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Behaviour of Internally Strengthening Hollow Stainless-Steel Hot-Rolled Circular Columns Filled With Crumb Rubber and Recycled Aggregate Concrete

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RESEARCH ARTICLE

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ABSTRACT

Stainless-steel sections are increasingly being utilised in favour of their higher durability. Simultaneously, the use of recycled materials in concrete is aligned with the global concern to encourage sustainable and environmentally friendly construction. The paper examined the behaviour of stainless-steel columns filled with concrete with crumb rubber (CR) and recycled aggregate (RA). It analysed the effect of different percentages of CR (0, 15, and 30) and RA (0, 15, and 50) on the compressive strength of the concrete and the performance of the columns using stainless-steel hollow sections. 20 specimens were manufactured, 18 of which were cast with concrete containing RA and CR at different percentages. A hollow stainless steel circular section with a 100 mm diameter, 600 mm height, and 1.5 mm thickness was tested. To increase the section strength and reduce the weight, two types of stiffeners were added to the specimens: V-shaped and round-shaped. The addition of stiffeners improved the column performance. However, the inclusion of RA and CR led to a reduction in compressive strength and overall column capacity. The most common failure mode observed was local buckling, with V-shaped stiffeners performing better than round-shaped stiffeners in resisting axial loads due to the smaller area deduction from the concrete. Experimental results are compared with those obtained using the proposed equations from various design codes. The proposed equations from the following codes: American Code (AISC 360-22), Eurocode (EN 1994-1-1), Japanese code (AIJ), and Chinese Code (GB/T 51446-21) are conservative and give good agreement with the experimental results.

Keywords: Stainless steel, Crumb rubber, Column, Behaviour, Recycled aggregate

1. Introduction

1.1. Background and motivation

The construction industry is experiencing a major revolution, which has been motivated by the growing need to lower environmental effects, enhance sustainability, and increase the serviceability of structures.

A possible solution is the incorporation of waste tire rubber and recycled aggregates in concrete as one of the promising solutions, since it not only consumes fewer natural resources but also eliminates the waste. It has been demonstrated that these sustainable concretes can increase ductility, toughness, and energy absorption, but tend to be weaker in

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compressive strength than traditional mixes. The first to show that shredded tires can be used as a partial substitute for aggregates include Ganjian et al. [1] and Girgis et al. [2], who found that toughness and ductility were improved. On top of this, Venkatesan and others [3] pretreated tire particles using potassium hydroxide, which increased the adhesion and resulted in concrete increase in flexural, tensile, and compressive strengths. In the study by Barrera et al. [4], the method of curing rubberized concrete used was hot water, which produced better deformation and mechanical characteristics. Likewise, Zaleska et al. [5] substituted sand and gravel with tire waste with a 10–30 percent concentration and found that the density was lower and less thermally conductive; however, the strength and fire resistance were lower.

1.2. Sustainability and environmental benefits of rubberized concrete

The environmental advantages of rubberized concretes have also been measured. Xiong et al. [6] demonstrated that using less than 20 percent of natural aggregate with rubber kept the structural performance satisfactory and reduced the CO₂ emissions by 15–17 percent using concretes with the 30–40 MPa. In a study by Villanueva et al. [7], microconcretes containing 10–30 percent rubber granules were tested, and it was observed that ductility increased drastically, but compressive strength decreased with increased replacement. Al-Nimr and Shaaban [8] made comparisons on self-compacting, rolled, and conventional concretes and found that ideal replacement ratios were 25 percent coarse aggregate in conventional mixes, 10 percent fine in SCC and rubber mixes. These investigations substantiate that with increased substitution levels, and despite the possibly damaged mechanical performance, the positive features of environmental and ductility advantages suggest crumb rubber concrete as a potentially viable, sustainable substitute.

1.3. Recycled aggregate concrete and stainless-steel confinement

Similar studies have also been conducted on recycled aggregate concretes (RACs) in stainless steel tube structures, where confinement is used to increase performance. Yang and Ma [9] experimented with circular and square hollow stainless steel with recycled concrete at replacement values that reached 75 percent of the original, and they discovered that confinement and load-bearing capacity were significantly improved. He et al. [10] investigated flexural buckling of RAC-filled tubes of stainless steel, the

durations of which identified the impact of tube size, replacement ratio, and column length on resistance. According to these works, it can be argued that stainless steel confinement can negate some of the natural weakening of strengths of RACs, making such systems good contenders for sustainable construction.

1.4. Concrete-filled stainless-steel tubular (CFSST) systems

Concrete-filled steel tubes (CFSTs) are long known at the structural level to be efficient in mobilizing the compressive strength of concrete and the tensile strength of steel. They are most employed in high-rise buildings, offshore platforms, and bridges because of their high level of load-bearing capacity and ductility. Nevertheless, although the use of traditional carbon steel tubes under aggressive conditions is a problem, corrosion compromises performance and durability. To eliminate this, focus has moved to concrete-filled stainless-steel tubes (CFSSTs) that possess better corrosion resistance, fire resistance, and life cycle, and lower the maintenance cost [11–13].

1.5. Review of existing studies on CFSSTs

Significant changes have occurred in the understanding of CFSSTs since the time of the initial studies on the topic. The behaviour of CFSSTs has been tested experimentally and numerically over wide ranges. Lam et al. [14] studied circular short columns in axial compression with maximum focus on the influence of the concrete strength and a nonstop method of determining the strength approach to predict the capacity to the continuous approach. Uy et al. [15] focused on short and slim CFSST columns and found that current design codes offer conservative predictions. Tests and FE analyses of fiber-reinforced CFSSTs by Ellobody et al. [16, 17] showed that the Eurocode 4 predicts the strengths of fiber-reinforced CFSSTs to be lower than they are, particularly when subjected to eccentric loading. Tokgoz et al. [18] investigated the aspect of biaxial bending on plain and steel-fiber CFSSTs, and found cross-sectional shape and concrete strength, eccentricity, and slenderness as the regulating components. These findings were extended through further studies. In the study by Hassanein et al. [19], flexural buckling of slender CFSSTs was studied by FE modelling and presented correct predictive models. Elsisy et al. [20] compared stiffened and unstiffened austenitic CFSSTs and concluded that Eurocode 4 is still conservative with respect to hollow sections that are stiffened. Al-Mekhlafi et al. [21] investigated CFRP confined eccentrically loaded CFSST stub columns, in which strength was found to

