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ENHANCEMENT OF RECYCLED AGGREGATE CONCRETE PROPERTIES BY A NEW TREATMENT METHOD

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ABSTRACT: Recently, decreasing natural sources of aggregate accompanied by increasing large quantities of construction and demolition waste (CDW) cause challenges for environment and construction industry. A significant solution for this is to recycle CDW as a new aggregate source for concrete. However, using recycled concrete aggregate (RCA) in concrete involves various obstacles and controversial issues in controlling the quality of recycled aggregate concrete (RAC). This study is an effort to improve the quality of RAC containing 100% coarse RCA by using pozzolanic and sodium silicate solution as new treatment solutions. This study examined performance abilities of RAC after being treated with new treatment solutions and a new mixing procedure. The mechanical properties of RAC were evaluated based on testing of concrete under various conditions. The significant results indicated that sodium silicate combined with pozzolanic materials can improve mechanical properties of RAC containing 100% coarse RCA. At 20% concentration of sodium silicate and silica fume, the compressive strength of RAC could improve up to 36%. Achievements of this approach demonstrated its effectiveness in enhancing the strength of RAC, which is potentially applied to treating RCA for concrete in the future.

Keywords: Recycled Aggregate Concrete; Sodium Silicate; Pozzolanic Materials; Treatment Method

1. INTRODUCTION

In recent years, with the increased development of construction industry, the demands of concrete have been increasing relentlessly more than 15 billion tonnes annually, which is accompanied by a huge requirement in consuming aggregate products approximately 11 billion tonnes each year [1]. Furthermore, the increase of large quantities of the construction and demolition waste (CDW) due to the end of service life of infrastructures, wars, natural disasters, and human activities causes extreme challenges for environmental protections in the construction industry [2]. It is estimated that the amount of CDW occupies about 40% of the total waste [3], becoming burdens of many nations. For that reason, recycling CDW as a new aggregate source for concrete has received much more attention due to its feasibility, as well as its environmental and economic benefits [4]. Using recycled concrete aggregate (RCA) for concrete structures in many countries is still controversial and not easy to implement because of the lower qualities of RAC [5] and more complicated microstructure [6] such as containing large flat $Ca(OH)_2$ crystals (CH crystal, about 20-25% of the volume of solids in the hydrated paste) which accumulated in the voids and in the cement paste [7]; a huge amount of pores and cracks; especially when it holds two interfacial transition zone (ITZ) systems including: new ITZ between RCA and new cement paste; old ITZ between old natural aggregate and old adhered mortar [6], which causes negative effects on performance of RAC [8]. Which is why, numerous studies have been conducted to evaluate and improve the mechanical and durability properties of RAC. In order to enhance the properties of RAC, several techniques have been developed [9]. Recently, using pretreating method for RCA such as surface modification treatment of RCA with pozzolanic admixtures is one of the solutions for improving the quality of RAC, saving consumption of energy and being environmentally friendly [10]. Pozzolanic admixtures such as fly ash (FA), silica fume (SF), metakaolin (MK), and blast furnace slag (GGBS) can enhance microstructure of RAC for two reasons: pozzolanic admixtures operate as a micro filler, filling in pores and cracks of RCA; pozzolanic materials will consume CH crystals in RAC to form C-S-H gel ($CaO.SiO_2.H_2O$) to fill up voids of RCA [11]. Nevertheless, the existing methods have improved mechanical properties of RAC in a certain extent. Therefore, in this paper, we proposed three kinds of solution (1- solution type G including pozzolanic powder, alkali solution, and sodium silicate; 2- solution type S including pozzolanic powder and sodium silicate; 3- sodium silicate (SS)) for pre-treating RCA in order to improve the properties of RCA with the purpose of creating twofold efficiency in reducing maximally the amount of CH crystal in RAC. Sodium silicate will consume the amount of portlandite (CH crystal) in RCA to form C-S-H gel according to reaction (1). As a result, the properties of RCA have been enhanced such as decreased permeability and increased hardness [12].

