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FLEXURAL BEHAVIOR OF REINFORCED CONCRETE BEAMS USING SYNTHETIC AGGREGATES PRODUCED FROM CONCRETE WASTE POWDER IN VIETNAM

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ABSTRACT: The use of recycled aggregates from construction and demolition waste (CDW) in concrete mixes is widely practiced in developed countries. To promote the recycling of CDW, using recycled aggregates in the construction field needs to be more widely studied. However, there are still limitations in recycling powder waste generated from the crushing process of CDW. In this study, a type of artificial aggregate called synthetic aggregates (SA), made from waste concrete recycled fine powder (WFC), is used as recycled coarse aggregates (RCA) in concrete mixes. Reinforced concrete (RC) beams were made with five different SA contents (0%, 25%, 50%, 75%, and 100%) for the replacement of natural coarse aggregates (NCA). The 4-point bending test was used to analyze the bending behavior of reinforced SA-concrete (CSA) beams with reference to equivalent conventional concrete (CC), such as cracking load, ultimate load, maximum deflection, failure mode, and ultimate flexural strength. The results showed that there was no significant difference in the ultimate load of CSA beams compared to CC beams (2.42–4.41%). However, the first cracking loads of CSA beams reduced significantly by 28% and 49% when the SA contents were at 75% and 100%. Furthermore, as the number of flexural cracks increased, the mid-span deflection of the CSA beams also increased with the SA content, indicating a decrease in the stiffness of the beam. These results may serve as recommendations for the design of flexural CSA beam members in Vietnam.

Keywords: Synthetic aggregate; Construction and demolition waste; Waste concrete recycled fine powder; Recycled aggregates; Flexural strength of beams.

1. INTRODUCTION

The rapid development of urbanization in Vietnam has generated a great demand for constructing new buildings and renovating and demolishing old buildings. This development has consumed a large amount of natural resources and caused severe environmental issues for society. Moreover, CDW is not properly collected and recycled. In Hanoi city, the amount of CDW was estimated to be approximately 4,186 tons/day in 2021. This amount will reach 9,431 tons/day in 2025 [1]. It was reported by the Ministry of Natural Resources and Environment (MONRE) in 2019 that the total amount of CDW generated in Vietnam was approximately 20 million tons [2], and most of this CDW was used for landfill purposes without any treatment. A large amount of CDW is illegally dumped in public areas, causing adverse social and environmental impacts.

Recycling CDW as a construction aggregate is one of the key solutions for saving natural resources and protecting the environment. A number of studies have been carried out on the use of recycled aggregates for concrete. However, much waste powder generated during the CDW crushing process is still discharged into the environment without treatment. Producing RCA generates approximately 15–35% of waste concrete powder and is discharged in landfills without reuse or recycling [3]. Many studies have been carried out to support the development of the concrete industry. Many types of recycled waste materials, such as recycled aggregates from CDW [4], waste glass [5], pumice stone [6], and bauxite material [7], have been used as aggregates in concrete production. Therefore, in recent years, researchers have started to study the application of powder waste to make RCA in concrete [8].

SA manufacturing technology combines waste fine powder aggregates with a binder. The powdered material is bonded together, hardened, and ultimately formed into granular materials with specific aggregate sizes. There are two methods used to manufacture SA: (i) cold-bonded SA and (ii) sintered SA [8]. Many types of solid waste, such as fly ash [9], recycled CDW [10], quarry waste [11], rice husk ash and iron ore dust [12], polypropylene waste [13], and waste bricks [14], are considered raw materials for SA production as coarse aggregates for concrete. Many studies stated that SA concrete decreased its durability and mechanical properties compared to conventional concrete based on the tested results from compressive strength, elastic modulus, splitting tensile strength, and so on, and few studies have focused on applying SA to concrete structures. The performance of SA concrete structures needs to be studied for durability, deflection, and so on. Zhang et al. (2021) [15] utilized RCA for structural applications to prepare RC beams with cross-sections of 100×250×1800 mm. Replacement ratios of 30%, 70% and 100% were used. The results showed that using SA did not significantly affect the crack pattern, failure mode, or bending moment capacity of the tested beams. Samadi et al. (2022) [16] used recycled ceramic as the cement and aggregate. It was reported that the flexural strength of recycled aggregate concrete beams was 6% lower than that of the control concrete beams at a similar cracking level. Pamudji et al. (2021) [17] used SA manufactured from sand-coated polypropylene with different water-to-cement (w/c) ratios. The flexural strengths of RC beams with w/c ratios of 0.35 and 0.36 were reduced by 4.89% and 5.04% compared with the flexural strength of beams with a w/c ratio of 0.30 [17].