increase, and the prediction was conservative. Patel et al. [22] used the nonlinear modelling approach to predict a three-stage stress-strain relationship that well replicated the load-strain behaviour. He et al. [23] emphasized the value of confinement coefficients and compression area, whereas Tang et al. [24] presented an empirical equation for axial strength. Duan et al. [25] studied recycled CFSSTs, and compressive strength is found to be mainly determined by the steel ratio. Liao et al. [26] compared circular and square sections with a high confinement as per stainless steel, but limited predictions of the axial capacity. Ding et al. [27] verified the superposition technique of estimating the axial strength, and Dai et al. [28] verified the effect of tube thickness and concrete grade in square CFSSTs. The other investigations dealt with the rectangular and composite designs with the axial and eccentric loading [29–32].

1.6. Material characteristics of stainless steel

Stainless steel has a nonlinear stress-strain behaviour with a lower modulus of elasticity (≈ 190 GPa) and greater strain hardening behaviour than traditional carbon steel (≈ 210 GPa), which results in increased ductility and strain absorption [33]. These features enhance the composite interrelationship and confinement between the steel tube and the concrete core, leading to the high post-yield performance and local buckling delay in CFSST columns [15]. Therefore, stainless steel offers better deformation capacity and stability in the case of axial and cyclic loads.

1.7. Identified research gap and rationale for current study

Despite significant advancements having been made in the research on concrete-filled stainless-steel tubular (CFSST) columns, there are still significant gaps in the research. Although stainless steel has shown to have increased performance of confinement and durability, not many studies have researched CFSSTs that use rubberized or recycled concrete. Past research has mainly investigated crumb rubber (CR) or recycled aggregate (RA) alone, but their combined application creates intricate mechanical interactions, which affect the transfer of stress, the confinement efficiency, and the local buckling resistance because of changes in stiffness, porosity, and the interfacial bonding. Since there has been growing concern on environmentally friendly construction materials requiring sustainable construction materials, the axial capacity and buckling behaviour of CFSST systems that use CR + RA as the main construction material, as well as its failure mechanisms, should be assessed.

The combination of the corrosion resistance of stainless steel with the environmental advantage of CR and RA is a potentially promising avenue toward creating a stable and sustainable structural system, and should be the target of a particular study, instead of relying on the current literature that focuses on the properties of individual materials.

1.8. Aim and scope of the study

This study primarily aims to investigate the structural behaviour of hollow stainless-steel columns filled with recycled and rubberized concrete mixtures and will thus be used to develop more sustainable composite structural systems. Two kinds of internal stiffeners, V-shaped and round-shaped, are applied to the selected specimens to determine the impact on the column performance. This research gives detailed experimental results and modelling analysis to gain better insights into the load-bearing capacity, deformation behaviour, and failure of concrete-filled stainless-steel tubular (CFSST) columns using crumb rubber (CR) and recycled aggregate (RA), including and without internal stiffeners. Specifically, the study evaluates the structural performance and sustainability potential of columns in the CFSST made using different ratios of CR and RA replacement and analyzes their consequences to confinement efficiency and failure modes. The experimental findings are also related to the predictions made by the available design provisions to provide recommendations on how the performance and sustainability of future CFSST systems can be improved.

1.9. The research hypothesis

The study examines the structural behaviour of concrete-filled stainless steel tubular columns (CFSST) that have two kinds of internal stiffeners embedded in them and filled with concrete that has crumb rubber replacing fine aggregate partially and recycled aggregate replacing coarse aggregate partially. The study also gives a comparative evaluation of the results of the experiment and the assumptions made in the design equations of theoretical design codes given in international design codes. The most important aspect is the performance assessment of the stainless-steel circular hollow-section columns filled with such sustainable concrete mixtures and reinforced with various stiffener patterns. The research will contribute to the development of sustainable construction techniques and structural performance of CFSST systems by comparing the mechanical and environmental advantages of using waste materials in

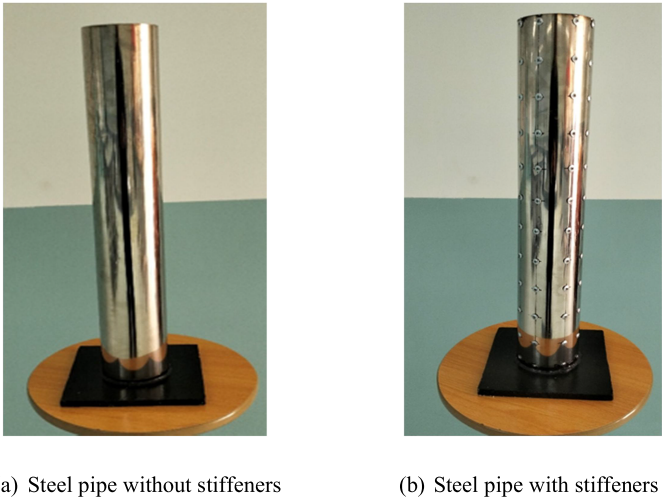


Fig. 1. Steel pipe.

