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Influence of Surface Treatment of Recycled Aggregates on Mechanical Properties and Bond Strength of Self-Compacting Concrete

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Abstract: In the last decade there has been a massive growth for development of concrete infrastructures all around the world. Take into account environmental concerns, concrete technology should direct efforts toward assuring development and fabrication of sustainable and resilient concrete. For this purpose, incorporation of recycled concrete aggregate in concrete products particularly self-compacting concrete (SCC) for structural and non-structural application would be significant achievement. In this study the fresh and hardened properties of SCC prepared by substituting natural aggregates (NA) with recycled coarse aggregates (RCA). In addition, bonding behaviour of reinforced RCA-SCC for structural application was investigated. Moreover, surface treatment of RCA using lithium silicate solution was proposed to investigate its feasibility to improve the fresh and hardened properties of SCC as well as its bonding strength. The mechanical properties including compressive strength, tensile strength and elastic modulus of SCC mixes using untreated RCA and treated RCA (TRCA) were investigated. The results showed an improvement in performance of SCC mixes made with TRCA in compare with the untreated samples. The bond behaviour between SCC made with RCA and steel reinforcement was studied and the relationship between the brittleness and bonding of SCC mixes using untreated RCA and TRCA determined. The effect of surface treatment on the interfacial transition zone (ITZ) between adhered mortar and RCA studied using scanning electron microscope (SEM). It was determined that the treatment of RCA improved the bond at the ITZ through densification. The results gave experimental evidence of the suitability of RCA-SCC for structural use and application in reinforced concrete.

Keywords: recycled aggregates; self-compacting concrete; sustainability; structural application; surface treatment

1. Introduction

Concrete is the most extensively used material in construction industry all around the world and the demand for construction increases as the population grows. Thus, the consumption of natural resources that are used as building material in concrete structure is increasing to meet this demand. As a result, it has a significant negative effect on the environment and limits the available natural resources. More importantly, the large amounts of waste concrete arising from old demolished concrete structures brings significant environmental problems for their removal or disposal. These corresponding impacts emphasizes the necessity to develop an effective environmentally sustainable resources and establish the fundamental concept for the utilization of recycled coarse aggregates (RCA) in the construction industry [1]. Recently, studies on utilization of RCA for structural application as well as pavement strengthening systems have been carried [2–4]. Certainly, RCA can provide the concrete industry with the noticeable reduction of carbon footprint left by the rapid growth of construction [5].

On the other hand, self-compacting concrete (SCC) recently has received enormous attention and is now widely used in the building industry because of its fresh-state and rheological properties [6]. SCC provides an easy settlement into formwork without vibration that subsequently decreases the costs and energy associated with the casting process [7–9]. Such properties are associated with the mix design, high content of fine aggregates and incorporation of chemical admixtures [10,11]. Therefore, the use of RCA in SCC can trigger the development of a new green high-performance concrete by offering the benefits of using construction waste in the self-consolidating concrete without vibration. Previous studies on RCA-SCC have been carried out and the effect of RCA on fresh and hardened properties of SCC have been characterized [7,8,12–17].

In general, RCA has a higher tendency of water absorption than natural aggregates (NA) because of the existing attached old cement mortar. This attribute would result in reduction in workability, strength and durability of RCA which consequently restricts RCA application in SCC [18]. The effect of RCA incorporation on the mechanical and hardened properties of SCC depends on different parameters such as mix proportion and RCA replacement percentage, RCA sources, crushing method, size and quality of RCA and supplementary materials. Revathi, Selvi [19] reported that the compressive strength of SCC containing RCA with the replacement percentage of 50% and 100% decreased by 4.1% and 16.3%, respectively. Etxeberria, Mari [20] observed that the compressive strength decreased by 20–25% for full replacement of coarse RCA, while no significant change observed for 25% of RCA replacement. In addition, it was reported that the tensile strength declined by incorporation of RCA with value of 16.8 to 58.5% by the increasing of replacement percentage from 25 to 100%, respectively [21]. Poon, Kou [22] demonstrated a decrease in tensile strengths with increasing recycled fine aggregated (RFA) replacement percentage. In the research conducted by Carro-López, González-Fonteboa [23], the reduction in the compressive strength of SCC containing RFA ranged from 8 to 47% with the replacement of 20 to 100%, respectively. Finding a suitable solution to overcome the undesired properties resulted from utilization of RCA in concrete is crucial. Several works have been carried out to improve RCA quality by removal the adhered mortar or stretching adhered mortar [3,24–26]. In the first approach RCA are usually pre-soaked in various kind of acids like HCl, H_2SO_4 or H_3PO_4 to remove the old adhered mortar. However, the use of acidic solvent which is toxic leads in the formation of disposal wastes [27]. In the second approach a surface modification like coating is carried out to improve the RCA quality without removing the adhered cement mortar [28]. In this context, coating materials such as microbial carbonate precipitation [29], silane-based water repellent [30], Polyvinyl Alcohol [31], alkaline organosilicon modifier [18], silicate-based solution [28], pozzolanic materials [32] and carbonation [33] have been used with varying degrees of success in improving the performance of RCA. Although, the mentioned methods might improve the RCA properties, they still have negative impacts on environment which limits their application.

