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Shear Behaviour of Reinforced Self-Compacting Concrete Beams Made with Treated Recycled Aggregate

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ABSTRACT

In this paper, an experimental work was conducted to investigate the possibility of improving the structural performance of reinforced self-compacting concrete (SCC) beams cast with 100% treated and untreated recycled aggregate (RA). RA was first exposed to a simple treatment method to reduce the amount of its adhered mortar and to improve its performance by the impregnation in polyvinyl alcohol (PVA) polymer solution. After completing RA treatments, rectangular simply supported reinforced SCC beams cast with RA, treated recycled aggregate (TRA) as well as normal aggregate (NA), were prepared and tested under two-point loading up to failure. Half of the prepared beams were tested to evaluate the shear behaviour of normal strength (NS) SCC mixes, while the other half was tested for high strength (HS) SCC mixes. The results were evaluated with regards to load deflection response, ultimate failure load, first crack load, and cracking pattern. The main experimental results demonstrated that using treated RA considerably improved the shear capacity of reinforced SCC beams in comparison with that of untreated RA. Based on the ACI 318-14 and Euro codes, the shear strength values showed that the treated RA beams were considered more conservative compared to the RA beams in both strength grades.

1. Introduction

The necessity for the utilization of sustainable and recyclable resources in concrete industries is of prime importance in different construction applications. In the field of concrete technology, one of the reasonable and sustainable approach is the use of recycled aggregate (RA) instead of normal aggregate (NA). The use of this recyclable materials has positively affected the environment and economic by reducing the consumption of natural resources in the construction industry and reducing the landfill areas. In spite of these positive influences, the majority of the previous studies indicated that the use of RA in concrete construction has negatively influenced its structural performance in terms of shear capacity, deflection, and cracking pattern. The experimental studies conducted in some research work have shown a decrease in the maximum shear strength of the reinforced concrete beams when RA was used [1, 2]. Besides, higher

deflection values and wider cracks were noticed in the tested beams made of RA. Gonzalez and Martinez [3] tested 8 reinforced concrete beam specimens with 3% reinforcement ratio and 50 % RA. The test results revealed a marginal increase in the beams deflection values with a slight decrease in their shear capacity when NA was replaced by RA. This behaviour was also noticed in other research works [4–6]. Moreover, it was found that the general cracking behaviour of the RA concrete beams were somewhat comparable to that of NA concrete beams [2, 7–11]. Katkhuda and Shatarat [12] investigated several concrete beam specimens made of NA, RA, and TRA and differing in the shear span to depth ratios. RA materials were immersed in hydrochloric acid for 24 hours to minimize their attached old mortar. After HCl treatment process, RAs were soaked in sodium metasilicate pentahydrate solution to treat their surface layers

Nomenclature			
HCl	Hydrochloric acid	*NA*	Normal aggregate
HS	High compressive strength	*NVC*	Normal vibrated concrete
ITZ	Interfacial transition zone	*NS*	Normal compressive strength
Kg	Kilogram	*PVA*	Polyvinyl alcohol
KN	Kilo Newton	*RA*	Recycled concrete aggregate
LP	Limestone powder	*SCC*	Self-compacting concrete
LVDT	Linear variable differential transformer	*TRA*	Treated recycled concrete aggregate
m	Meter	$V_{c\ exp}$	Experimental shear load
mm	Millimeter	$V_{c\ theo}$	Theoretical shear load
MPa	Mega Pascal		

and to improve their physical properties. The findings showed that when TRA was used, a slight improvement in the ultimate shear capacity of concrete beams (with no stirrups reinforcement) compared with that of NA and RA beams. The existence of the old cement paste in the natural aggregate playas an essential role in changing the microstructure of RA concrete. This has been reported by many researchers [13–16]. Concrete made with RA contains two types of interfacial transition zone (ITZ), one of them is between the original aggregate and residual mortar, and the other one is between the RA and new cement paste [17]. The presence of these ITZs leads to high water absorption, high porosity, and low density and, thus, resulting in less mechanical performance of RA concrete. Consequently, the properties of RA need to be improved to attain an appropriate performance before being used in concrete construction.