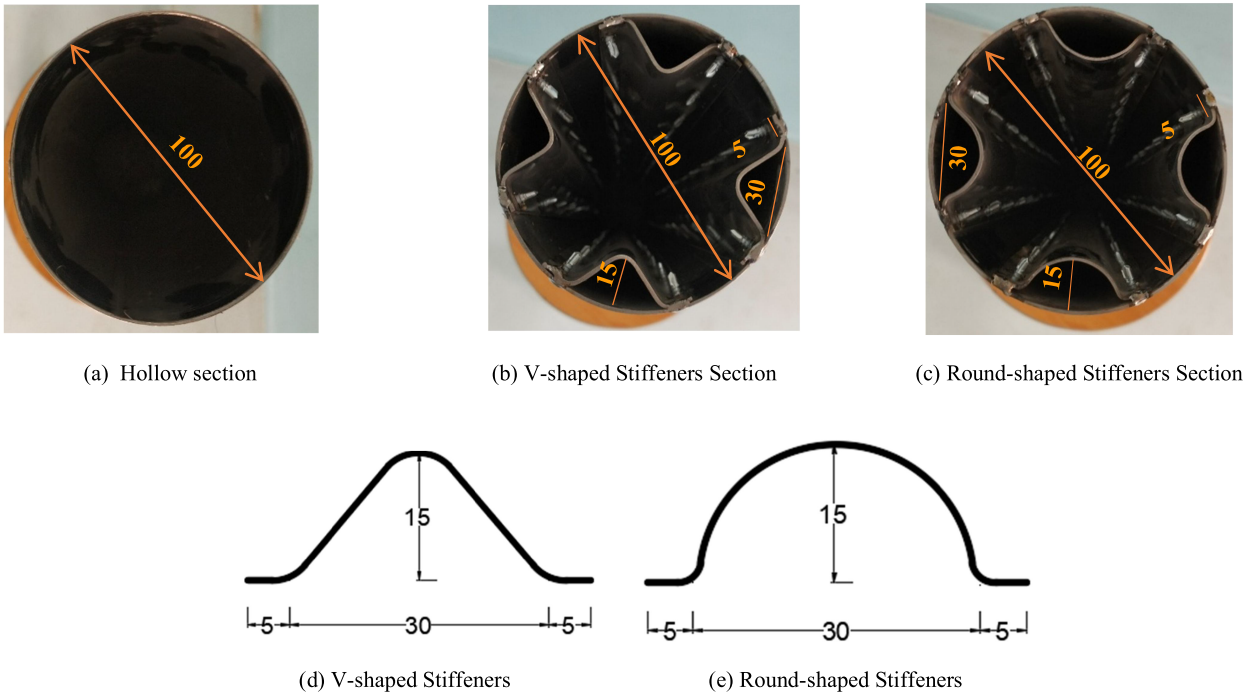


Fig. 2. Section and stiffeners details.

concrete and the structural enhancement that internal stiffeners provide.

2. Experimental work

2.1. Specimen details

To study the overall performance of stainless-steel hollow columns internally strengthened and provided with enhanced interaction with concrete, two types of internal stiffeners were used: V-shaped and Round-shaped. The hollow steel section has a diameter of

100 mm, a height of 600 mm, and a thickness of 1.5 mm. It is made from stainless steel grade 304. The stiffeners were made from the same plate of pipe (1.5 mm thickness) with 15 mm height and 30 mm base for V-shaped, and 30 mm diameter for rounded shape, with 5 mm extension for each side for fixing. Four pieces of stiffeners will be used to enhance the strength and the concrete steel connections. To install each piece of stiffener interior, two rows of connection bolts were secured using self-drilling screws, placed at 50 mm intervals. Figs. 1 and 2 show the section details.

Table 1. Specimens details.

Group No.	Specimen Designation	Stiffeners	Recycled Aggregate %	Crumb Rubber %
1	CN-Empty	Without	-	-
	CV-Empty	V-shaped	-	-
2	CN-0%RA-0%CR	Without	0	0
	CV-0%RA-0%CR	V-shaped	0	0
	CC-0%RA-0%CR	Round-shaped	0	0
3	CN-25%RA-0%CR	Without	25	0
	CV-25%RA-0%CR	V-shaped	25	0
	CC-25%RA-0%CR	Round-shaped	25	0
4	CN-25%RA-15%CR	Without	25	15
	CV-25%RA-15%CR	V-shaped	25	15
	CC-25%RA-15%CR	Round-shaped	25	15
5	CN-25%RA-30%CR	Without	25	30
	CV-25%RA-30%CR	V-shaped	25	30
	CC-25%RA-30%CR	Round-shaped	25	30
6	CN-50%RA-15%CR	Without	50	15
	CV-50%RA-15%CR	V-shaped	50	15
	CC-50%RA-15%CR	Round-shaped	50	15
7	CN-50%RA-30%CR	Without	50	30
	CV-50%RA-30%CR	V-shaped	50	30
	CC-50%RA-30%CR	Round-shaped	50	30

To produce lightweight concrete, crumb rubber was implemented to replace the fine aggregate. Three varying proportions of crumb rubber (0%, 15%, and 30%) by volume were assumed. In addition, recycled aggregate obtained from crushing blocks was used to replace the natural coarse aggregate at different proportions (0%, 25%, and 50%) by weight of the coarse aggregate.

In this study, twenty specimens were tested. The specimens were divided into seven groups, each group containing three specimens (except for the group without fillers, which contained two specimens). One of these specimens was without stiffeners, while the other two were designed with V-shaped and round-shaped stiffeners.

The first group consisted of a hollow steel section (without filler). Other groups were filled with concrete with varied ratios of crumb rubbers and recycled aggregate as listed in Table 1.

The designation is used to categorize the tested specimens, depending on stiffeners (V and round shapes), recycled aggregate ratios (0, 25, 50) %, and crumb rubber ratios (0, 15, 30) %.

2.2. Material properties

2.2.1. Cement

Ordinary Portland Cement was used in this research and specifying the specifications outlined in the British Standard BS EN 197-1:2011-CEM [34].

2.2.2. Fine aggregate

The natural fine aggregate, with a maximum aggregate size of 5 mm and specific gravity of

2.65, was used. A sieve analysis of the aggregate was performed, and the results were compared with British Standard BS 882:1992 [35], as shown in Fig. 3a.

2.2.3. Coarse aggregate

Natural crushed coarse aggregate, with a maximum aggregate size of 20 mm, was used. The coarse aggregate was subjected to sieve analysis, and the results were compared with British Standard BS 882:1992 [35] to ensure its compliance with the basic requirements for production materials, as shown in Fig. 3b.

2.2.4. Recycled aggregate

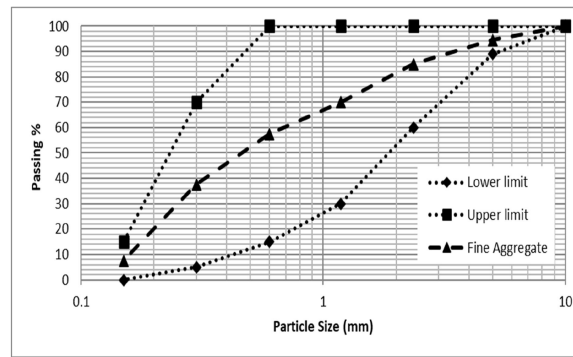
The recycled aggregate was obtained by crushing the concrete block in the concrete lab using a jaw crusher with a maximum aggregate size of 20 mm. The results of sieve analysis were then compared with the specifications outlined in the British Standard BS 882:1992 [35], as shown in Fig. 3c.

