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Mechanical properties of concrete containing 100% treated coarse recycled concrete aggregate

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HIGHLIGHTS

- An environmental friendly method for improving properties of RAC was suggested.
- The proposed method significantly improved the mechanical properties of RAC.
- The direct tensile strength of treated RAC at early age was higher than the splitting tensile strength.
- The compressive strength of treated RAC was estimated at any age.
- The relationships between mechanical properties of treated RAC were presented.

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ABSTRACT

An environmental friendly method for enhancing mechanical properties of recycled aggregate concrete (RAC) is proposed by using sodium silicate and silica fume. The proposed method, applied to 100% coarse recycled concrete aggregate compared to untreated RAC, can improve compressive strength up to 33–50%, splitting tensile strength 33–41%, and elastic modulus 15.5–42.5%. Tests revealed that the direct tensile strength of RAC and natural aggregate concrete (NAC) were notably lower than the splitting tensile strength, but at 7 days, these values of treated RAC were higher than the splitting tensile strength. From the experimental data, the compressive strength of the treated RAC can be estimated at any age. Besides, the relationships between mechanical properties of treated RAC which were established were significantly different from those of NAC and untreated RAC in previous studies.

1. Introduction

With the development of today's infrastructures, the demands for concrete and concrete aggregates have been rising significantly [1]. The sources of natural aggregates (NA) are dwindling whereas the amount of construction and demolition waste (CDW) is increasing rapidly, causing environmental problems [2]. Using recycled concrete aggregate (RCA) from recycled CDW is both feasible and valuable to protect the environment, produce economic benefits, as well as reserving NA sources [3,4]. Generally, the obstacles to using recycled aggregate concrete (RAC) for realistic structures are lower mechanical and durability properties in comparison with that of natural aggregate concrete (NAC) [5]. RCA holds an amount of attached cement mortar which has a higher porosity and lower strength than that of NA [6]. Therefore, many methodologies have been developed to improve the properties of recycled aggregate concrete (RAC) [7]. The methods of removing adhered mortar [8–10] to recover the NA in old concrete, save NA sources, and produce high quality RCA. However, the methods of removal of adhered mortar created disposal waste [11]. On the other hand, the methods of strengthening adhered mortar have been developed by some researchers, recently, to improve the quality of RAC. Kou and Poon [12] proposed that by using polyvinyl alcohol, the properties of RCA were improved, at 90 days, mechanical and durability properties of RAC were comparable to that of NAC. Tam et al. [13], Xuan et al. [11], and Zhang et al. [14], using the reactions between CO_2 and hydration products of old adhered mortar to reduce the porosity of the adhered mortar, developed a carbonation technique to enhance the quality of RCA. Wang et al. [6] developed a method to improve attached mortar in RCA which was based on the idea that bacteria induced the precipitation of $CaCO_3$ in adhered mortar. A silane-based water repellent method [15,16] enhanced properties of RCA such as decreasing water absorption of RCA and heightened durability.

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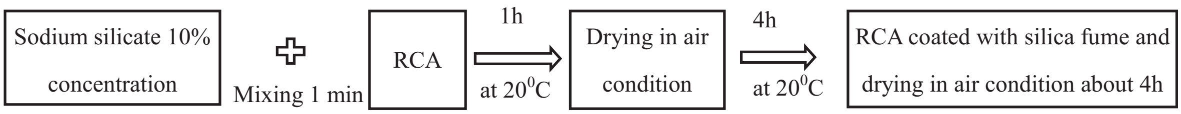

Fig. 1. Pre-treating process for RCA with sodium silicate and silica fume.

Table 1
Chemical compositions of materials for concrete (%).

Material	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	MnO	Fe_2O_3
Cement	1.07	0.78	3.47	22.63	0.42	62.57	0.23	0.10	3.29
SF	1.13	1.11	3.04	94.05	0.92	0.31	0.01	0.11	1.61
NA	4.39	2.43	16.87	58.40	0.68	7.46	0.97	0.17	10.32
RCA	2.69	1.83	12.52	62.56	1.30	12.01	0.62	0.12	5.82