$$Na_2SiO_3+H_2O+Ca(OH)_2 \rightarrow x(CaO.SiO_2)H_2O+Na_2O \quad (1)$$

Furthermore, pozzolanic powders contain a high content of Silicon (Si) and Aluminun (Al) which reacts with an alkaline solution and sodium silicate to generate a gel [13]. This gel can fill up pores, defects, and cracks in the attached mortar of RCA to make ITZ much denser. However, there is still limited studies to confirm the efficiency of combination between pozzolanic materials and sodium silicate in enhancing the performance of RAC. Therefore, the aim of this study is to propose new treatment solutions to improve mechanical properties of RAC.

2. PRETREATING RCA METHODOLOGY

Three kinds of treatment solutions (namely solution type G, solution type S, sodium silicate (SS)) were proposed to improve the quality of RCA, compared with natural aggregate concrete (NAC) and untreated RAC, and the detail components of treatment solutions are composed of sodium silicate or alkaline activator (sodium silicate and sodium hydroxide (NaOH)) and one of pozzolanic material, as specified in Table 1 and Table 2. Different treatment solutions were prepared with various concentrations (10%, 20%, and 30%). Solution type G, which is a combination of pozzolanic powder, sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH), was designed with the proportion in Eq. (2) and Eq. (3) as follows:

$$\frac{\text{Sodium silicate } (Na_2SiO_3)}{\text{Sodium Hydroxide (NaOH)}} = 1.5 \quad (2)$$

$$\frac{\text{Alkali activator } (Na_2SiO_3\text{+NaOH})}{\text{Pozzolanic Powder}} = 0.6 \quad (3)$$

Different solutions type G were prepared with three concentrations (see Table 1) including GFA (Fly ash + Na_2SiO_3 + NaOH), GSF (Silica fume + Na_2SiO_3 + NaOH), and GMK (Metakaolin + Na_2SiO_3 + NaOH).

Table 1 Components of treatment solution type G for 1000g

Solution concentration (%)	NaOH	Na_2SiO_3	Pozzolanic	Water
10	15	22.5	62.5	900
20	30	45	125	800
30	45	67.5	187.5	700

Solution type S, which was combination of pozzolanic powder and sodium silicate (Na_2SiO_3), was designed with the ratio in Eq. (4) as follow:

$$\frac{\text{Sodium silicate } (Na_2SiO_3)}{\text{Pozzolanic Powder}} = 0.6 \quad (4)$$

The ratios of treatment solutions were designed at Eq. (2), Eq. (3), and Eq. (4) based on proportion ratio of geopolymer binder as shown in the previous study [14]. Various solutions type S were prepared with three concentrations (see Table 2) including SFA (Fly ash + Na_2SiO_3), SSF (Silica fume + Na_2SiO_3), and SMK (Metakaolin + Na_2SiO_3).

Table 2 Components of treatment solution type S for 1000g

Solution concentration (%)	Na_2SiO_3	Pozzolanic	Water
10	37.5	63	900
20	75	125	800
30	112.5	188	700

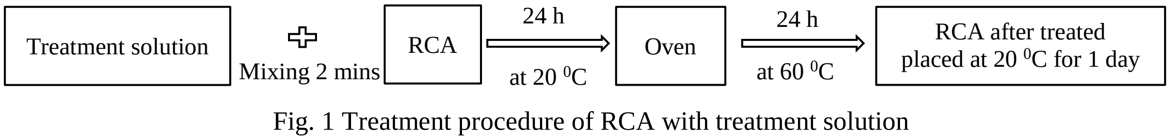

Fig. 1 Treatment procedure of RCA with treatment solution

The third treatment solution was sodium silicate (SS) with 10, 20, and 30% concentration. After preparing treatment solutions and RCA at dry condition, firstly, RCA was soaked in treatment solution under environmental condition in laboratory at around 20 ^{0}C for 24 h in order to form a thin film layer of pozzolanic particles and sodium silicate on the surface of RCA to consume CH product and make a denser structure for RCA by filled up into pores and cracks of RCA. Secondly, all samples of RCA were dried in an oven at a temperature of 60 ^{0}C for 24 h, followed by air-drying process at about 20 ^{0}C for one day as illustrated in Fig. 1. After the treatment process, water absorption coefficient was evaluated based on ASTM C127-07 standard [15].