2.2.5. Crumb rubber

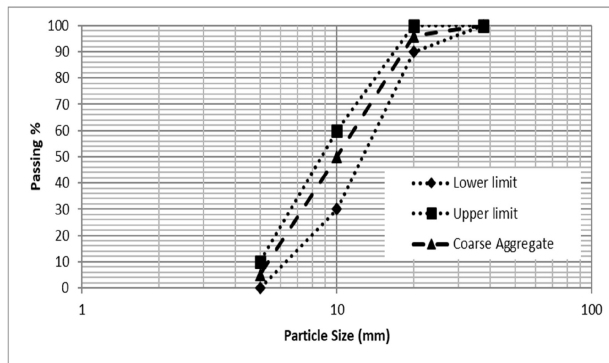
Used tires can be shredded into large pieces to replace coarse aggregate, converted into crumbs to replace the fine aggregate, or ground into powder for use as filler in concrete. In this research, crumb rubbers with a size range between 2.36 and 1.18mm, and a specific gravity of 1.1 were used.

2.2.6. Water

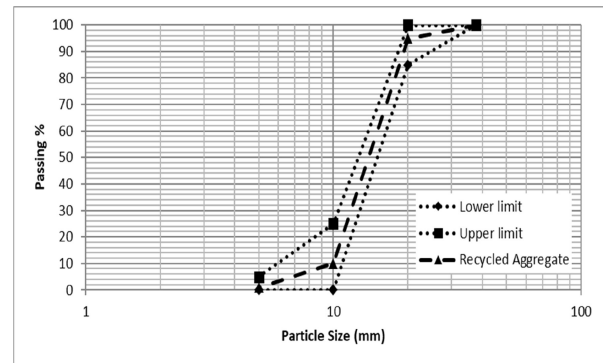
Drinking water was used both in the preparation of the trial mixes and for the curing process.



(a) Sieve Analysis of Fine Aggregate



(b) Sieve Analysis of Coarse Aggregate



(c) Sieve Analysis of Recycled Aggregate

Fig. 3. Sieve analysis of aggregate.

2.2.7. Steel section

A hot-rolled steel section was used to produce the hollow steel section, which has a 100 mm (diameter), 600 mm (height), and 1.5 mm (thickness). It is made from stainless steel grade 304 and has a 240 MPa yield strength and 196 GPa elastic modulus.

2.2.8. Steel stiffeners

Four V-shaped sections, each with a 30 mm base, 15 mm height, and 5 mm extension from each side, were used as V-shaped stiffeners. Also, four rounded sections, each with a 30 mm diameter, and 5 mm extension from each side, were used as rounded-shaped stiffeners. The stiffeners were made from the same plate of pipe (stainless steel grade 304, 1.5 mm thickness).

2.2.9. Bolts

A self-drilling screw, truss Philips zinc, 3.5×11 mm, was used to install the stiffener plates; two rows of bolts every 50 mm were used to fix each stiffener section.

2.3. Concrete mixture

Concrete is a mixture of cement, sand, gravel, and water, and is generally applicable in the construction

sector because it is strong and enduring. Nonetheless, environmental concerns regarding waste materials disposal, including the crumb rubber and recycled aggregate, have led researchers to investigate alternative applications of these products. The use of crumb rubber as a partial substitute for fine aggregate in concrete is one such strategy. The recycled aggregate will be incorporated in concrete as a partial substitute for coarse aggregate. The paper examines the effects of the addition of crumb rubber and recycled aggregate to concrete blends and the effects it has on the mechanical properties of the concrete. The concrete mix of this work was ready using various percentages of crumb rubber replacement (0, 15, and 30) and varying percentages of recycled aggregates (0, 25, and 50). The samples of the concrete were then tested for compressive strength. These experiments were done to compare the ability of the fine aggregate and coarse aggregate to withstand compressive forces on the replacement of crumb rubber and recycled aggregate, respectively. This paper sought to establish the feasibility of using the recycled crumb rubber and aggregate as a way of offering practical solutions to the problems of tire disposal and concrete demolition on the environment.

Table 2. Concrete trial mixes for 1 m³.

Trial Mixes	Recycled Aggregate %	Crumb Rubber %	Cement (kg)	Sand (kg)	Crumb Rubber (kg)	Gravel (kg)	Crushed Block (kg)	Water (Liter)
1	0	0	315	630	0	1260	0	157
2	25	0	315	630	0	945	315	157
3	25	15	315	535	40	945	315	157
4	25	30	315	440	80	945	315	157
5	50	15	315	535	40	630	630	157
6	50	30	315	440	80	630	630	157

Table 3. Concrete compressive strength.

Trial Mixes	Recycled Aggregate (%)	Crumb Rubber (%)	f_{cu} (MPa)
1	0	0	37.3
2	25	0	32.5
3	25	15	29.4
4	25	30	26.7
5	50	15	25.4
6	50	30	21.5

2.3.1. Trial mix

Mixing of the concrete must be properly done because it is the only way that the performance and characteristics of the final product will be as measured. Concrete trial mixes are aimed at evaluating the main characteristics of the material, including strength, workability, density, economic factors, etc. Table 2 presents the concrete trial mixes proportions to be used in this study. The slump test gave the workability of each trial mix, and the values are above 60 mm.

2.3.2. Preparing, casting, and curing of samples

The making and curing of the Portland cement concrete specimens should be done under a standardized process to be accurate and consistent in the effects. These are essential in determining the power and nice of the concrete trial blend, which are essential in determining its performance towards construction functions. The individual trials are tested to determine their compressive energy. Three sub-columns were cast in each concrete trial mix to have variety in the forms of the test. Three cubes were cast and experimented with to measure the compressive strength of the concrete. All these specimen types are aimed at giving a complete analysis of the concrete characteristics under different loading. The process of casting was done according to the guidelines provided in the British Standard BS 1881:1983, and all the specimens were done as per the internationally accepted methods of concrete testing. The samples were also cured under a controlled environment so that the cement was well hydrated and the concrete mix did not suffer any damage. Curing is a vital process in the production of concrete because it ensures

that the material acquires the required strength and durability.