Based on the previously published studies about RA, the majority of them have highlighted the structural behaviour of reinforced normal vibrated concrete (NVC) instead of self-compacting concrete (SCC). In this paper, the aim was to experimentally assess the possibility of enhancing the structural performance of self-compacting concrete mixes made with 100% RA. Different rectangular shaped beams, made with untreated RA, treated RA (TRA) as well as NA, were prepared and tested in order to investigate their shear behaviour in terms of load versus deflection response, shear cracking and ultimate load, and cracking pattern. A comparison between the experimental test results of this study and those calculated according to ACI-code and Euro-code are also performed in this study.

2. Experimental Program

2.1. Materials

Type I Portland cement was used in this investigation. Coarse aggregate (20 mm maximum size) of three different types were used. They were natural aggregate (NA), recycled aggregate (RA), and treated recycled aggregate (TRA). Crushed old concrete cubes specimens were the source of the used RA. To prepare SCC mixes, fine aggregate of 4.75 mm size, limestone powder (LP) as well as Viscocrete-5930 superplasticizer were used. In this experimental work, polyvinyl alcohol (PVA) polymer solution was used for treatment of RA. The treatment process involved two-stage method, they were (1) minimizing the adhered weak mortar from RA surfaces, and (2) soaking it in polyvinyl alcohol (PVA) polymer solution.

To minimize the adhered mortar, RA was subjected to washing process into a concrete mixer until loose particles were removed with the discharged water. After that, the prepared RA was soaked in PVA solution for 24 hours and left to air-dry in the laboratory environment in order to be used in SCC mixes.

2.2. Concrete specimens casting and testing

Relatively normal (NS) and high strength (HS) self-compacting concrete (SCC) mixes, with target compressive of 30 and 50 MPa, were respectively prepared. Different types of coarse aggregates (natural, recycled, and treated recycled aggregates) were used in these mixes. The prepared SCC mixes were designed according to the mix proportioning method adopted in [18,19]. The adopted mix design method is based on constructed design charts for each mix grade. A volumetric substitution of normal aggregate (NA) by 100% RA and 100% TRA was performed according to their specific gravity, which are 2.35 and 2.42 for RA and TRA, respectively. In each of SCC mix grade, the amounts of cement, water, fine aggregate, and limestone powder were kept constant. The amount of ingredients used in NS and HS mixes are shown in Table 1.

The workability of SCC mixes were checked based on BS EN 206-9 [20] and EFNARC [21]. According to these standard specifications, the produced TRA mixes have satisfied the necessary self- compacting criteria of flow-ability and passing-ability. In this regards, the prepared SCC mixes have complied with class 2 slump flow (SF2) that ranges from 650 to 750 mm. To attain this range of flow, the super-plasticiser dosages were altered to 3.5 and 6.0 kg for NS and HS mix grades, respectively. Furthermore, the investigated fresh SCC mixes showed no sign of segregation, indicated by no blockage occurred during the flow and after it has stopped, and the coarse aggregate homogeneously distributed in the fresh mix.

In this study, the hardened properties of the prepared SCC mixes (using different aggregate types) were evaluated based on compressive strength test, measured according to BS EN 12390-3 [22]. For each mix, the average value of three $100 \times 100 \times 100$ mm cube specimens was calculated. The test results demonstrated that the substitution of RA with TRA has positively influenced the compressive strength of SCC mixes. An increase of about 14.7% and 11.8% in TRA concrete compressive strength was registered for NS and HS, respectively, compared with RA concrete mix.

Table 1: Amounts of the materials used in SCC mixes, kg/m³

Concrete grade	Cement	Water	w/c	Limestone powder	Fine aggregate	Coarse aggregate
Normal strength	350	199	0.57	160	770	830
High strength	492	172	0.35	108	755	852

2.3. Details of the tested reinforced SCC beams

The experimental work of this study includes testing of six rectangular beams having cross-section dimensions of 250 mm depth, 150 mm width, and 1550 mm clear span length. The specimens were subjected to two-point load test. Figure 1 shows the details and steel reinforcement of the specimens. The clear concrete cover of the reinforcement was 25 mm from all sides. The SCC beams were divided into two groups (Group1 and Group 2 as presented in Table 2). Group 1 was prepared for investigating the shear behaviour of normal strength beams, while Group 2 was for high strength beams. These beams were reinforced with two Ø16 mm steel reinforcing bars provided as a main reinforcement at the bottom, in addition to one Ø8 mm bar provided at the top of beam. For a practical reason, two stirrups of Ø10 mm bar spaced at 25 mm were placed at the beginning and end of beam out of its clear span.
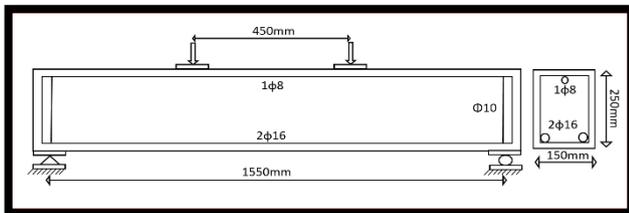