Recently, more attention has been given to the influence of pozzolanic additives, which are recognized as effective admixtures to avoid alkali-silica reactivity phenomena. In a pozzolanic reaction, $Ca(OH)_2$ is consumed and hydrated calcium silicates with a low C/S ratio is formed [34]. Katz [35] proposed the impregnation of RCA with a silica fume solution to strengthen the structure of the RCA particularly the interfacial transition zone (ITZ) between the RCA and the cement paste. Spaeth and Djerbi Tegguer [28] observed that surface coating treatment using silicon-based polymer remarkably decreased the water absorption of RCA aggregates. Ismail and Ramli [36] impregnated RCA in calcium metasilicate solution which resulted in the enhancement of the properties of RCA. They reported the reduction in the static modulus of elasticity of the concrete containing 60% of RCA after two-stage treatment, including acid treatment and surface modification using calcium metasilicate, was only approximately 4% compared with that of the control concrete. Katz [35] observed an increase of 15% in the compressive strength at 28-day age after the silica fume treatment of RCA. Ismail and Ramli [37] investigated the combined treatment in two stages of acid treatment and calcium silicate impregnation and increased the compressive strength of concrete. Bui et al, [27] proposed using sodium silicate and silica fume to treat RCA and improved its mechanical properties. They observed improvement in compressive strength of concrete up to 50%, splitting tensile strength of 41%, and elastic modulus 42.5% in comparison with untreated RCAs. Kazemian, Rooholamini [38] reported that the 28 days compressive strength of concrete with 50% substitution of NA with RCA increased 12.5% after acid treatment along with surface modification with calcium metasilicate slurry. In general, coating of RCA with different pozzolanic additives aims to fill the weak areas and develop stronger ITZs between RCA and cement paste. However, surface modification of RCA with sodium silicate solutions increases risk of alkalis-aggregate reaction which may sacrifice the durability of concrete [39]. Up to now, little attention has been devoted to surface modification of RCA using weaker base solution such as lithium silicate. Lithium silicate solution is a commercial and relatively inexpensive product which is often employed as concrete sealers and densifiers. In comparison with sodium densifier, the lower concentration of lithium densifiers is required to achieve the same effect. In addition, the potential of the formation of efflorescence by lithium silicate is lower in comparison with sodium silicate. It has been shown that use of lithium technologies controls the expansion due to alkali-silica reaction [1,40]. The silicate solution penetrates the aggregates and reacts with calcium hydroxide (C-H). This reaction leads to form calcium silicate hydrates (C-S-H), which provides strength in hardened cement paste. In addition, it results in lower porous microstructure and greater durability [41]. Lithium ions typically do not react in concrete which is a beneficial implication. Therefore, the aim of this study is to propose an environmentally friendly treatment method for improving properties of RCA using lithium silicate for the first time.

Besides the mechanical strength and fracture toughness of concrete, the characteristics of the RCA affect the bond behaviour [42–45]. The bond behaviour between concrete and steel bars is an important index to inform their collaborative effectiveness. Many scholars extensively investigated the bond behaviour between conventional concrete made with NA and steel reinforcement, but only a few studied the bond between concrete using RCA and steel bars [44,46]. Several parameters such as embedment length, bar diameter and concrete strength affecting the bond performance have been reported [47]. However, the influence of using RCA and surface treatment has not been fully established.

To evaluate the effect of the proposed treatment solution in this study, the mechanical properties of RCA-SCC, including compressive strength, splitting tensile strength and elastic modulus, were examined. The objective of this study was to investigate the effects of the RCA replacement level and surface treatment using lithium silicate on the bond behaviour of reinforced SCC samples. The last but not least, the microstructure study on the ITZ of the designed RCA-SCC mixes were investigated to evaluate the effect of the treatment method in this study.

2. Experimental Details

2.1. Materials and Sample Preparation

In this study, Type II Portland cement from Boral Cements Blue Circle® in accordance with AS 3972 was used. Sikament NN was used as superplasticizer in all mixes to varying degrees to achieve SCC requirements. Fly ash was used as a cementitious replacement in accordance with AS3582.1 for all mixes. The NA used in this study was crushed gravel and both recycled coarse aggregate (RCA) and recycled fine aggregate (RFA) were supplied by Concrush Company, Newcastle, Australia. NA and RCA supplied were graded to 10 mm. According to Table 1, a reference concrete (NAC) and six mixes contain RCA, treated RCA (TRCA) and RFA were prepared. In addition, the ratio of water to cementitious material (cement and fly ash) was 0.36. In order to investigate the effect of RCA replacement percentage, NA replaced with 50% and 100% (by weight) of RCA. RCA50 and RCA100 referred to the mix samples with 50% and 100% replacement, respectively. TRCA50 and TRCA100 mixes referred to the mix samples using TRCA with 50% and 100% replacement, respectively. Furthermore, RCA100-RFA100 is associated to the mix sample with 100% replacement of NA with RCA and 100% replacement of fine NA (FNA) with RFA. While TRCA100-RFA100 represents the sample with 100% replacement of NA with TRCA and 100% replacement of FNA with RFA.

Table 1. The details of mix proportions of concrete samples.

Mix Code	Cement (kg/m^3)	Fly Ash (kg/m^3)	Coarse Natural Aggregate (NA) (kg/m^3)	Fine Natural Aggregate (FNA) (kg/m^3)	Water (kg/m^3)	Recycled Fine Aggregate (RFA) (kg/m^3)	Recycled Coarse Aggregate (RCA) (kg/m^3)	Super-Plasticizer (mL)
NAC	320	220	870	645	195	0	0	120
RCA50	320	220	435	645	195	0	435	120
RCA100	320	220	0	645	195	0	870	140
TRCA50	320	220	435	645	195	0	435	200
TRCA100	320	220	0	645	195	0	870	200
RCA100-RFA100	320	220	0	0	195	645	870	300
TRCA100-RFA100	320	220	0	0	195	645	870	300

2.2. Treatment Procedure for RCA

Lithium silicate solution with concentration of 8.8% of solids purchased from Concrete Colour Solution, Australia was used as the coating solution. In order to treat the surface of aggregates, RCAs were submerged in lithium silicate solution and cured for 24 h at room temperature (25 °C). Then, the aggregates were air-dried until no moisture was present on the surface of RCA. Figure 1 illustrates the treatment process. Figure 2 shows the immersed RCA in the lithium silicate solution and the water resistance behaviour of TRCA.

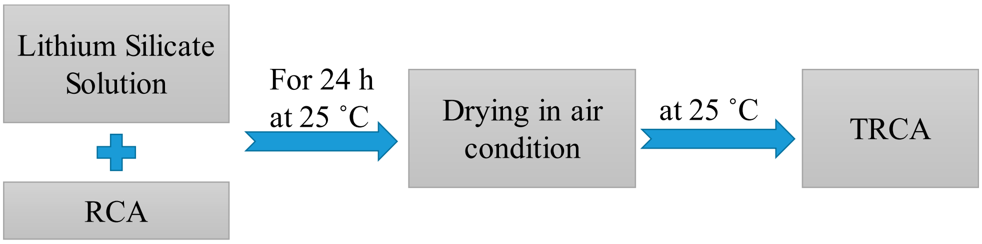


Figure 1. Treatment process for RCA with lithium silicate solution to prepare treated RCA (TRCA).