2.3.3. Concrete compressive strength

Table 3 indicates compressive strength of concrete cubes (f_{cu}), average compressive strength of three normal cubes (150 × 150 × 150 mm) at the end of 28 days of drying, which is used to show the effect of crumb rubber and recycled aggregate on the concrete strength. It used the procedures of the British Standard BS 1881:1983 [36] in casting and testing. The statistical discussion indicates that recycled aggregate (RA) and crumb rubber (CR) have significant effects on the compressive strength of concrete, which reduces the concrete strength. The RA content (-0.91) and the CR content (-0.87) showed a strong negative correlation with the strength, which depicts that the higher the replacement level, the lower the performance. The blends with zero amounts of recycled materials had the greatest strength (37.3 MPa), whereas the mixture with 50% RA and 30% CR had the lowest strength (21.5 MPa). Altogether, these findings prove the hypothesis that the use of RA and CR influences the concrete strength significantly, although RA influences the concrete strength more than CR.

2.4. Test setup and loading procedure

This study utilized a loading frame, shown in Fig. 4, to test column specimens. The loading frame could adjust to accommodate specimens of varying lengths and could withstand compressive loads up to 1500 kN. A load cell capable of measuring up to 600 kN was connected to the loading frame to measure the load application. Data acquisition technology was

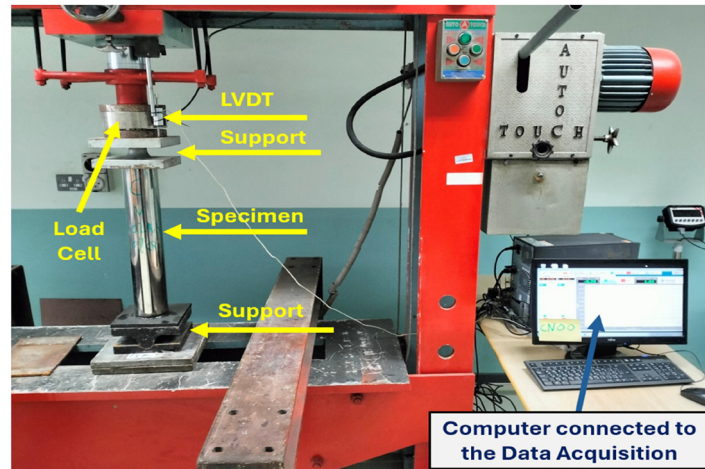


Fig. 4. Test setup for specimens.



(a) Local Buckling



(b) Local and Flexural Buckling



(c) Bulge

Fig. 5. Failure modes.

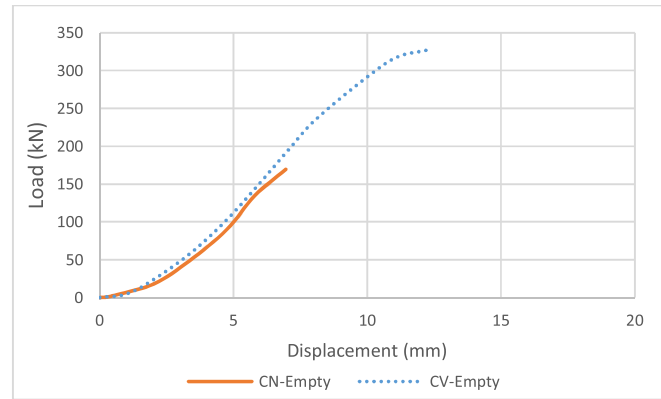
employed to record the load and axial shortening data from the LVDT. The load was applied incrementally, from zero loading up to failure, as a static load, with a rate of 50 kN / minute. The load-axial shortening curves, as well as the column strengths and failure modes, were observed and recorded during the tests. To provide a concentric axial load, the specimen was placed between the top and bottom supports. Each support consists of dual 200 × 200 × 25 mm steel plates. The column shortening was measured by fixing one LVDT, with an accuracy of 0.00001 mm, at the top support, as shown in Fig. 4.

3. Experimental results and discussion

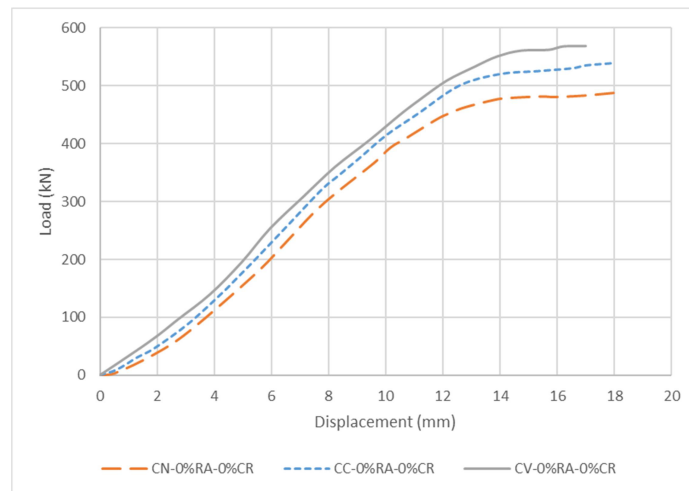
The column test behaviour, including failure modes and load-to-axial shortening relationship, was observed for each specimen.