3. EXPERIMENTAL PROGRAM

3.1 Materials

Cement

Portland cement ASTM type I was supplied by Hitachi Company. The density of the cement was 3.15 g/cm^3 and its chemical composition was shown in Table 3.

Aggregate

Natural coarse aggregate (NA) was obtained in the quarry (Tokyo Sekkai Kougyo Limited). RCA derived from CDW of old concrete structures was provided by a local aggregate manufacturer in Miyagi Prefecture, Japan. The chemical components of aggregates were detailed in Table 3. The coarse aggregate gradations for both natural aggregate (NA) and RCA according to ASTM C33/C33M-13 [16] had 12.5 mm as nominal aggregate size.

Fine aggregate, which was crushed from natural stone, had gradation distribution following ASTM C33/C33M -13 [16]. The fineness modulus of fine aggregate was 2.5. The relative density and absorption of aggregate were determined by ASTM C127-07 [15] for coarse aggregate and ASTM C128-97 [17] for fine aggregate. Weight and moisture content of aggregate were measured according to ASTM C29/C 29M-07 [18] and ASTM C566-13 [19], respectively, and the results were indicated in Table 4 and Table 5a, b, c.

Table 3 Chemical compositions of materials for concrete mixes (%)

Materials	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
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
Silica fume	1.13	1.11	3.04	94.05	0.92	0.31	0.01	0.11	1.61
Metakaolin	0.81	0.03	54.77	49.71	0.01	0.06	1.48	-	0.34
Fly ash	1.16	1.44	24.9	58.8	1.34	5.51	1.18	0.05	5.35

Note: The chemical compositions of materials for concrete mixtures were measured by Epsilon 5 X-ray fluorescence (XRF) spectrometer – PANalytical.

Table 4 Properties of fine aggregate

Aggregate Properties	Fine aggregate
Relative density SSD	2.40
Apparent relative density	2.48
Relative density oven-dry basis	2.35
Water absorption (%)	2.21
Unit weight (bulk density) (kg/m^3)	1454.44
Moisture content (%)	0.91

Pozzolanic material and sodium silicate

Pozzolanic materials used; including Class F fly ash containing less than 7% CaO, silica fume, and metakaolin; are commercially available in Japan and its chemical properties were shown in Table 3. Sodium silicate solution is a kind of soluble polymer material in water. This study used sodium silicate liquid JIS3 of Sangokeisan Soda manufacture. SiO_2/Na_2O molar ratio of sodium silicate is 3 with 30% SiO_2. The density of sodium silicate is 1.40 (kg/l).

Table 5a Properties of natural coarse aggregate and treated recycled concrete aggregate

Properties	10SS	20SS	30SS	10GFA	20GFA	30GFA	10SSF	20SSF
Relative density SSD	2.42	2.44	2.42	2.44	2.42	2.40	2.40	2.37
Apparent relative density	2.63	2.63	2.60	2.62	2.62	2.62	2.63	2.62
Relative density oven-dry basis	2.29	2.32	2.31	2.33	2.29	2.26	2.27	2.22
Water absorption (%)	5.61	5.06	4.78	4.86	5.42	6.01	6.14	6.95

Table 5b Properties of natural aggregate and treated recycled concrete aggregate

Properties	NA	RCA	30SSF	10GMK	20GMK	30GMK	10SMK	10SFA
Relative density SSD	2.83	2.36	2.37	2.42	2.41	2.38	2.39	2.40
Apparent relative density	2.91	2.62	2.62	2.62	2.63	2.63	2.64	2.64
Relative density oven-dry basis	2.79	2.20	2.22	2.29	2.28	2.23	2.24	2.26
Water absorption (%)	1.52	7.24	6.95	5.47	5.91	6.97	6.80	6.38