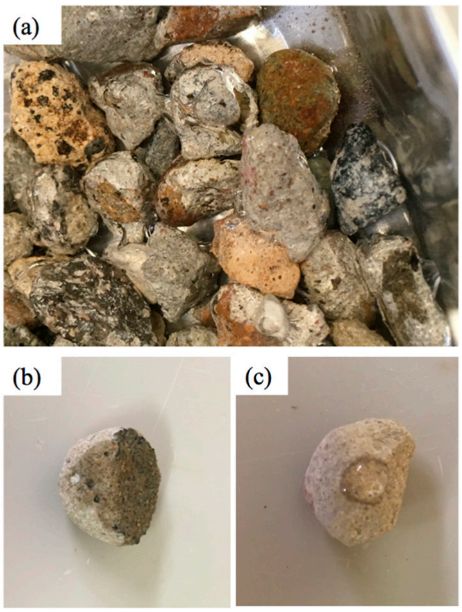


Figure 2. (**a**) Immersed RCA in the lithium silicate solution; (**b**) water absorbed in an individual untreated RCA; (**c**) water-resisting on a TRCA.

2.3. Physical and Mechanical Tests

The particle distributions of the aggregates were evaluated in accordance with AS 1141.11.1 [48]. In addition, the three different types of coarse aggregate including NA, RCA and TRCA were subjected to water absorption testing in accordance with AS1141.6.2.

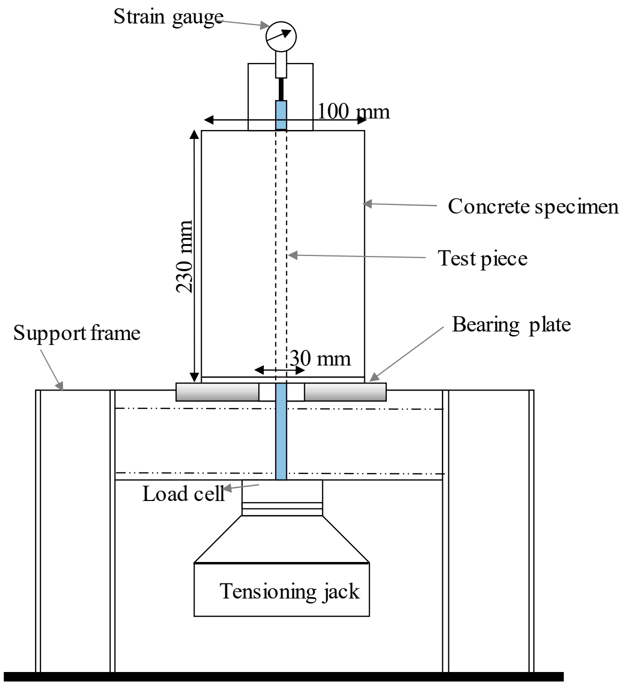
Workability of the SCC was determined using the slump flow test. The slump flow was conducted to evaluate the fresh properties of SCC. In this regard, the slump cone is filled with mixes and then lifted vertically to measure time for the mix to reach 500 mm diameter (T500 time) and the final mean diameter. The slump flow diameter required to be in the range of 550 to 900 mm for SCC mixes in accordance with EFNARC 2005 [49]. The viscosity of the SCC can be evaluated by T500 slump flow time. The classifications of slump flow and viscosity as well as target limits with respect to EFNARC are presented in Table 2.

Table 2. Classification of slump flow and viscosity according EFNARC 2005.

Test	EFNARC 2005 [49]	
	Class	**Target Limits**
Slump Flow Diameter (mm)	SF1	(520–700 ± 80)
	SF2	(640–800 ± 80)
	SF3	(740–900 ± 80)
Viscosity T500 (s)	VS1	≤2
	VS2	>2

The cylindrical specimens with dimension of 100 mm dia. and 200 mm long were cast to determine the compressive of the concrete samples at 7 and 28 days and splitting strengths of concrete samples at 28 days. For each test, three samples were tested and the average, including the error bar, was reported. The compressive strength and splitting strength testing was conducted in accordance with AS 1012.9 (2014) and AS1012.10, respectively. The hardened density of mixes was evaluated in accordance with AS1012.12.1. In addition, three cylindrical specimens with sizes of 100 mm dia. and 200 mm long were used for the elastic modulus as per AS.1012.17. In order to conduct the pull-out test, three prismatic specimens with a dimension of 100 × 100 × 230 mm were fabricated for each mix. The embedded length was five times of the rebar diameter (12 mm) to define the bond stress-slip relationship (Xiao and Falkner, 2007). A bar was fixed through a hole in a steel mould and its unbounded part was encased in a polyvinyl chloride (PVC) tube to avoid additional restraints. All specimens were demoulded and transferred to a standard curing room after 24 h of casting. All specimens were allowed to air dry in the laboratory before testing. The pull-out test was performed in accordance with AS/NZS 4671:2001 as shown in Figure 3. The slip between the unloaded end of the bar and the bottom end of the prism was measured by a strain gauge attached to the end of the rebar.

Moreover, scanning electron microscopy (SEM) analysis was conducted to study the microstructure of ITZ of SCC samples at 28 days. The machine used for microstructure analysis of the mortar specimens was the ZEISS Sigma VP (secondary electron detector). The samples were cut to 70 × 70 × 15 mm prisms, using a masonry table saw. Samples are sufficiently dried in oven at the temperature of 105 °C before testing. The effect of the RCA replacement and its treatment on the microstructure-property of the samples was investigated.



(**a**)

(**b**)

Figure 3. (**a**) Schematic diagram of the pull-out test setup and (**b**) pull-out samples.

3. Results and Discussion

The physical and mechanical properties of SCC were tested in the fresh and hardened state. In addition, the bond behaviour and microstructure of RCA-SCC were investigated.

3.1. Particle Size Distribution

The sieve analysis was conducted to evaluate the particle sizes distribution of NA and RCA and the results for fine and coarse aggregate are displayed in Figure 4. It is found that the coarse aggregate followed a narrow gradation and fairly uniform size distribution with size of 10 mm for NC and RCA. This is because of the used separation equipment and the specification size requirement which define a narrow field of particle sizing. However, larger irregularities in particles were noticed for RCA. As shown in Figure 4, recycled particles were slightly larger than NA particles. In contrast, the fine aggregate size distributions were highly variable. The RFA composed of larger particles due to the passing of fewer particles through each sieve which indicated less stringent specifications of fine particles. This shows the alternate class of fine aggregates which used in this study. The used FNA was quarry sand and the used RFA consisted of crushed aggregate and mortar particles.