Although the properties of RAC have been improved, some methods still have negative environmental impacts or limitations in technique for treating procedure. Therefore, the aim of this study is to propose an environmentally friendly treatment method for improving properties of RAC. In the proposed treatment method, RCA is firstly soaked in sodium silicate (Na_2SiO_3) solution for pre-treating and then coated with various percentages of silica fume. In the treatment process, sodium silicate will penetrate the RCA structure to seal cracks and react with portlandite (calcium hydroxide ($Ca(OH)_2$-CH crystals) of RCA to make stronger C-S-H (calcium silicate hydrate ($CaO.SiO_2{\cdot}H_2O$)) product in concrete as in the following reaction:

$$Na_2SiO_3 + Ca(OH)_2 + H_2O \rightarrow CaO.SiO_2.H_2O + NaOH \quad (1)$$

Sodium silicate is a commercial product which was known as the best material to activate pozzolans, inexpensive, and environmentally friendly [17]. Sodium silicate is an important constituent as an activator in geopolymer concrete [18]. Additionally, Spaeth and Tegguer [19] indicated that sodium silicate can reduce the water absorption coefficient of RCA. Besides, silica fume can fill in pores and cracks of RCA and convert CH crystals into C-S-H gel [20], they also fill up in cracks of RCA and enhance mechanical properties of RAC [21]. Particularly, silica fume can control and counteract the alkali-silica reaction to suppress expansion in concrete, which has been proven over a long period of field observations [22,23]. In this study, in order to evaluate the effectiveness of the proposed solution, the study examined mechanical properties of RAC including compressive strength, elastic modulus, splitting tensile strength, and direct tensile strength of RAC. The tensile strength of concrete might be determined by experiment and defined in one of three ways: splitting tensile strength, flexural strength, or direct tensile strength [24]. The splitting tensile strength is widely measured to evaluate tensile strength due to its simplicity although the direct tensile strength test method supplies reasonable and reliable results [25]. Furthermore, understanding the direct tensile strength of concrete is very important because this property affects the deflections, cracking, shear, and bonding properties of the concrete [26]. Hence, this work investigated the direct tensile strength of RAC after treated with the proposed method. Additionally, from determination of mechanical properties, relationships between mechanical properties of RAC were established. Clearly, establishing relationships of mechanical properties of RAC is a crucial issue for designing and analyzing concrete structures [27]. Although these relations were established extensively for NAC in previous literature, these relationships of NAC cannot be applied to RAC structure [28,29]. A few recent studies of RAC have shown relationships between mechanical properties with different replacement percentages [24,27,30–33]. However, the relations in the case of RAC pre-treating with silica fume and sodium silicate have been paid little attention. Thus, it is necessary to establish reliable relationships between various mechanical properties by using 100% coarse RCA with new treatment methods.

Table 2
Properties of natural aggregate and recycled concrete aggregate.

Aggregate Properties	FA	NA	RCA
Relative density SSD	2.41	2.83	2.36
Apparent relative density	2.48	2.91	2.62
Relative density oven-dry basis	2.36	2.79	2.20
Water absorption (%)	2.19	1.29	6.50

Note: SSD = saturated-surface-dry; FA = fine aggregate.

2. A pre-treating procedure for RCA

The treatment solution is sodium silicate (SS) which was prepared at 10% concentration. Firstly, RCA was soaked in SS solution about 1 h at around 20 °C. Then, the samples of RCA were dried in air conditioning at 20 °C about 4 h until the surface of RCA reached the dry-wet condition. After that, RCA was coated with silica fume (SF) at different percentages of 3, 5, 7% cement weight and dried in air conditioning about 4 h. The treatment process was illustrated in Fig. 1.

3. Materials

The properties and characterization of all materials used for this study including cement, sodium silicate, silica fume, and aggregate were presented in this section.

3.1. Cement

Portland cement type I was supplied by Hitachi Company. The density of the cement was 3.15 g/cm^3 and its chemical compositions were listed in Table 1.

3.2. Sodium silicate

Sodium silicate (SS) solution is a kind of soluble polymer material in water. Sodium silicate JIS3 was manufactured by Sangokeisan Soda company and had SiO_2/Na_2O ratio of 3, about 30% SiO_2.

3.3. Silica fume

Silica fume (SF) had chemical compositions as given in Table 1.

3.4. Aggregate

Natural coarse aggregate (NA) was obtained in Tokyo Sekkai Kougyo Limited, Japan. RCA was provided by the local manufacturer in Miyagi Prefecture, Japan. The chemical components of RCA and NA were detailed in Table 1. The coarse