Figure 1: Details of beam reinforcement

Table 2: Notations of the tested beams

Group number	Beam notation	Beams details
Group 1	NANS-S	Normal aggregate- Normal strength
	RANS-S	Recycled aggregate* - Normal strength
	TRANS-S	Treated recycled aggregate*- Normal strength
Group 2	NAHS-S	Normal aggregate - High strength
	RAHS-S	Recycled aggregate* - High strength
	TRAHS-S	Treated recycled aggregate*- High strength

*The replacement level of NA with RA or TRA is 100%.

Figure 2. Testing machine and load pattern

2.4. Test setup and instrumentations

A hydraulic universal testing machine (shown in Figure 2) with a capacity of 2000 kN was used to test the beam specimens in this study. The machine was available in the Structural Laboratory of Civil Engineering Department at Al-Qadisiyah University. A Linear variable differential transformer (LVDT) was used to measure the lateral displacement at the beam mid span. The used LVDT has a maximum bearing capacity of 50 mm. The beam deflection values were recorded when the load was applied on the beam.

3. Results and Discussion

3.1. Load-mid span deflection

In this study, the test results of the tested specimens are presented in Table 3. They involve the values of compressive strength, first shear cracking load, and ultimate shear load at failure. The behaviour of the six tested beams is shown in Figures 3 and 4 with regard to the experimental load against mid-span deflection for NS and HS, respectively. For both strength grades, it can be seen that, at a same shear load value, the deflection of TRA-SCC beams was less than that of RA-SCC beams. The results also showed that the shear cracking load of TRA-SCC increased approximately 38.9% and 16.7% for NS and HS, respectively, compared with RA-SCC beams.

Figure 3 shows that NANS-S beam has the maximum shear load capacity compared with TRANS-S and RANS-S beams. They both exhibited a reduction in shear load capacity of 10.3% and 32.0%, respectively, compared with the reference beam (NANS-S). However, beams cast with treated RA (TRANS-S) demonstrated 32.2% increase in the ultimate shear load compared with that of untreated RA (RANS-S) beam, as clearly seen in Table 3. This indicates to the effectiveness of the proposed treatment method in enhancing the properties of RA.

Figure 4 shows the load versus deflection curves for the tested HS beams. The results indicated that the control beam (NAHS-S) possessed the maximum shear capacity compared with TRAHS-S and RAHS-S beam. They both demonstrated a reduction of 7.2% and 19.2%, respectively in their shear capacity. However, compared to RAHS-S, TRAHS-S beam exhibited 14.9%, increase in shear capacity (see Table 3). This is mainly due to the removal of the weak adhered mortar of RA, as well as to the PVA-impregnation that filled the pores and cracks of RA, resulting in enhancing its bond with new cement matrix. Apart from its enhancement of concrete structural properties, PVA considerably improves mechanical properties of numerous construction materials, such as, concrete [23], gypsum [24], and clay brick [25], due to its ability to change the material microstructure and decrease its pores volume.

Table 3: Test results of the tested SCC beams

Beam notation	Compressive strength (MPa)	Shear cracking load (kN)	Ultimate load (kN)	Load ratio relative to the control*
NANS-S	32.4	86	97.74	1.00
TRANS-S	30.5	75	87.72	0.89
RANS-S	26.6	54	66.38	0.68
NAHS-S	53.4	93	106.41	1.00
TRAHS-S	51.3	84	98.75	0.93
RAHS-S	45.9	72	85.98	0.81

*This is the ratio of the ultimate load of beams relative to the reference beam cast with natural aggregate (0% RA replacement)