The objective of this study is to use SA produced from waste concrete recycled fine powder (WCF) for partially or entirely replacing natural coarse aggregates in the concrete mix and evaluate its impact on the flexural behaviors of RC beams, including cracking load, ultimate load, maximum deflection, failure mode, and flexural strength. For these purposes, the 4-point bending test was carried out in the laboratory to analyze the flexural behavior of CSA beams. Five types of beams were used in the trials, and afterward, the findings were analyzed and discussed.

2. RESEARCH SIGNIFICANCE

In this study, a type of recycled aggregates called SA has been produced from waste concrete recycled fine powder that was sorted from construction and demolition waste. This type of SA has properties that satisfy the necessary conditions to replace NCA in concrete production. The physical and mechanical properties of concrete using SA aggregate replacement of NAC have been studied. Since then, this study has used SA aggregates to evaluate the flexural behavior of RC beams. This study proposes the appropriate SA content in concrete mixture design for building structures. This will contribute to protecting the environment and saving the increasingly limited supply of natural resources.

3. MATERIALS AND EXPERIMENTAL PROGRAM

3.1 SA properties

SA was produced from WCF and cement. The mixture was composed of WCF (85%) and cement (15%) by weight, and water was continuously added until the SA seeds formed. The SA material was produced using a pelletizer and stored at room temperature for at least 28 days until it completely hardened. These aggregates were classified into two types of varying sizes: (i) from 5 to 10 mm and (ii) from 10 to 20 mm, as shown in Fig. 1. They were used to replace NCA in concrete. Physical and mechanical properties such as apparent specific gravity, dry bulk specific gravity, water absorption, crushing value, and Los Angeles abrasion value were determined according to the Vietnamese standard TCVN 7572:2006 [18]. The physical and mechanical properties of the SA are presented in Table 1.

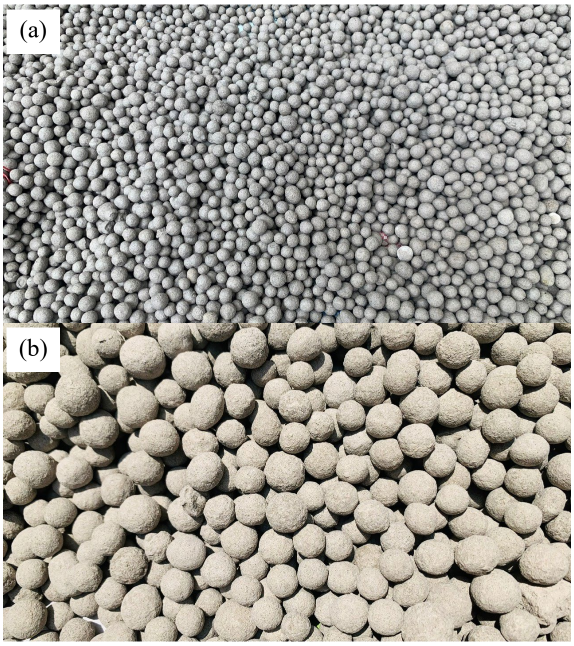


Fig. 1 SA materials: (a) particle size 5-10 mm; (b) particle size 10-20 mm

Table 1. Physical and mechanical properties of SA [19]

Size (mm)	5-10	10-20
Specific gravity (g/cm^3)	2.55	2.45
Dry bulk specific gravity (g/cm^3)	1.90	1.85
Saturated bulk specific gravity (g/cm^3)	2.15	2.10
Crushing value (%)	19.2	27.9
Los Angeles Abrasion (%)	23	33
Water absorption (%)	13.2	13.2