3.1. Crack pattern and failure modes

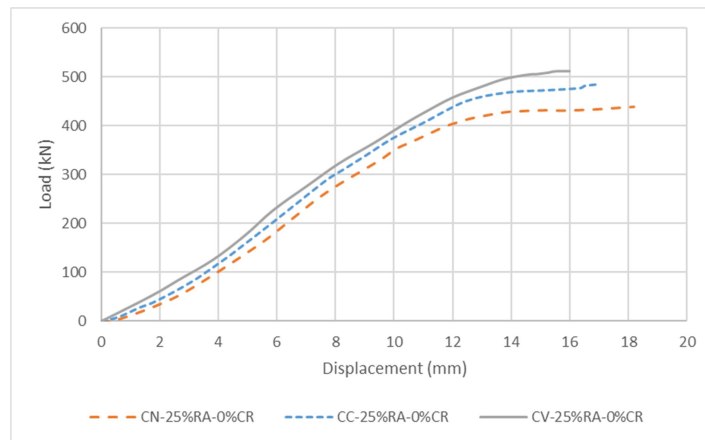
Various failure modes were observed, as shown in Fig. 5, and the failure type for each specimen was listed in Table 4. These modes included steel tube local buckling, bulge, and flexural buckling. Local buckling of the stainless-steel tube occurred if the diameter to thickness ratio exceeded the limitation of ANSI/AISC 360-22 [37]. In these cases, the stainless-steel tube buckled in the areas below or near the top-loading plate where the load was applied. In the concrete-filled stainless steel column tests, the predominant failure modes were local buckling coupled with concrete crushing. Concrete crushing followed local buckling due to the loss of the composite effect after the stainless-steel tube was subjected to local buckling. In the concrete-filled stainless steel column tests, the predominant failure modes were



(a) Hollow Stainless-Steel Column Sections (Group-1)

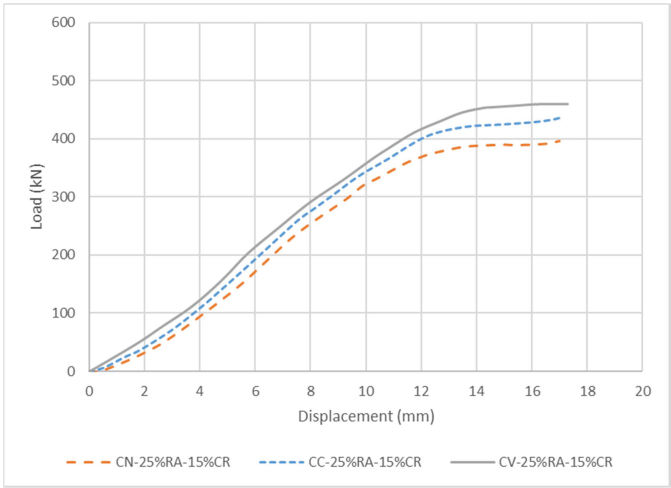


(b) Stainless steel columns filled with concrete with 0% RA and 0% CR (Group-2)

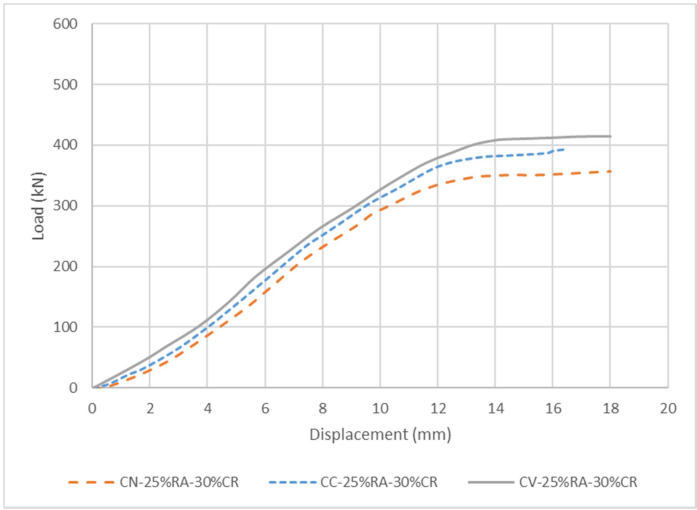


(c) Stainless steel columns filled with concrete with 25% RA and 0% CR (Group-3)

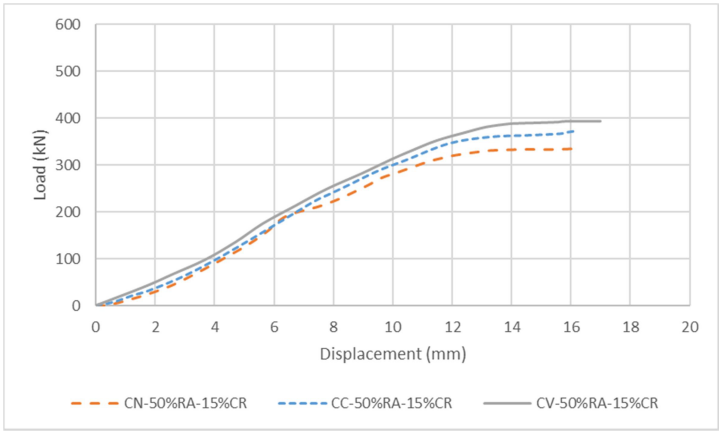
Fig. 6. Continue.



(d) Stainless steel columns filled with concrete with 25% RA and 15% CR (Group-4)

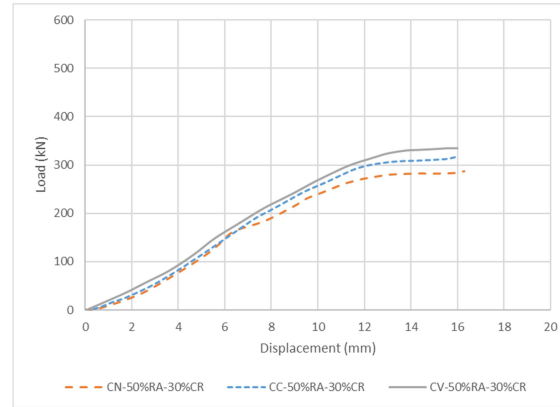


(e) Stainless steel columns filled with concrete with 25% RA and 30% CR (Group-5)



(f) Stainless steel columns filled with concrete with 50% RA and 15% CR (Group-6)

Fig. 6. Continue.



(g) Stainless steel columns filled with concrete with 50% RA and 30% CR (Group-7)

Fig. 6. Axial load vs axial shortening curves for tested specimens.

Table 4. Results of tested specimens.