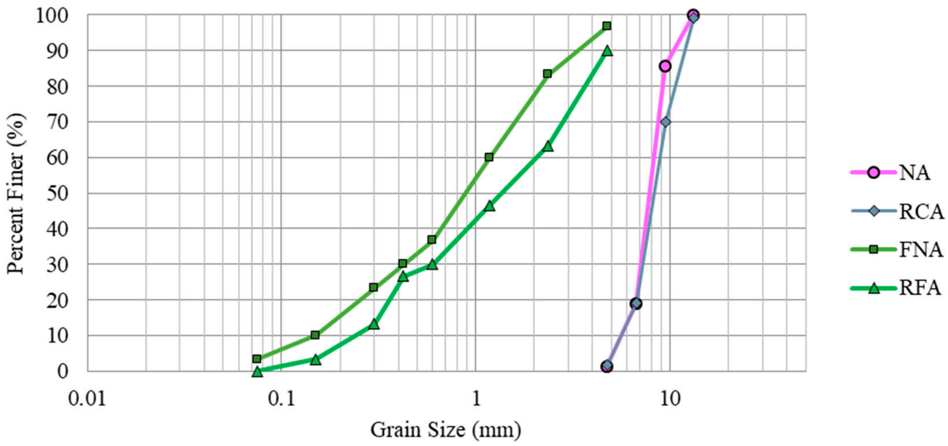


Figure 4. Particle size distribution chart for the used coarse and fine aggregates.

3.2. Water Absorption

The water absorption tests were performed on NA, RCA and TRCA and the results are shown in Figure 5. As can be seen, the water absorption of the RCA is considerably higher than NA. Untreated RCA sample showed 8.1% of water absorption, which is in the range of reported water absorption values in the literature between 5% and 17% [18]. It is attributed mainly to the presence of primary adhered mortar of RCA [28]. However, the results showed that the surface treatment of RCA with lithium silicate solution had a significant influence on the water penetration and decreased the absorption about 50%. In fact, lithium silicate fills the RCA porous network which corresponded to the reduction of water penetration of TRCA. It indicates that the lithium silicate solution treatment provides a suitable coating and enhances the physical performance of RCA. Thus, this treatment was found effective to densify the RCA structure by reacting with the presented mortar in the aggregate. The immersion of RCA into lithium silicate resulting in a hydration reaction between free calcium and lithium silicate and forms C-S-H gel and consequently a decrease in water absorption [50]. More discussion about the effect of surface treatment on microstructure is given in Section 3.7.

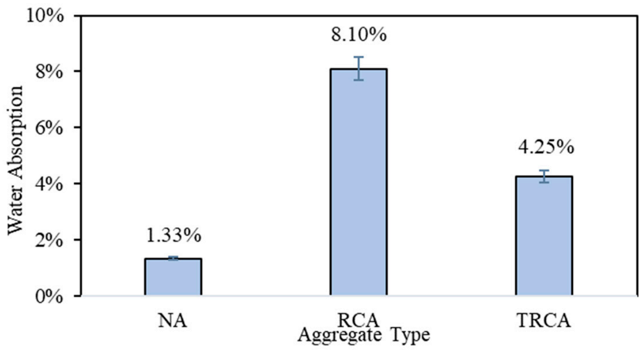


Figure 5. The water absorption results of NA, RCA and TRCA.

3.3. Workability and Density

As indicated in Table 3, the slump flow results for all mixes ranged between 520 and 790 mm which satisfied the suggested range of 520–900 mm, as outlined by the European Guidelines [49]. It should be noted that no segregation and bleeding were observed during the slump flow tests. Accordingly, the reference sample (NAC) was classified as SF2, while RCA50, RCA100, RCA100-RFA100 and TRCA100-RFA100 were classified as SF1 and TRCA50 and TRCA100 were classified as SF3.

Table 3. EFNARC 2005 Fresh properties of SCC mixes (Slump flow and T500 time).

Mix Code	Slump Flow Diameter (mm)	Slump Flow Class [49]	T500 (s)	Viscosity Class [49]
NAC	700	SF2	0.98	VS1
RCA50	570	SF1	1.9	VS1
RCA100	520	SF1	1.2	VS1
TRCA50	790	SF3	1.0	VS1
TRCA100	700	SF3	1.1	VS1
RCA100-RFA100	520	SF1	4.95	VS2
TRCA100-RFA100	570	SF1	2.32	VS2

According to the results, the slump flow of RCA50 is less than reference sample (NAC) in spite of the addition of same amount of superplasticizer in both mixes. This demonstrated that the RCA replacement resulted in a considerable loss of flowability. This is contributed with the porosity of RCA which absorb more water and reduce the flowability. This result is in agreement with other research results [16,17,51]. Similarly, the slump flow diameter of RCA100 decreased to 520 mm in spite of increased amount of superplasticizer. However, it was observed that the treatment of RCA with lithium silicate solution resulted in an increase in slump diameter due to the reduction in water absorption in comparison to untreated RCA-SCC samples. Despite of higher amount of superplasticizer in the sample of RCA100-RFA100, the addition of RFA resulted in a reduction in the slump flow diameter of the fresh concrete compared to TRCA. For the RCA100-RFA100 mix, it took approximately 4.9 s to reach the 520 mm flow slump diameter on the slump flow board. This is the highest T500 time among all the mixes despite of using highest amount of superplasticizer. This is mainly due to the effect of the porous nature of the RFA in the fresh mix.

The average density of each SCC mixes is listed in Table 4. The densities of all mixes are in the range of 2330 to 2095 kg/m^3 and the density of the RCA-SCC samples is less than the reference sample (NAC). Accordingly, there was no significant decrease in overall average density of the RCA-SCC mixes. Moreover, a relationship between total density and slump diameter of SCC mixes is described in Figure 6. It can be seen that the trend of slump diameter and density is similar with the addition of RCA percentage and the RCA treatment.

Table 4. The density of SCC mixes.