Scanning electron microscopy (SEM) technique was used to observe the microstructure of the SA, as shown in Fig. 2. SEM images were obtained using energy-dispersive X-ray spectroscopy (TM4000Plus, Hitachi High-Tech Corp., Tokyo, Japan, and AZtecOneGO, Oxford Instruments, Abington, UK). The SEM images revealed a uniform distribution of WCF in the SA concrete. The chemical analysis showed that the mineral components of SA were amorphous ~55% SiO_2 (Quartz), ~39% $CaCO_3$

(Calcite), and the minor component of ~6% $CaMg(CO_3)_2$ (Dolomite). Fig. 2 shows some particles of large sizes with polygonal and irregular shapes scattered on the surface in SA. In general, WCF particles are pretty uniform in size and evenly distributed in SA.

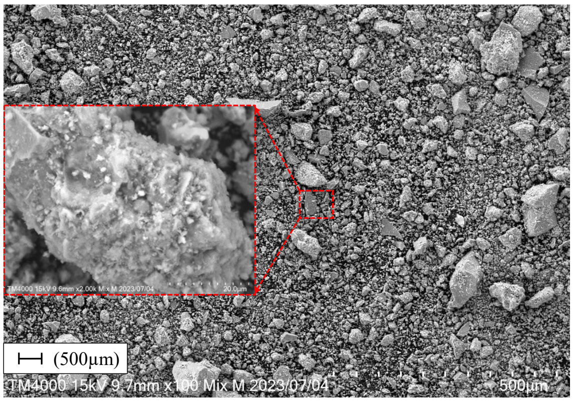


Fig. 2 SEM images of SA

3.2 Materials and mix proportions

In this study, PC40 Portland cement manufactured by But Son factory according to Vietnamese standard TCVN 2682:2009 [20] was used as the binder; the fine aggregate used was yellow sand, in accordance with Vietnamese standard TCVN 7570:2006 [21]; and the coarse aggregate was crushed stone from Cam Pha, Quang Ninh Province, with a maximum size of 20 mm, following Vietnamese standard TCVN 7570:2006 [21]. The gradation curve of the coarse aggregates is shown in Fig. 3.

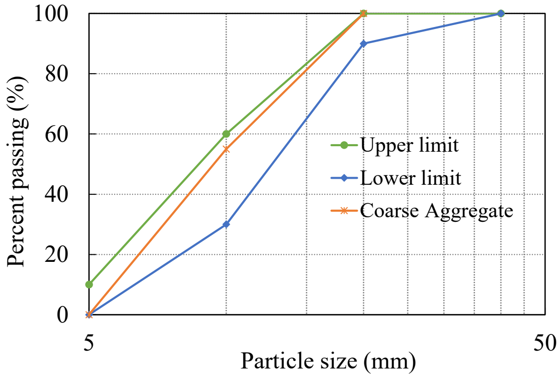


Fig. 3 Gradation of coarse aggregates (5-20 mm)

The mixture of used concretes is listed in Table 2. In this study, five concrete mixtures with different SA contents were studied, including CC mix referred to conventional concrete containing 100% NCA and CSA mixes assigned to a numeration at the end, which represents the content of SA used to replace NCA with 25%, 50%, 75%, and 100% replacement rates, respectively. The w/c ratio in all the concrete mixtures was 0.48. The superplastic admixture is a superplasticizer.

Table 2. Concrete mixtures.

Mix	CC	CSA25	CSA50	CSA75	CSA100
Cement (kg)	344	344	344	344	344
Water (kg)	165	165	165	165	165
Sand (kg)	751	751	751	751	751
NCA (5-10 mm)	570	427	285	142	-
NCA (10-20 mm)	466	350	233	117	-
SA (5-10 mm)	-	142	285	427	570
SA (10-20 mm)	-	117	233	350	466
Admixture (liter)		1.72	1.72	1.72	1.72

3.3. Details of the beam specimens

A total of fourteen RC beams with dimensions of 150×200×1800 mm, as illustrated in Fig. 4, were manufactured in the laboratory and stored under similar environmental conditions (e.g., temperature and humidity). The beam specimens had four longitudinal steel rebars, including 2Φ10 (deformed rebars) at the top layer and 2Φ12 (deformed rebars) at the bottom layer. The stirrups were Φ6 with a regular spacing of 80 mm (plain bar) within 640 mm from the beam ends and a regular spacing of 150 mm within 450 mm at the middle span.