Group	Specimen	P_u (kN)	P_u/P_{ur}	P_u/P_{ugr}	Failure Type
1	CN-Empty	169	1.00	1.00	Local buckling
	CV-Empty	327	1.93	1.93	Local buckling
2	CN-0%RA-0%CR	488	2.89	1.00	Local buckling
	CV-0%RA-0%CR	568	3.36	1.16	Mid bulge
3	CC-0%RA-0%CR	539	3.19	1.10	Local buckling
	CN-25%RA-0%CR	443	2.62	1.00	Local buckling
	CV-25%RA-0%CR	512	3.03	1.16	Local buckling
4	CC-25%RA-0%CR	485	2.87	1.09	Local buckling
	CN-25%RA-15%CR	397	2.35	1.00	Local buckling
	CV-25%RA-15%CR	460	2.72	1.16	Local buckling
5	CC-25%RA-15%CR	437	2.59	1.10	Flexural buckling
	CN-25%RA-30%CR	356	2.11	1.00	End bulge
	CV-25%RA-30%CR	414	2.45	1.16	End bulge
6	CC-25%RA-30%CR	393	2.33	1.10	Local buckling
	CN-50%RA-15%CR	335	1.98	1.00	End bulge
	CV-50%RA-15%CR	394	2.33	1.18	Flexural buckling
7	CC-50%RA-15%CR	373	2.21	1.11	Local buckling
	CN-50%RA-30%CR	286	1.69	1.00	Local buckling
	CV-50%RA-30%CR	335	1.98	1.17	Local buckling
	CC-50%RA-30%CR	317	1.88	1.11	Flexural buckling

Where: P_{ur} is the reference specimen (CN), P_{ugr} is the reference for each group.

a combination of flexural buckling and local buckling. In another case, concrete crushing may occur before steel local buckling, and this makes a bulge in the section. Finally, a flexural failure mode or bulge was observed in some concrete-filled stainless-steel columns.

3.2. Ultimate load

Adding V-shaped stiffeners to the hollow stainless-steel sections' columns increases the ultimate load by about 93%, as listed in Table 4. These increases occurred due to the change in section size, and these strengthening elements acted as a support for the thin layer of the hollow section.

Fig. 6 shows that stiffeners improve the performance of concrete-filled stainless-steel columns made from recycled aggregate and crumb rubber. The round-shaped stiffener increases the ultimate load by approximately 9% to 11%, while the V-shaped stiffener increases the ultimate load by approximately 16% to 18%, as shown in Table 4. V-shaped stiffeners provide a further improvement, as the removed area of the infilled concrete is approximately 68% smaller than that removed using spherical stiffeners.

From Table 4, the maximum observed ultimate load was for the normal concrete with V-shaped stiffeners (CV-0%RA-0%CR) specimen; the effect of filled material and stiffener enhances the strength of the hollow section by about 336%. Enhancement strength of hollow section decreased to 169% for the

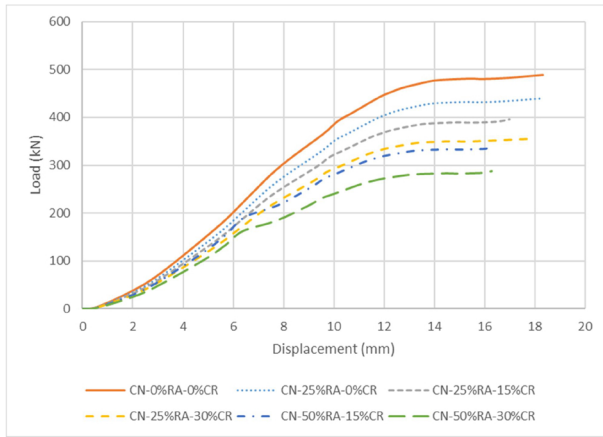


Fig. 7. Effect of RA% and CR% for sections without stiffeners.

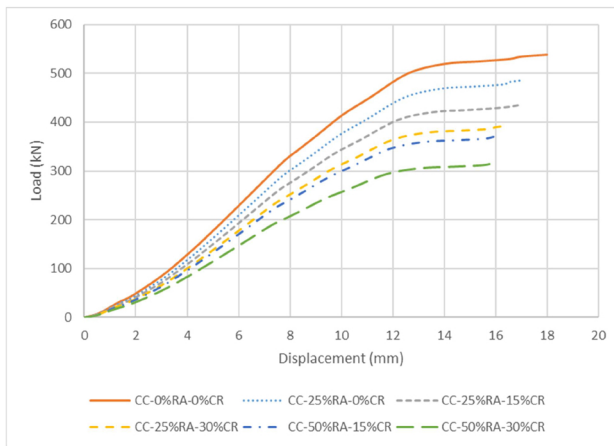


Fig. 8. Effect of RA% and CR% for sections with round-shaped stiffeners.

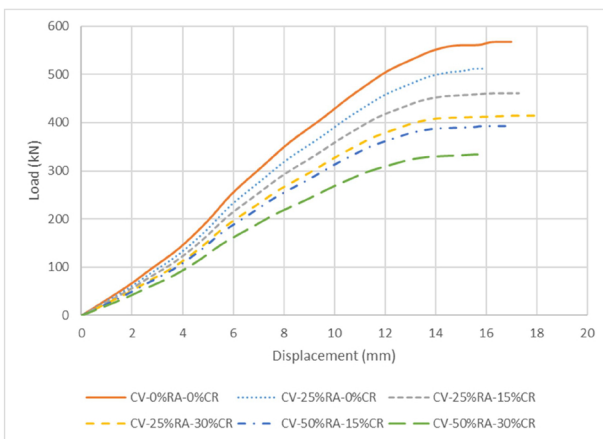


Fig. 9. Effect of RA% and CR% for sections with V-shaped stiffeners.

specimen with 50% recycled aggregate with 30% crumbed rubber (CN-50%RA-30%CR). Also, there is only a slight enhancement in the strength of the hollow stiffener specimen when filled by 50% recycled aggregate and 30% crumbed rubber (for specimens CV-50%RA-30%CR and CC-50%RA-30%CR).