Table 5c Properties of natural aggregate and treated recycled concrete aggregate

Properties	30SMK	20SMK	20SFA	30SFA	10GSF	20GSF	30GSF
Relative density SSD	2.39	2.40	2.40	2.36	2.38	2.36	2.37
Apparent relative density	2.61	2.62	2.63	2.58	2.63	2.59	2.61
Relative density oven-dry basis	2.25	2.26	2.25	2.22	2.23	2.21	2.23
Water absorption (%)	6.07	6.13	6.36	6.31	6.91	6.67	6.59

3.2 Mixture Proportion

ACI 211 method [20] was used to design mixture proportion for both NAC and RAC with the water/ cement ratio of 0.45. The mix proportions of concretes were presented in Table 6.

Table 6: Mix proportion of concrete (kg/m^3)

Sample	Water	Cement	Coarse NA	Coarse RCA	Fine aggregate
NAC	208.1	428.9	1021.6	0	627.2
RAC	246.9	428.9	0	811.9	670.7
10GMK	236.1	428.9	0	804.9	670.7
20GMK	235.1	428.9	0	805.9	670.7
30GMK	231.5	428.9	0	809.5	670.7
10GFA	243.6	428.9	0	807.8	670.7
20GFA	242.9	428.9	0	808.5	670.7
30GFA	230.6	428.9	0	820.8	670.7
10GSF	228.9	428.9	0	822.5	670.7
20GSF	205.9	428.9	0	845.5	670.7
30GSF	219.1	428.9	0	832.4	670.7
10SS	240.1	428.9	0	811.3	670.7
20SS	241.5	428.9	0	809.9	670.7
30SS	239.4	428.9	0	811.9	670.7
10SFA	236.8	428.9	0	806.5	670.7
20SFA	228.2	428.9	0	823.2	670.7
30SFA	222.4	428.9	0	821.0	670.7
10SSF	234.2	428.9	0	806.8	670.7
20SSF	236.8	428.9	0	804.1	670.7
30SSF	235.3	428.9	0	805.7	670.7
10SMK	217.7	428.9	0	823.3	670.7
20SMK	232.6	428.9	0	808.4	670.7
30SMK	232.5	428.9	0	808.5	670.7

3.3 Mixing Procedure

Recent researches have considered concrete mixing procedure as a key technique in improving the quality of RAC [21],[22]. Accordingly, this study proposed a new mixing procedure for RAC with the purpose of expecting that process can help to fill up cement paste into pores and cracks, as resulting in a denser concrete structure, and higher strength compared to traditional mixing procedure as given in Fig. 2. The amount of water for concrete was divided into two parts and poured into mixer at two different times separately during concrete mixing procedure.

3.4 Specimen Preparation

All specimens were cast into plastic cylindrical molds. The cylinders were stored one day at 20 ^{0}C. The day after casting, the specimens were removed from the molds and cured in the water at about 20^{o}C according to ASTM C192/C192M-06 [23].

3.5 Test Methods

The compressive strength of concrete was measured by Shimadzu machine with 1000 kN axial load capacity at a rate of axial loading constant of 0.25 MPa/s according to ASTM C39/C39M-14 [24]. The compressive strength was determined at the age of 7 and 28 days. The water absorption coefficient was measured following ASTM C127-07 [15]. The elastic modulus and axial strains were measured by using strain gages following ASTM C469-02 [25]. The splitting tensile strength test was carried out at the loading rate of 0.7-1.4 MPa/min in accordance with ASTM C 496/C496M-04 [26].