3.2. Crack patterns

The crack patterns of beam specimens for NS and HS concrete were presented in Figures 5 and 6. At the beam maximum moment (mid-span), the first flexural cracks initiated between two points of applied load. With increasing the load application, new cracks (due to flexural load) started to appear and propagated. After that, flexural shear cracks began to form and becoming inclined toward neutral axis. The flexural shear cracks became wider with increasing the amount of the applied load. Then, main diagonal shear cracks appeared, which are the consequences of the beam failure and concrete crushing in the shear region. Figures 5 and 6 showed that the shear crack patterns of SCC beam specimens made with NA, TRA, and RA concrete were generally identical in each strength grade.
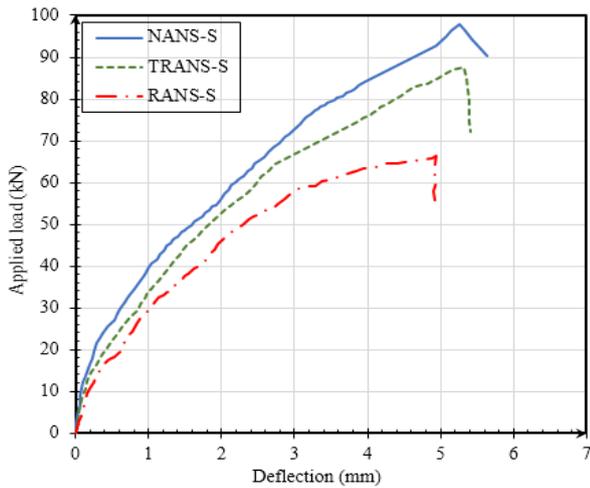

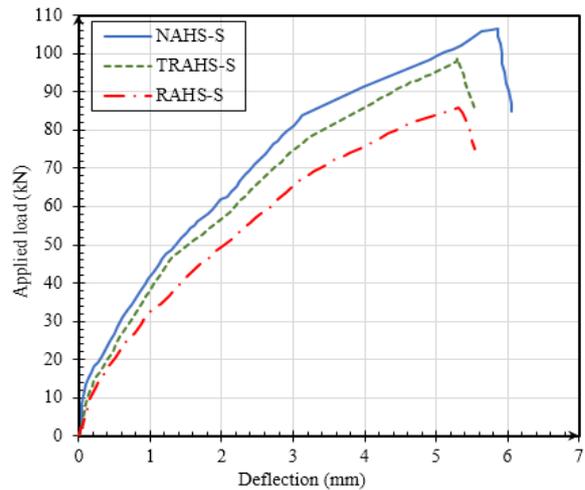**Figure 3: Load-mid span deflection for beams of Group 1**

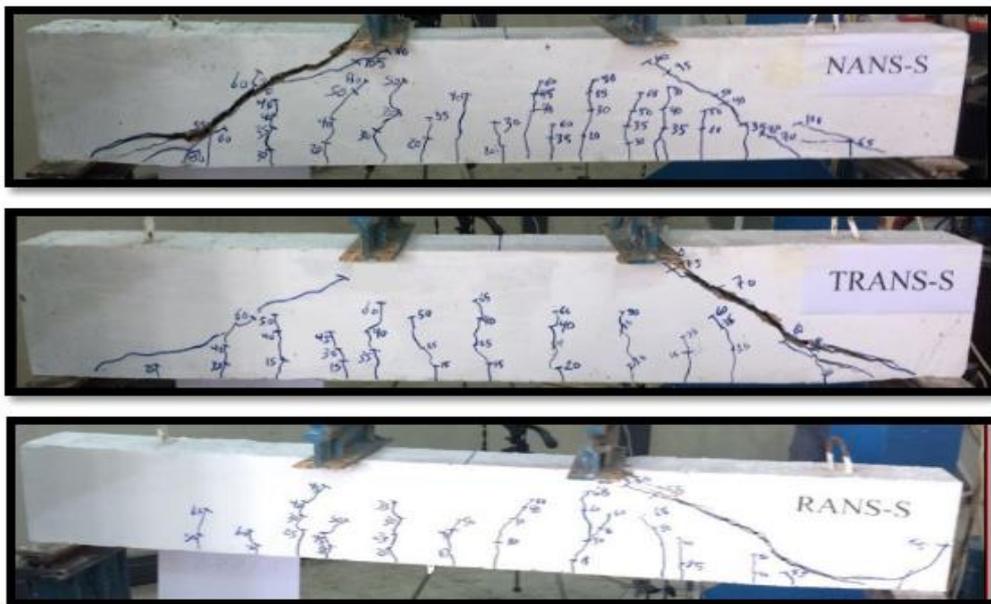**Figure 4: Load-mid span deflection for beams of Group 2**