Figs. 7 to 9 illustrate the effect of the compressive strength of the infilled concrete on the behaviour of concrete-filled stainless-steel columns containing recycled aggregate and crumb rubber for sections with/ without stiffeners. The addition of RA and CR by several percentages reduces the compressive strength of the concrete, resulting in a reduced load-bearing capacity of the concrete-filled stainless-steel columns. This result remains true even with the use of V-shaped and Round-shaped stiffeners. As mentioned by Huiyong Ban et al. [38], if there is no significant decrease in the length, the loading was stopped if the specimen shortening exceeded 4% of its length.

4. Theoretical results

The results of maximum applied loads from experiments will be compared with the theoretical results of the proposed equations of design codes. The proposed equations of concrete-filled steel tube columns from the following codes: American code (AISC 360-22) [37], Eurocode (EN 1994-1-1) [39], Japanese code (AIJ) [40], and Chinese Code (GB/T 51446-21) [41] will be used to make a comparison with the experimental results. Table 5 summarizes of proposed equations in existing design codes for circular compact concrete-filled steel tube columns.

Where: A_s is the area of steel section; A_c is the area of concrete; f_y is the steel yielding strength; f'_c is the compressive strength of cylinder concrete specimen (assumed equivalent to $0.8 f_{cu}$); η_a and η_c are the code coefficients; D/t is the diameter to thickness of steel section ratio; $\xi = A_s f_y / A_c f'_c$

Table 6 shows the comparison between different codes' proposed equations of column and experimental results. The results of the mean values for these codes are conservative (prediction values are greater than experimental results).

The prediction values from AISC are more conservative, with an average result greater than 29% from experimental results, with a 0.015 coefficient of variation. While GB/T with an average result greater than 6% from experimental results with a 0.009 coefficient of variation. The prediction values from EN and AIJ with an average result greater than 20%, and

Table 5. Design code equations for CFST columns.

Code	N_u	D/t critical ratio
AISC 360-22	$P_u = A_s f_y + 0.95 A_c f'_c$	$0.09 E / f_y$
EN 1994-1-1	$P_u = \eta_a A_s f_y + A_c f'_c (1 + \eta_c t f_y / D f'_c)$	$21150 / f_y$
AIJ	$P_u = 1.27 A_s f_y + 0.85 A_c f'_c$	$36000 / f_y$
GB/T 51446-21	$P_u = (A_s + A_c)(1.14 + 1.02 \xi) f_{ck}$	$25250 / f_y$

Table 6. Comparison between codes, proposed equations, and experimental results.

Spec.	Exp.		Theoretical Load (kN)						
	P_u (kN)	AISC	P_{ex}/P_{th}	EN	P_{ex}/P_{th}	AIJ	P_{ex}/P_{th}	GB/T	P_{ex}/P_{th}
CN-0%RA-0%CR	488	338	1.45	374	1.30	345	1.41	408	1.20
CV-0%RA-0%CR	568	388	1.47	406	1.40	418	1.36	480	1.18
CC-0%RA-0%CR	539	380	1.42	395	1.37	414	1.30	474	1.14
CN-25%RA-0%CR	443	309	1.43	346	1.28	319	1.39	371	1.19
CV-25%RA-0%CR	512	362	1.41	381	1.35	395	1.29	446	1.15
CC-25%RA-0%CR	485	356	1.36	371	1.31	393	1.24	442	1.10
CN-25%RA-15%CR	397	290	1.37	328	1.21	303	1.31	348	1.14
CV-25%RA-15%CR	460	346	1.33	364	1.26	381	1.21	424	1.08
CC-25%RA-15%CR	437	341	1.28	355	1.23	379	1.15	421	1.04
CN-25%RA-30%CR	356	274	1.30	313	1.14	289	1.23	327	1.09
CV-25%RA-30%CR	414	332	1.25	350	1.18	368	1.12	405	1.02
CC-25%RA-30%CR	393	328	1.20	342	1.15	367	1.07	404	0.97
CN-50%RA-15%CR	335	267	1.26	305	1.10	282	1.19	317	1.06
CV-50%RA-15%CR	394	325	1.21	343	1.15	362	1.09	396	1.00
CC-50%RA-15%CR	373	321	1.16	336	1.11	362	1.03	395	0.94
CN-50%RA-30%CR	286	243	1.18	283	1.01	261	1.10	288	0.99
CV-50%RA-30%CR	335	304	1.10	322	1.04	343	0.98	368	0.91
CC-50%RA-30%CR	317	302	1.05	316	1.00	345	0.92	369	0.86
Mean value			1.29		1.20		1.19		1.06
COV			0.015		0.014		0.019		0.009

19% from experimental results, with 0.014 and 0.019 coefficient of variation, respectively.

5. Conclusions

The behaviour of stainless-steel columns filled with crumb rubber and recycled aggregate concrete was investigated. The results of various tests indicated that:

1. Adding V-shaped stiffeners improves the behavior of the stainless-steel column, either as hollow sections or as concrete-filled sections.
2. Using RA and CR reduces the compressive strength of concrete, which is used as a filler material for the stainless-steel hollow sections' columns. A reduction will follow this reduction in column capacity.
3. The common failure shape of the columns is local buckling. Also, the investigations show failure due to flexural buckling and bulge due to concrete crushing.
4. The V-shaped stiffeners increase the column's ability to resist the axial load more than the

rounded-shaped as the deducted area from concrete is less.

5. The ultimate load capacity of CFST columns predicted by the design codes (AISC, EN, AIJ, and GB/T) is conservatively in comparison with experimental results, and the best predictors were proposed by GB/T.
6. The study's findings contribute to a better understanding of sustainable production practices and highlight the potential of using recycled materials in concrete production.

Author contributions

Wadhah M. Tawfeeq contributed to the conceptualization, methodology design, supervision, original draft preparation, project administration, and funding acquisition. **Mohammed M. Rasheed** was responsible for numerical modeling, formal analysis, data curation, and review and editing of the manuscript. **Mithaq Kohees** handled validation and visualization. **Ahmed W. Al Zand** contributed to structural analysis, provision of resources, and manuscript review and editing. **Saif Al-Balushi** was involved in laboratory work, sample preparation, and

data acquisition, while **Hamed Al Abdul Salam** assisted with experimentation, technical support, and validation.

Conflict of interest

The authors declare that they have no conflicts of interest relevant to this work.

Data availability

All data and materials generated or analyzed during this study are included in the published article.

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