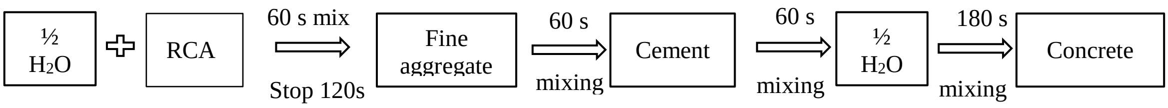

Fig. 2 Mixing procedure of RAC

4. RESULTS AND DISCUSSION

4.1 Water Absorption Coefficient

After finishing treatment process, RCA was evaluated by water absorption coefficient following ASTM C127-07 method for its conveniences [27] as the results in the Fig. 3. Generally, the results have shown the significant reduction in water absorption coefficient of treated RCA with treatment solutions type S, G, and SS in comparison with untreated RCA. The reduction of water absorption of RCA depended on the type of solutions and concentrations. The water absorption coefficient decreased with the increase of concentration in specimens treated by SS, SFA, GSF, SMK while the opposite results were found in GFA, SSF, GMK. Besides, sodium silicate (SS) had more effective results than solution type S and G in decreasing the water absorption coefficient of RCA. The water absorption coefficient of RCA treated with sodium silicate (SS) at 30% concentration dropped to about 34%, whereas this figure at 10% concentration was 22.46% which is in line with the results in the previous research [28]. These results can be explained that when RCA soaked into the treatment solutions, the pozzolanic particles and sodium silicate might be diffused into pores and cracks of RCA, and at high temperature (60 ^{0}C) the reaction between alkali activator and pozzolanic effectively happened to create a thin layer and seal the surface of RCA particles, which leaded to decrease the penetration of water into RCA. However, in the case of RCA treated with solution type S and G, a pozzolanic layer was formed on the surface of RCA particles. This pozzolanic layer may keep water on the surface aggregate particles when the RCA was immersed in water for making aggregate with the saturated surface-dry condition in the process of determining water absorption coefficient, which caused the water absorption capacity of RCA treated with solutions type S and G were higher than that of SS.

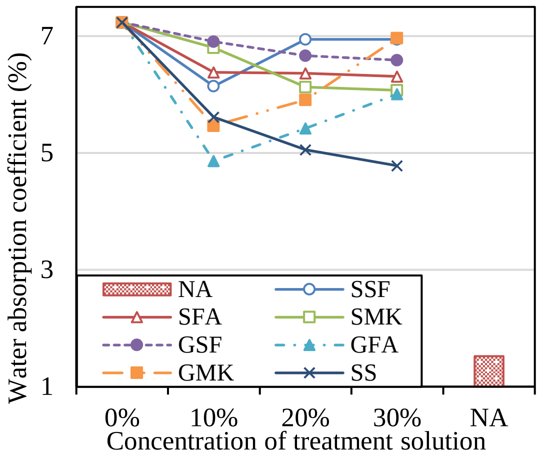

Fig. 3 Water absorption coefficients of treated RCA, untreated RCA (at 0% treatment solution) comparing to NA

4.2 Compressive Strength

The compressive strength of concretes was illustrated in Fig. 4 at the 7 days and Fig. 5 at 28 days of age. At 7 days, the compressive strength of RAC treated with three kinds of treatment solutions increased significantly in comparison with untreated RAC, excepted samples treated with 30GSF and 20GFA. An interesting result can be observed in Fig. 4, At the early age, with the support of treatment solution type S, the compressive strength of RAC strongly soared up about 23-50% compared to untreated RAC, and it was around 1.7-6.9% higher than that of NAC. This observation indicated that the combination between solution type S and pozzolanic materials promoted the increase of the compressive strength of RAC at the early age more effectively than other methods [29].