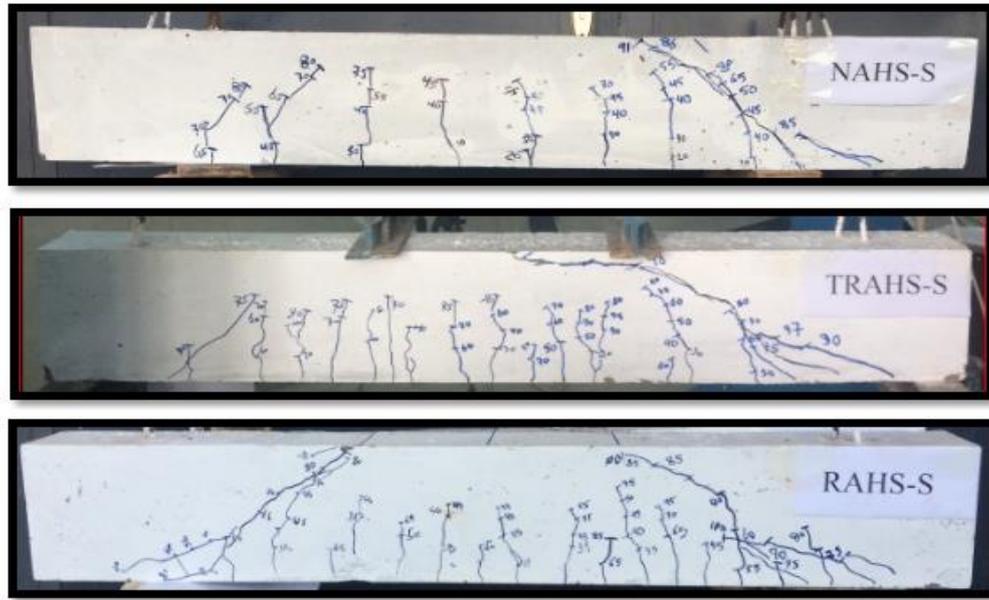**Figure 5: The cracks pattern of NANS-S (top), TRANS-S (middle), and RANS-S (bottom) beams**

Figure 6: The cracks pattern of NAHS-S (top), TRAHS-S (middle), and RAHS-S (bottom) beams.

3.3. Comparison of calculated and experimental shear strength

In this study, the ultimate shear strength was found from the experimental test results, whereas the theoretical ultimate strength was determined by ACI Committee 318 code (2014) [26] using Eq. 1, and the Euro-code 2-05 [27] using Eq. 2. The theoretical shear load ($V_{c\ theo}$) from the ACI Code was calculated for the tested beam specimens by adopting the equation below.

$$Vc = \left(0.16\sqrt{fc} + 17\frac{\rho}{a/d}\right)bd \le 0.29\sqrt{fc}\ bd \tag{1}$$

Here:

V_c: shear strength (theoretical), kN.

ρ: the longitudinal reinforcement ratio of beam.

f_c: the concrete compressive strength (MPa).

b: width of the section (mm)

d: effective depth of beam (mm).

a: shear span (mm).

The shear force ($V_{c\ theo}$) based on Euro code 2-05 can be determined by equation below.

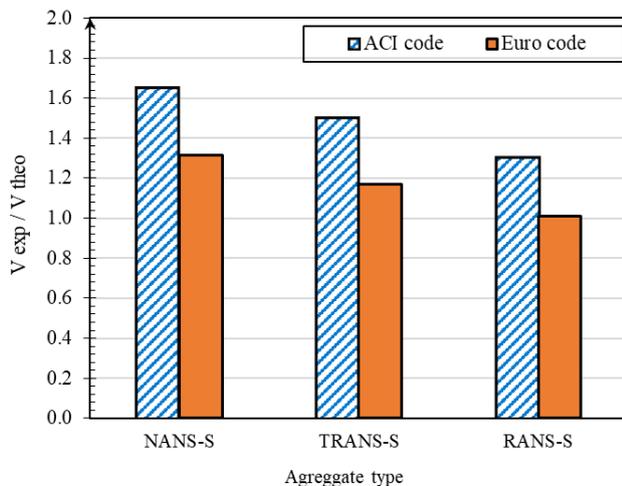$$Vc = \left(0.18\ K(100\ \rho\ fc)^{1/3}\right)bd \ge \left(0.035\ K^{3/2}\sqrt{fc}\right)bd \tag{2}$$