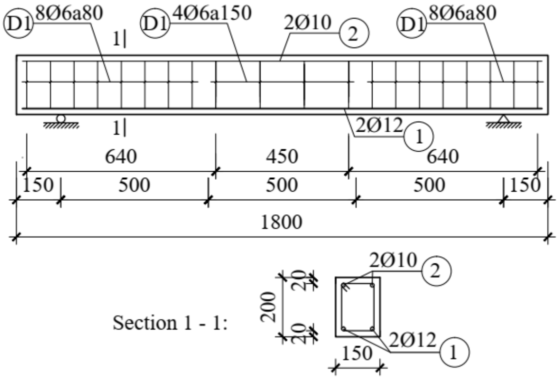


Fig. 4 Detailed layout of the RC beams

Before casting, a tensile test was performed to determine the mechanical properties of the steel reinforcement. The results showed that the yield strength became 375 MPa and 435 MPa for the 10 mm and 12 mm steel rebars, respectively, while the tensile strength became 495 MPa and 550 MPa, respectively.

3.4 Four-point bending test setup

The flexural behavior of the RC beams was tested using the 4-point bending test, as illustrated in Fig. 5.

The applied load, denoted P, was initiated from the hydraulic jack (HJ) and the steel beam (SB) mounted above the specimen. A load cell (LC) with a maximum capacity of 100 kN was attached between the HJ, and the loading rate was maintained at 5 kN/min.

During the loading, the vertical displacements of the beam were recorded by three linear variable displacement transducers (LVDTs), named I1, I2, and I3, positioned at the supports and the middle span of the beam. Then, the deflection at the middle span of the tested beam was calculated. Two strain gauges, denoted SSG1 and SSG2, were bonded on the two tension steel rebars at the middle span to measure the strain of the longitudinal reinforcement under loading. Moreover, a strain gauge, denoted CSG1-PL-60-11-3L, was glued on the top side of the beam, as shown in Fig. 5, to measure the strain of the concrete in the compression zone. The 4-point bending test on a typical beam specimen. During the test, all sides of the beam were carefully observed to determine the cracking load corresponding to the first crack of the concrete due to the loading, and the crack pattern on both opposing sides was drawn.

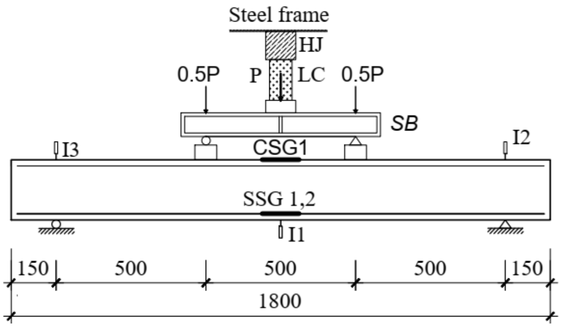


Fig. 5 Arrangement of the 4-point bending test

4. RESULTS AND DISCUSSION

4.1 Compressive strength, tensile strength, and elastic modulus of concretes used

Compressive strength and elastic modulus tests were performed on cylindrical samples with dimensions of 150 mm in diameter and 300 mm in length, according to TCVN 5726:2022 [22].

Table 3. Compressive strength, tensile strength, and elastic modulus, of concretes

Mix	Compressive strength (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)
CC	42.4	6.98	40.5
CSA25	39.8	6.90	33.8
CSA50	34.6	6.27	27.8
CSA75	32.1	5.84	26.1
CSA100	32.6	5.76	23.2

Table 3 lists the compressive strength, tensile strength, and elastic modulus of the tested concrete specimens after 28 days of curing. The compressive strength of CSA concretes decreased with increasing amounts of SA materials in the concrete mixture. The compressive strength of the CSA concrete with 100% SA was 23.2% lower than that of the CC concrete, but the elastic modulus of the CSA100 was 42.7% lower. The strength of SA was weaker than that of NA, partly showing its influence on the properties of concrete. The reduction levels of the compressive strength and elastic modulus are identical to those in previous studies [11,13].

