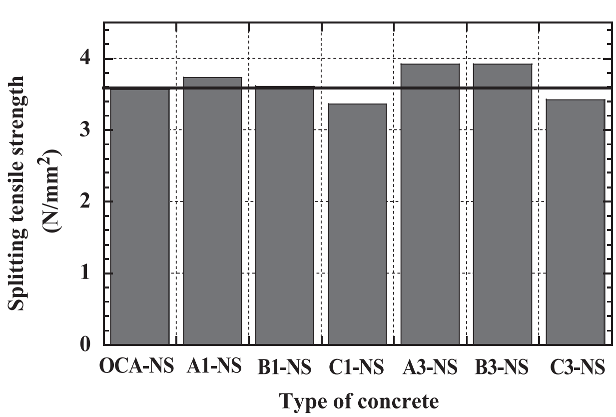

Fig. 7. Splitting tensile strength of the concretes incorporating various coarse aggregates.

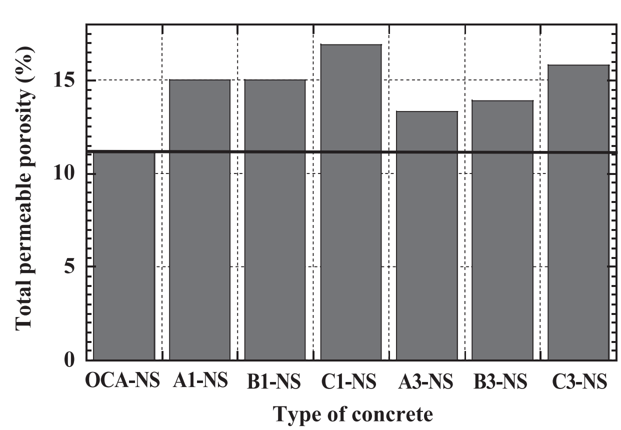

Fig. 8. Porosity of the concretes incorporating various coarse aggregates.

4. Conclusions

1. Microscopical analysis performed on OCA showed that sandstone particles contained noticeably segmented fissures. Moreover, some particles had coarse void defects, although those were in a minority in total aggregate population.
2. While double crushing of the source concretes (Level 1) considerably reduced the density of the cracks in the OCA by eliminating the particles with microdefects and irregular voids, processing up to Level 3 reintroduced negligible new cracks. Only a very minor amount of cracking could be detected in AM or at the interfacial transition zone. Consequently, the recycled concrete aggregates obtained at each stage of the recycling process did not show any loss of integrity. Beyond this, extending of the recycling process up to Level 3 efficiently increased the physical performance of the concrete aggregate by reducing the adhering mortar.
3. Unusual mechanical performance and porosity relationship of the concretes made with the recycled concrete aggregates could be easily explained by a positive change in the microstructural profile of the sandstone coarse aggregate used in the source concrete due to the recycling process. The recycled aggregate concretes containing almost microdefect-free sandstone aggregate with reduced size and concentration show equal or better mechanical performance than the concrete made with virgin sandstone aggregate, unless the quality of the AM is inferior to that of the new matrix. The compatible elastic behavior of the system composed of recycled concrete aggregate as coarse aggregate and surrounding cement matrix is also another important reason for unexpectedly good mechanical performance of recycled concrete.

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