Where

$$K = \left(1 + \sqrt{\frac{200}{d}}\right) \le 2.0$$

Figures 7 and 8 illustrate a comparison based on experimental shear strength relative to ACI and Euro code ($V_{c\ exp}/V_{c\ theo}$) for normal (NS) and high strength (HS). Based on ACI code, it is indicated that the shear strength values were conservative for all SCC beams, regardless the compressive strength beam grade. Based on Euro code, the control beams (NA-SCC) and treated RA beams (TRA-SCC) were more conservative compared with that of untreated RA beams, For NS, the ratio ranged between 1.3 to 1.64 for reference beam (NANS-S), 1.17 to 1.5 for TRANS-S beam, and 1.01 to 1.30 for RANS-S beam (see Figure 7). While for HS, the ratio ranged from 1.2 to 1.41 for control beam, 1.12 to 1.33 for TRAHS-S beam, and 1.0 to 1.2 for RAHS-S beam (Figure 8). It is worth noting that the ACI and Euro-code underestimated the shear strength for all of the tested beams. However, the ratio seems to decrease with increasing the beam concrete strength. In this regard, it is to be noted that the available standard codes could be used to design the TRA and RA concrete beam specimens.
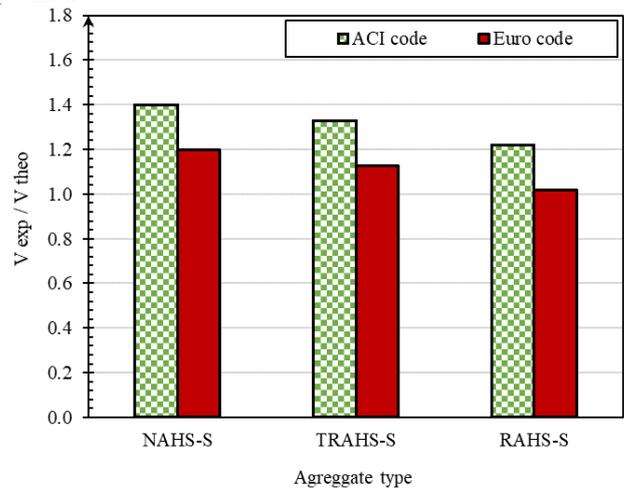

Figure 7: Comparsion of experimental results for beams of Group 1.

Figure 8: Comparsion of experimental results for beams of Group 2.

4. Conclusions

In this paper, successful sustainable reinforced SCC members have been prepared. The experimental test results showed that the proposed RA treatment method have played an essential role in improving the structural behavior of reinforced SCC beams. This primarily due to the removal of the loose old mortar of RA, as well as to the effectiveness of PVA polymer to fill the formed pores and cracks of RA, and improve the bond between particles of cement matrix. From the main findings of this study, the following conclusions can be drawn:

1. The ultimate shear load of treated RA self-compacting concrete beams was higher than that of untreated RA beams by 32.2% and 14.9% for normal and high strength, respectively.

2. The shear capacity of the untreated RA-SCC beams, cast with HS concrete, dropped approximately 19.2% compared with that of NA-SCC beams. However, shear capacity of the untreated RA beams cast with NS concrete dropped significantly (about 32.0%).

3. The shear cracking load of TRA-SCC increased approximately 38.9% and 16.7% for NS and HS, respectively, compared with RA-SCC beams.

4. The crack patterns of SCC beam specimens made with NA, TRA, and RA concrete were generally identical for each strength grade of the tested beams.

5. Based on the international standard codes (ACI 318-14 and Euro-code), the shear strength values of NA-SCC and TRA-SCC beams were more conservative compared with that of RA-SCC beams, regardless the compressive strength beam grade. Therefore, the available standard codes can be used to design the TRA and RA concrete beam specimens.

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