4.2 Load–deflection curves

Figure 6 shows the load–deflection curves of the tested beams. The flexural behavior of these control beams was characterized by three stages: (i) linear behavior before reaching the cracking load (denoted P_{cr}), (ii) nonlinear behavior from the cracking load to the applied load corresponding to steel yielding in the tension longitudinal reinforcement; this yielding was identified by the strain gages SSG1,2 (denoted P_y), and (iii) the failure stage when the deflection considerably increased and ended when the applied load reached the maximum load (denoted P_{ult}). As shown in Fig. 6, the behaviors of the beams were very similar within the applied load at the yielding of the longitudinal reinforcement. Afterward, the behavior was more scattered, resulting in differences in the maximum loads of 85.9 kN for the CC beam. The average mid-span deflection of the CC beams was 24.7 mm. The mid-span deflection of CSA beams increased as the SA replacement ratio increased.

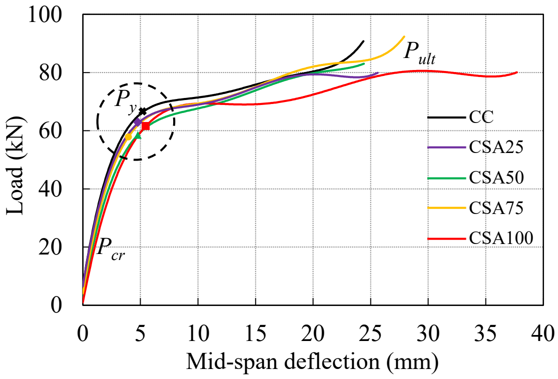


Fig. 6 Correlation of the applied loads at mid-span

Moreover, the ultimate loads of CSA beams were similar to the CC beams. The ultimate loads ranged from 83.5 kN to 89.7 kN (fluctuating approximately 2.42–4.41%) compared to those of the CC beams (see Table 4). The maximum deflections of the CSA beams were 25.5 mm (CSA25), 25.8 mm (CSA50), and 27.8 mm (CSA75), with increases of 3.00%, 4.49%, and 12.4% compared to those of the CC beams. The mid-span deflections of the CSA100 beams were different from those of the other beams. The mid-span deflection was 35.5 mm on average, which was 44% greater than the CC beams (35.5 mm versus 24.7 mm). This accurately reflected the experimental results of the elastic modulus of sample CSA100; the elastic modulus of CSA100 was 42.7% lower than that of CC (see Table 3).

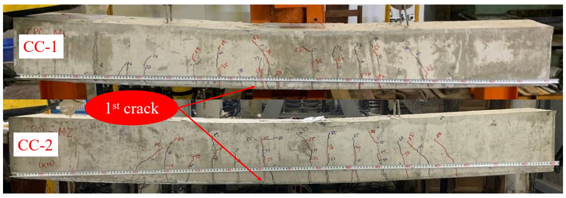
Table 4. Maximum load and deflection of the tested beams

Mix	ID	Ultimate load (kN)	Average load (kN)	Deflection (mm)	Average deflection (mm)
CC	(1)	81.9	85.9	23.5	24.7
	(2)	90.0		27.9	
CSA 25	(1)	91.3	83.5	26.7	25.5
	(2)	81.3		23.0	
	(3)	78.0		26.7	
CSA 50	(1)	82.6	86.2	24.2	25.8
	(2)	91.3		24.4	
	(3)	84.6		28.9	
CSA 75	(1)	92.0	89.7	27.8	27.8
	(2)	88.6		27.6	
	(3)	88.6		27.9	
CSA 100	(1)	87.3	84.2	33.8	35.5
	(2)	88.6		35.1	
	(3)	76.6		37.7	