Mix Code	Density (kg/m^3)
NAC	2330.16
RCA50	2235.26
RCA100	2262.27
TRCA50	2226.09
TRCA100	2161.99
RCA100-RFA100	2095.99
TRCA100-RFA100	2114.96

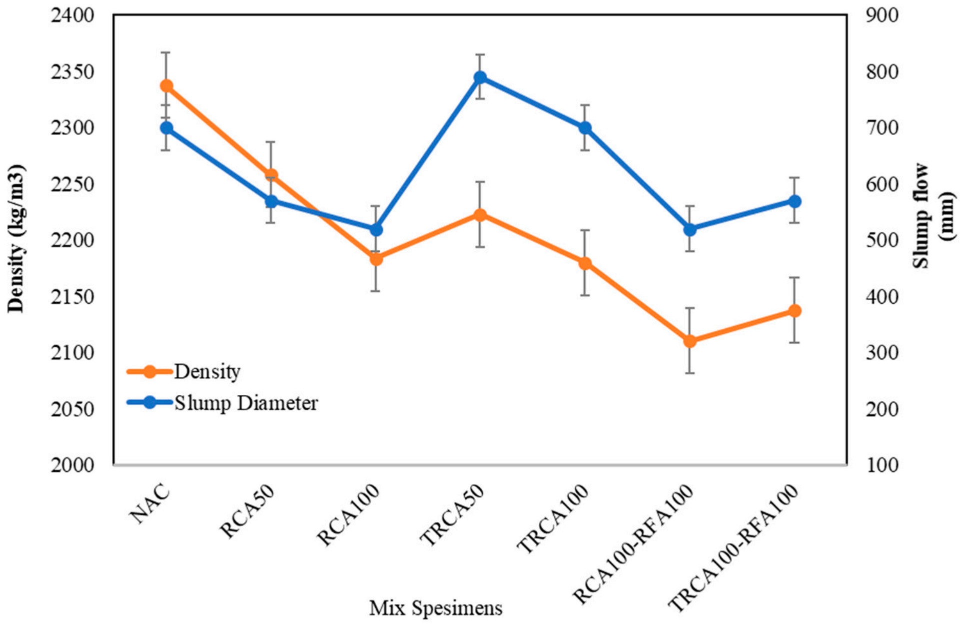


Figure 6. The relationship between the density and slump flow diameter of SCC mixes.

3.4. Compressive Strength

The effect of RCA incorporation on the mechanical and hardened properties of SCC depends on different parameters such as mix proportion and the RCA replacement percentage, size and quality of RCA and supplementary materials. In general, low replacement percentage of RCA (up to 50%) are not significantly influenced the mechanical properties of SCC [52–55]. The strength of SCC is one of the most important factors to determine the application of RCA-SCC. The compressive strength the samples measured at different ages of 7 and 28 days are displayed in Figure 7. The 28-day compressive strength results followed a similar trend to that of the 7-day results. According to the results, by increasing the RCA content the compressive strength decreased at both 7 and 28 days of age.

The compressive strength of RCA50 and RCA100 decreased about 16.4% and 29.2%, respectively, compared to the reference sample (NAC). This is in agreement with other research works that the incorporation of RCA reduced the mechanical properties of concrete [19,20]. However, by using the surface treatment with lithium silicate solution, the 7 days and 28 days compressive strength of TRCA50 and TRCA100 improved by about 18.5% and 15.9%, compared to RCA50 and RCA100 samples, respectively. This attributed to the reduction in the porosity of RCA after treatment. Lithium silicate treatment reduce the water absorption of RCA by filling the RCA surface pores and strengthened the old and new cement pastes to create stronger products. According to Figure 7, the sample containing RFA, RCA100-RFA100 and TRCA100-RFA100, demonstrated the lowest compressive strength of 23.7 MPa and 25.1 MPa respectively. However, the surface treatment showed a minimal improvement at both ages of 7 and 28 days for the TRCA100-RFA100 sample.

3.5. Tensile Strength

Moreover, the results obtained from the 28-day splitting tensile strength revealed a fairly similar trend to the compressive strength as displayed in Figure 8. In a similar manner, there is a tendency for the tensile strengths of samples to reduce slightly with the increment of RCA replacement levels. As shown in Figure 8, the splitting tensile strength of the sample of RCA50 was 3.30 MPa which is lower than 3.90 MPa of the spilling tensile strength of the reference concrete. At the 50% RCA replacement level, the strong bond between the RCA and cement paste played a critical role which diminishes the influence of RCA weakness. It was found a decrease in the splitting tensile strength from 3.30 to 2.83 MPa in the RCA100 sample. In case of RCA100 with higher replacement content, the reason the strengths slightly declined is mainly due to the weakness of RCA. In overall, the influences of RCA were small on the tensile strength. In addition, the tensile results showed an increase to 3.90 and 3.25 MPa for TRCA50 and TRCA100, respectively, by using lithium silicate solution treatment. As illustrated, the splitting tensile strength of TRCA50 was comparable that of NAC. It is important to note that the proposed treatment method improved around 14–18% the splitting tensile strength of RAC when compared to the untreated one. In case of using RFA in mixes, the tensile strength of RCA100-RFA100 is lower than RCA50 and RCA100. The reason is mainly due to the remarkable high porosity of RFA. However, samples with TRCA such as TRCA100-RFA100 showed an improved in tensile strength with a value of 3.71 MPa. This is in agreement with the results of other research groups [21,22].

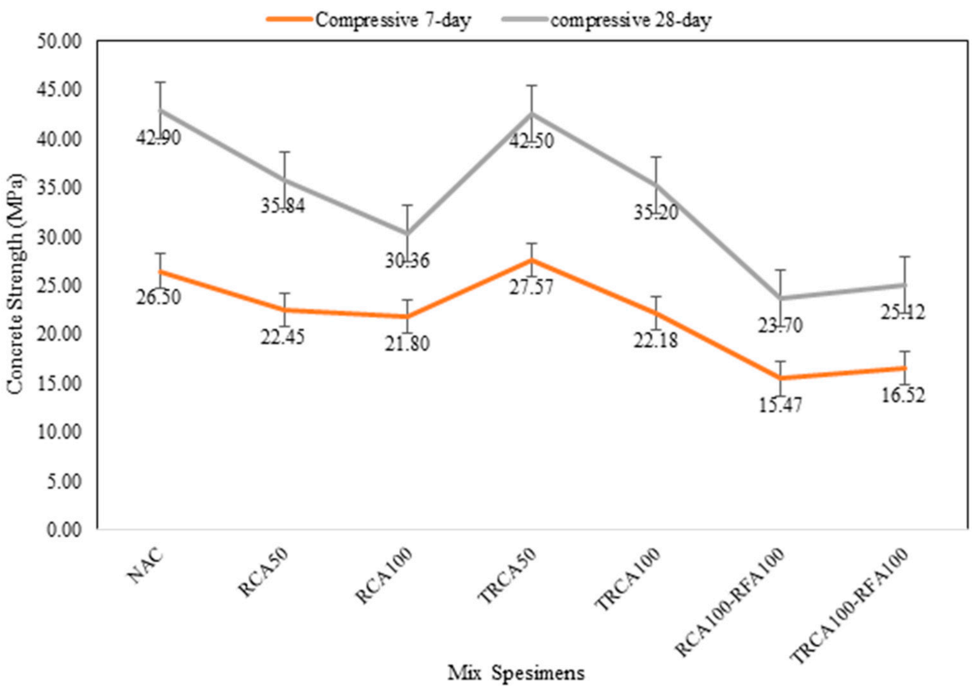


Figure 7. The compressive strength of SCC mixes.