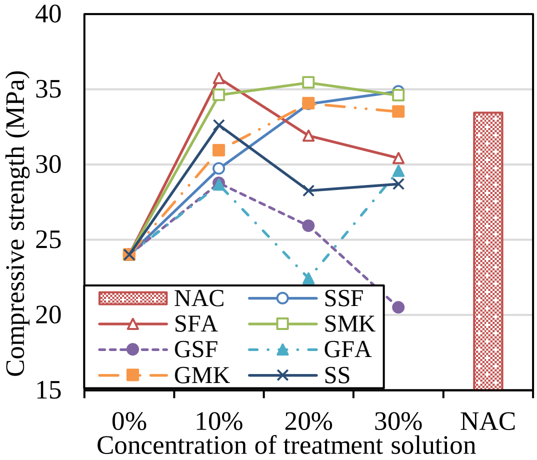

Fig. 4 Compressive strength of concrete at 7 days

At 28 days (see Fig. 5), it was found that RAC treated with the solution type S had more effective than the solution type G and sodium silicate at various concentrations in improving the compressive strength of RAC. It might be due to treatment solution type G contained a certain amount of sodium hydroxide as the alkaline activator for pozzolanic and sodium silicate, the amount of sodium hydroxide incompletely reacted with sodium silicate and pozzolanic powder, which caused a negative effect on the mechanical properties of the new concrete [30]. The compressive strength of RAC treated with SSF, SMK, and SFA enhanced about 28-36%, 13-29%, and 23-28% compared to that of untreated RAC, respectively, which is significantly higher than other observations in [10],[31]. It can be seen that the concentration of treatment solution considerably affected the compressive strength of RAC. Furthermore, using solution type S (SSF, SMK) at more than 20% concentration, the compressive strength of RAC had a decreasing trend. With treatment solution type G (GSF, GFA, GMK) and sodium silicate (SS), when the concentration of treatment solution was more than 10%, the effect of treatment solutions on improving the compressive strength of RAC was insignificant. It indicated that when RCA was treated with treatment solutions at a high concentration, the redundancy of sodium silicate, sodium hydroxide, and pozzolanic materials caused the reduction of the compressive strength of RAC. In addition, the results revealed that RAC treated with 20SSF had the highest value in compressive strength of concretes in comparison with other specimens and was comparable with that of NAC. Therefore, the combination between sodium silicate and silica fume created a good treatment solution for RCA which was higher than the existing method [29]. It could be explained that silica fume contained the high percentage of amorphous silica which was useful for the development of concrete strength [32] and silica fume in concrete gave the higher strength compared to that of fly ash [33].

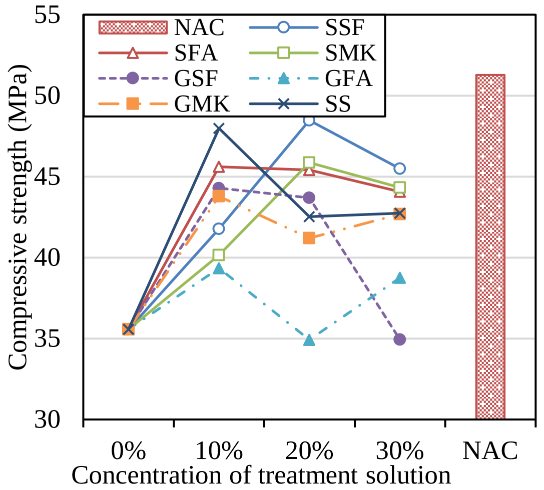

Fig. 5 Compressive strength of concrete at 28 days

4.3 Modulus of Elasticity

Fig. 6 indicated the elastic modulus of treated RAC compared to untreated RAC and NAC. As depicted in Fig. 6, it can be observed that the elastic modulus of RAC after treated with the proposed treatment solutions considerably increased. To specify, RCA treated with solutions such as 20SSF, 10SFA, 20SMK, the elastic modulus of RAC was enhanced about 39.8% compared to untreated RAC. Obviously, this result partly explained the important role of the treatment solutions on pre-treating RCA in increasing performance of RAC. The elastic modulus of RAC treated with the solution type S was higher than that of RAC treated with the solution type G and sodium silicate (SS). The solution type S improved 21.9 - 39.8% the elastic modulus of RAC, whereas solution type G and sodium silicate (SS) only enhanced 4.7-35.6% and 19.1- 31.4%, respectively. The improvement of the elastic modulus of RAC treated with treatment solution type S (SSF, SMK) was decreased with the increase of more than 20% concentration, whereas using more than 10% concentration of treatment solution type G and sodium silicate (SS), the elastic modulus of RAC was decreased. Although this improvement of elastic modulus of RAC was significant, the modulus of elasticity of RAC treated could not surpass that of NAC even when the compressive strength of treated RAC was higher or comparable to that of NAC, which agreed with the previous report [34].