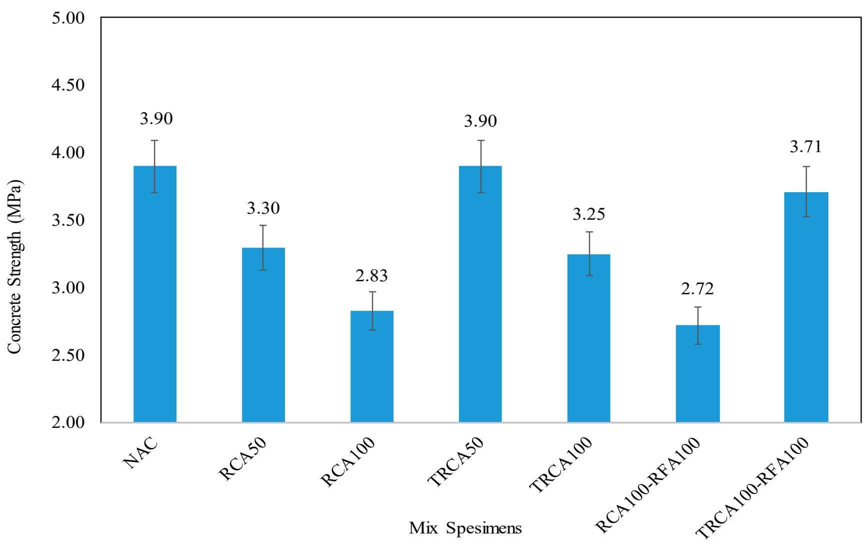


Figure 8. The splitting tensile strength of SCC mixes.

3.6. Elastic Modulus

The results of elastic modulus of all designated SCC mixes are shown in Figure 9. All SCC mixes containing untreated RCA and TRCA exhibited significantly lower elastic modulus than the reference sample mix, NAC. As RCA replacement level increased in the mixes the elastic modulus decreased. This is in agreement with Alengaram, Salam [56] which reported a decrease of 17.7% in modulus of elasticity of RCA-SCC when compared to the control sample. As can be seen there is a reduction of about 10 GPa in elastic modulus of RCA-SCC samples in comparison to NAC. The treatment of RCA using lithium silicate exhibited an increase in the elastic modulus of TRCA50 and TRCA100 samples compared to RCA50 and RCA100. The improvement observed in the elastic modulus of the TRCA50 and TRCA100 can be explained with the presence of good interface bonds between RCA and cement paste which consequently reduce the propagation of cracks during loading [37,57,58]. Furthermore, the incorporation of RFA resulted a significant drop in elastic modulus; however, treatment of RCA using lithium silicate solution showed a significant improvement in elastic modulus of TRCA100-RFA100 sample when compared with RCA100-RFA100.

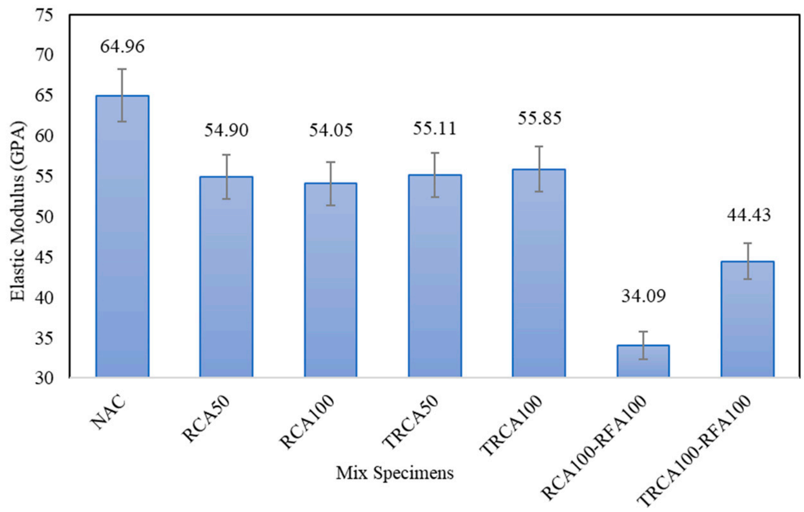


Figure 9. The 28-day elastic modulus results of SCC mixes.

3.7. Pull-Out Test

Bond strength and behaviour is one of the prominent parameters in structural design. Therefore, the effects of different levels of RCA replacement as well as RCA treatment on the bond behaviour were investigated in this study using the pull-out test. It has been shown that the bond strength consists of three forces: (1) adhesive force; (2) frictional force and (3) mechanical interlock between the reinforcing bar and concrete [47,59]. The mechanical interlock of ribbed bars is far greater than frictional and adhesive forces. Although the bond strength mainly relies on the mechanical interlock, the friction and adhesive forces play an important role in bond behaviour. The bond-slip curves of different SCC mixes including NAC, RCA50, RCA 100, TRCA50 and TRCA100 are plotted in Figure 10. Each curve represents the bond behaviour at different phases including micro-slip, internal cracking, pull-out, descending and residual stages [44,46].

From the bond-slip curves, it can be seen that the load-slip relationship is similar in the ascending part for the all mixes. However, the post-peak behaviour was quite different from the reference sample. The ascending part of curve consists of micro-slip (phase I) and internal cracking (phase II). In the micro-slip stage, the load-slip relationship is ascending steeply however without obvious slip occurrence at the free end of the bar. This stage is nearly linear and is up to about 60–70% of the ultimate load. The first phase is followed by internal cracking (phase II). At this stage, the free end of the rebar starts to slip by increasing the load toward the maximum value. In phase II, the load-slip relationship is still ascending; however, the curve becomes non-linear and the slip is increased with a relatively small increase in load. As the load increased further, a sharp change in slope was undergone which signified a breakdown of bond strength and developed the significant non-recoverable slip (phase III and IV). At the pull-out stage (phase III), the load reaches the maximum value which is accompanied by formation of longitudinal splitting cracks along the concrete cover. At the descending branch, the bond resistance declined rapidly, and the slip grows until the steel bar is thoroughly pulled out. At the phase IV, the bond strength dropped to the residual value and the pull-out load remained nearly constant and reached approximately less than one-sixth of the ultimate load.