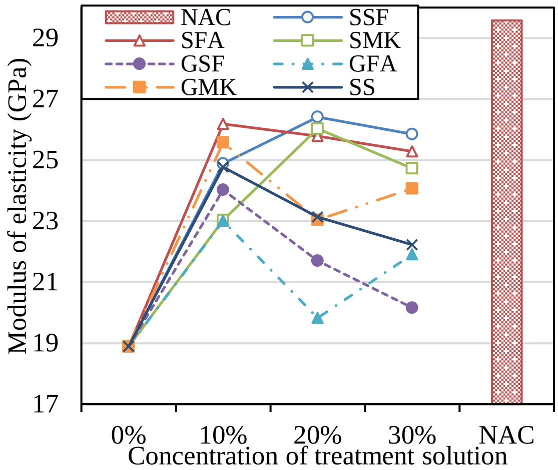

Fig. 6 Modulus of elasticity of concrete mixtures

4.4 Splitting Tensile Strength

The splitting tensile strength of RAC was shown in Fig. 7. A clear result can be seen that the treatment solution type S including SSF, SFA, and SMK improved significantly splitting tensile strength of RAC containing 100% coarse RCA about 9.7-29.7% with the highest value at 20% concentration of SMK.

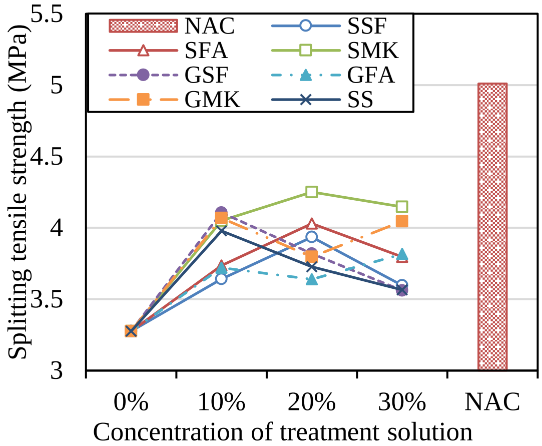

Fig. 7 Splitting tensile strength of concrete mixtures

The effectiveness of solution type S in enhancing the splitting tensile strength of RAC was higher than that of solution type G and sodium silicate (SS) because the splitting tensile strength of RAC treated solution type G and SS only increased about 8.6-25.3% and 8.8-21.4%, respectively. Although the compressive strength of several samples treated with the proposed solutions was comparable that of NAC, the splitting tensile strength of them was still lower than NAC, which consists with results of last research [35]. Moreover, the increase in splitting tensile strength was not as notable as the compressive strength and elastic modulus after affording to improve mechanical properties of RAC, which indicated the compressive strength and the modulus of elasticity of RAC were more affected by treatment solutions than splitting tensile strength.

5. CONCLUSION

As an attempt to improve the quality of RAC by using the proposed treatment solutions with various pozzolanic cementitious materials, the mechanical properties of RAC after treated with the proposed method were investigated in this study. From the experimental results, the important conclusions are summarized as follows:

1) The results indicated an improvement in reducing water absorption of RCA impregnated with the proposed treatment methods.

2) The proposed treatment methods for RCA significantly enhanced the mechanical properties of RAC including compressive strength, elastic modulus, and splitting tensile strength.

3) The combination between pozzolanic and solution type S improved the mechanical properties of RAC more effectively than solution type G and sodium silicate. The treatment solution type S might enhance about 36% the compressive strength, 39.8% the elastic modulus, and 29.7% the splitting tensile strength of RAC.

4) The treatment solution type S significantly improved the compressive strength of RAC at the early age which was comparable with that of NAC.

5) The combination between silica fume and solution S gave the better result than others in increasing the compressive strength of RAC, whereas the combination between solution type S and metakaolin provided the better result in the splitting tensile strength.

6) The concentration of treatment solutions considerably affected the strength of RAC.

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