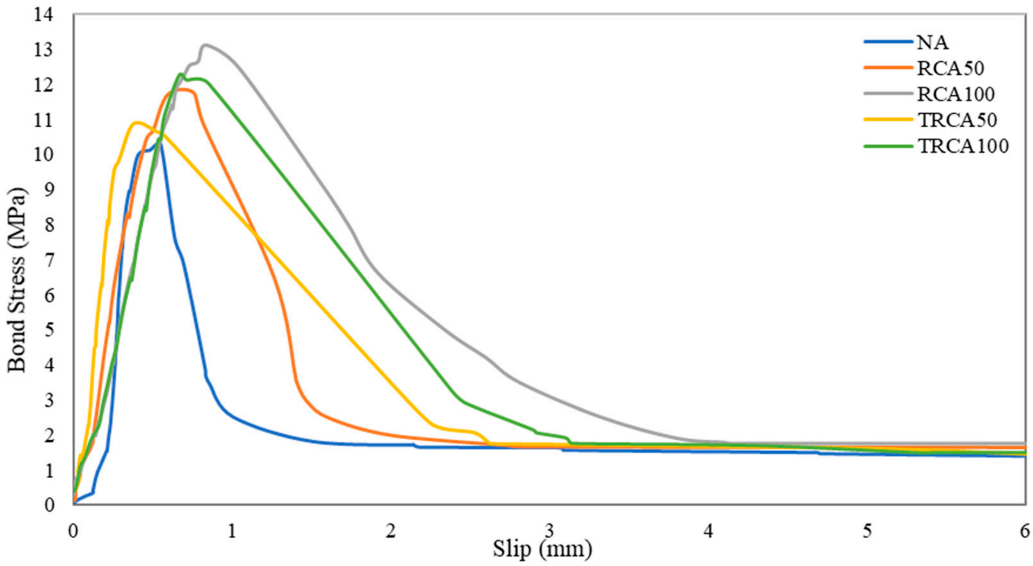


Figure 10. The bond-slip curves of SCC mixes from pull-out test.

Table 5 lists the results of bond strength of the pull-out test for tested mixes. As observed, the value of the bond strength for NAC is 10.28 MPa, whereas the corresponding value for RCA50 and RCA100 are 11.70 and 13.11 MPa, respectively. The results demonstrate an increase in the bond strength by 14.4% and 27.6% for RCA50 and RCA100, respectively, comparing to the reference sample. The higher bond strength of RCA-SCC mixes can be attributed to the smaller difference between the elastic moduli of the cement paste and the RCA than that of the cement paste and NA which results in a lower stress concentration at the interface between the steel and surrounding matrix and consequently higher bond strength [60]. Similar conclusions were drawn in other research work, which proposed that higher bond strength between RCA and steel bars developed in comparison with normal concrete of the same strength [44,46,61,62].

Table 5. The results of bond strength and brittleness index of SCC mixes.

Mix Code	Bond Strength (MPa)	BI
NAC	10.28	11.00
RCA50	11.76	10.87
RCA100	13.11	10.74
TRCA50	10.89	10.90
TRCA100	12.25	10.83

Moreover, the tensile properties of concrete particularly fracture toughness is a crucial parameter in bond strength [63]. Brittleness attributes to the fracture property of the concrete when subjected to the stress [44]. The brittleness of concretes is evaluated by brittleness index (BI) calculated from the following Equation (1):

$$BI = F_c/F_t \quad (1)$$

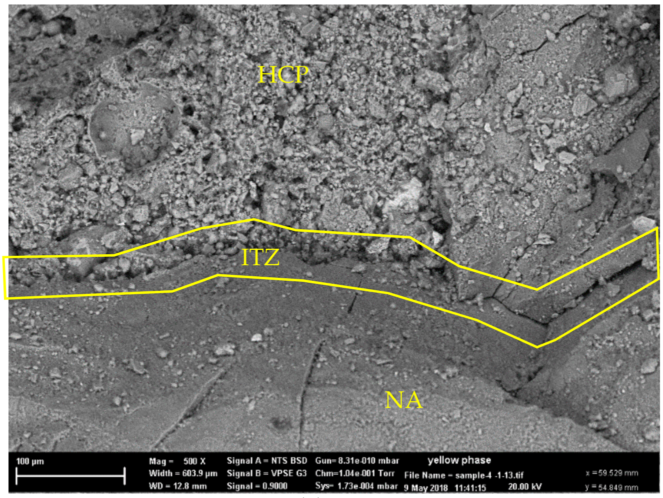
where F_c and F_t are the compressive and splitting tensile strengths of concrete, respectively. The BI results of the mixes are given in Table 5. The higher *BI* means the more brittleness of the material and hence the lower fracture toughness. It is demonstrated that the bond strength of concrete increases by a decrease of its brittleness index [64]. The results showed that replacement of RCA in with NA resulted in a decrease in brittleness index. In addition, the treatment of RCA led to decrease of bond strength of TRCA50 and TRCA100 by 12% and 9%, respectively, in comparison to RCA50 and RCA100 samples. The decrease in bond strength is contributed with the loss of surface roughness after treatment. In other words, the surface treatment smoothing the surface of the aggregates and decreases the frictional force. For this reason, some research studies have suggested the use of alternative techniques such as sprinkling and dripping for the surface treatment of RCA [65]. However, such treatment method demonstrated highly variable results.

3.8. Microstructure Observation

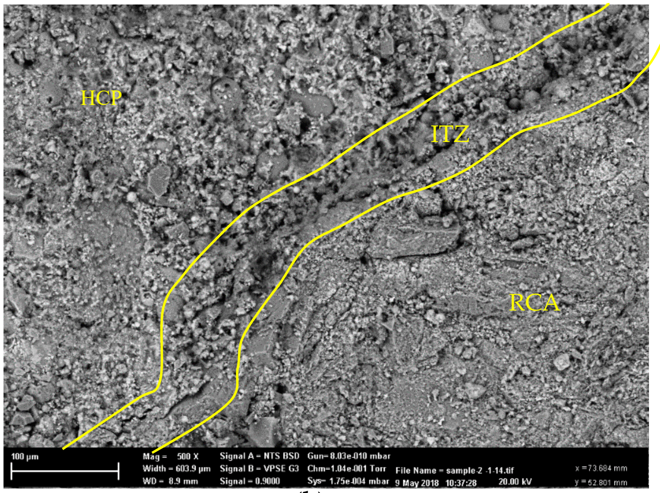
The SEM observation was performed to determine the microstructure of ITZ between hardened cement paste (HCP) and aggregates (NA, untreated RCA and TRCA) in the SCC. Figure 11 depicts the SEM images of microstructure of reference sample (NAC) and SCC mixes contained untreated RCA and TRCA. It is possible to distinguish the ITZ boundary that separates the new and old cement mortar in shades of grey. A darker shade of grey represents the old mortar in the samples while the new mortar appears as a lighter grey. The colour difference is due to the hydration difference of mortars in SCC samples [66].

It is observed that the ITZ of NAC and RCA concrete is slightly different. A porous microstructure can be observed with micro-cracking within the microstructure of ITZ in samples with untreated RCA. RCA tend to absorb more water than NA as they are porous in nature. The ITZ which interfaced between the NA and RCA and new mortar (new ITZ) is considered as a weak link in the SCC samples. The high water content area prevents a formation of strong bond between the aggregate and the cement paste. New ITZ comprises of region of loose hydrated particles contributed to the high porosity and high water absorption properties of RCA [67]. In contrast with NA, RCA consists of excess water in the form of internal and free surface water. The presence and evaporating of water around the RCA prevent the formation of hydration gel and generates a high-porosity region and consequently poor bond at the interface area.

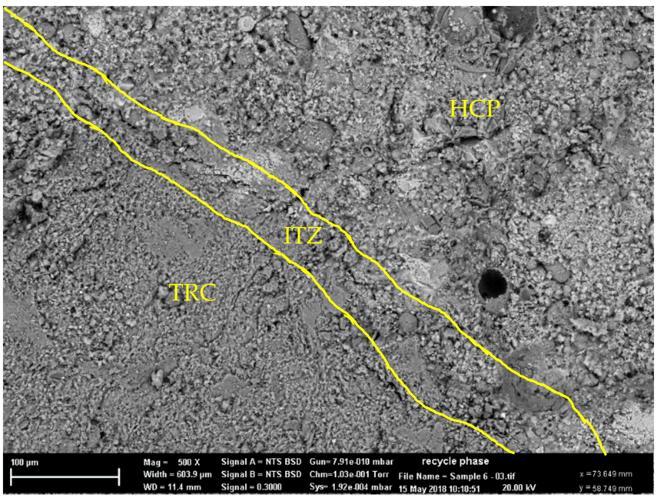
As shown in the Figure 11c, the ITZ of SCC containing TRCA was denser than that of SCC mix made with untreated RCA. In comparison, the microstructure of the TRCA samples displayed significantly less porous than the exhibited ITZ of untreated RCA. Moreover, no microcrack observed in the new ITZ for samples containing TRCA. However, some microcracks still observed in the microstructure of SCC made with TRCA which is attributed to the existing microcracks in the old ITZ of the used RCA. The results showed that the surface modification method using lithium silicate solution for the RCA led to a denser ITZ region. It is found that more durable concrete resulted from the denser ITZ region in concrete microstructure. In the proposed surface modification method, the lithium silicate solution (Li_2SiO_3), thoroughly penetrated the RCA structure and seal the cracks and porosity of old mortar. The lithium silicate solution through this modification reacts with calcium hydroxide ($Ca(OH)_2$-CH crystals) present in the RCA and creates the stronger C-S-H gel in concrete that resulted in densifying of the microstructure. In the hydration process, the calcium hydroxide dissolved in water and react with silicates. This newly formed C-S-H is deposited in the pores and voids of mortar. This indicated that the treatment procedure of RCA approached the desired reaction to form C-S-H. The formation of the secondary cementitious bond in the concrete structure boost the adhesive properties of the ITZ which also indicated in previous research studies [27,68]. Besides, the coated RCA by lithium silicate reduced the water surface of the RCA particles in the SCC mixes. This led to decrease the local w/c of the interface and consequently improve the new ITZ. Hence, the impregnation of RCA with a lithium silicate solution strengthened the structure of the RCA particularly the ITZ between the RCA surface and the cement paste.



(**a**)



(**b**)



(**c**)

Figure 11. Scanning electron microscope (SEM) images of interfacial transition zone (ITZ) of (**a**) NAC; (**b**) RCA100 and (**c**) TRCA100.

It can be concluded that lithium silicate penetrated the porous structure and capillaries of RCA and consequently hardened the RCA surface. Hence, the proposed treatment strengthened the ITZ microstructure between RCA and new cement paste which resulted in an increase in the mechanical properties of SCC containing TRCA as discussed before. The results coincide with the previous studies [27,67,69].

4. Conclusions

This experimental investigated the incorporation of RCA in the SCC mixes by implementing the surface treatment procedure using lithium silicate. The results showed that the water absorption of RCA significantly improved after implementing the proposed surface treatment. The slump flow test and T-500 tests performed on fresh SCC mixes revealed that the RCA replacement resulted in a considerable loss of flowability. However, the slump flow diameters of the SCC mix containing TRCA (TRCA50 and TRCA100 mixes) was higher than that of the SCC mix made with untreated RCA and the reference sample. Moreover, it was observed that by increasing the RCA content the compressive and tensile strength decreased. However, the treatment of RCA using lithium silicate solution enhanced both the compressive and tensile strengths of SCC mixes. In addition, all SCC mixes containing untreated RCA and TRCA exhibited lower elastic modulus than the reference sample. It is noteworthy that the surface treatment of RCA did not show a significant improvement in elastic modulus of SCC samples. Furthermore, the effects of different levels of RCA replacement as well as RCA treatment on the bond behaviour were studied. The pull-out test results demonstrated an increase in the bond strength for samples containing RCA. It also was concluded that brittleness of concrete is a crucial parameter in bond strength. It was demonstrated that the bond strength increases by decreasing of the brittleness index. However, the treatment of RCA led to decrease of bond strength due to the smoothing the surface of the aggregates and decrease in the frictional force. The interfacial transition zone (ITZ) and microstructure of the RCA-SCC mixes with TRCA and untreated RCA was investigated. The SEM analysis demonstrated that new ITZ in SCC mixes using TRCA provide denser, less porous and connected microstructure than the SCC mixes using untreated RCA. This is due to the recovery of microcracks in TRCA with new cement mortar of SCC mixes. However, it should be noted that the use of lithium silicate solution to coat RCA is still in its infancy, and there are many questions that will need to be answered in the future before such treatment is ready for real-world applications. In particular, the area of application of larger structures and the durability in terms of alkali-silica reaction should be examined. Studies from an environmental and economic point of view are also worthy to carry out.

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