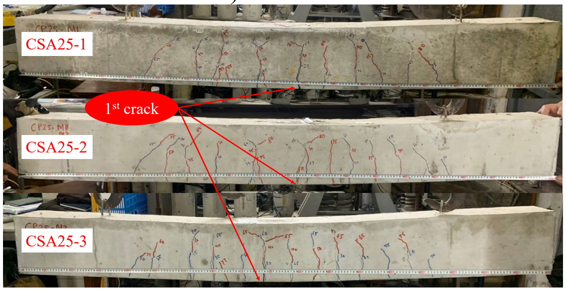
4.3 Cracking pattern and failure mode

The first cracks of all tested beams were observed, and the number of cracks and their patterns were studied to understand the performance of those beams. Fig. 7 shows the cracking pattern of all tested beams at the ultimate loads. It can be seen that most first cracks due to loading are vertical and are concentrated around the 900 mm midspan segment under pure bending, and the subsequent cracks spread to the supports of the beam as the load increased.

As the SA replacement rate increased, the cracking load of the tested beams decreased (Table 5). For the CSA100 beams, the first cracks appeared an at applied load of 12.8 kN on average, followed by 18 kN for the CSA75 beams, 23 kN for the CSA 50 beams, 24.3 kN for the CSA25 beams, and 25 kN for the CC beams. The cracking load of the CSA100 beams was reduced by 49% compared to that of the CC beams. The value of the crack load compared to the ultimate load (P_{cr}/P_{ult}) of the CSA beam also decreased sharply when the percentage of SA replacement ratio was 75% and 100% (CSA75 at 0.2, CSA100 at 0.15, CC at 0.29). The results showed that cracks appeared earlier in CSA with increasing SA content in the concrete mixture, indicating a decrease in stiffness. Moreover, the cracking loads of the CSA25 and CSA50 beams were only 3% and 8% less than that of the CC beams. The earlier cracking was caused by the lower tensile strength of the CSA concrete than that of the CC concrete [23-25]. However, the ultimate loads of the tested beams were similar [7,26]. This result indicated that the SA content in the concrete mix significantly affected the cracking load of RC beams. Based on the results obtained, 25% and 50% SA could be used to replace NCA because the cracking load shows a negligible decrease in stiffness of CSA compared to CC.

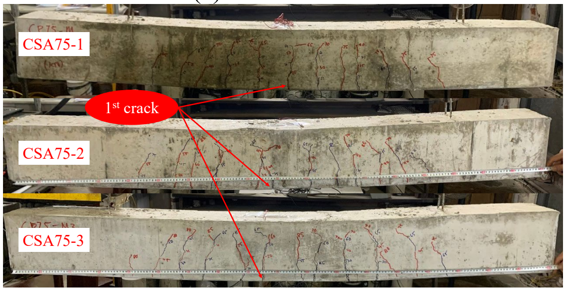


a) CC beams

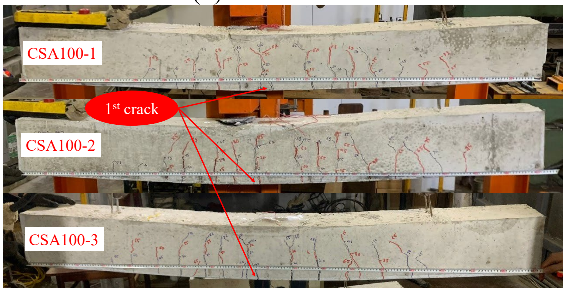


(b) CSA25 beams

(c) CSA50 beams



(d) CSA75 beams



(e) CSA100 beams

Fig. 7 Crack patterns of the tested beams at complete failure

Table 5. Applied loads and cracks in the tested beams

Mix	Beam ID	P_{cr} (kN) Value	Mean	Ratio P_{cr}/P_{ult}	Number of cracks
CC	(1)	25.0	25.0	0.29	15
	(2)	25.0			15
CSA25	(1)	25.0	24.3	0.29	13
	(2)	23.0			14
	(3)	25.0			14
CSA50	(1)	20.0	23.0	0.27	14
	(2)	20.0			14
	(3)	29.0			15
CSA75	(1)	17.0	18.0	0.20	12
	(2)	20.0			13
	(3)	17.0			13
CSA100	(1)	12.6	12.8	0.15	16
	(2)	12.7			15
	(3)	13.0			16

For different concrete mixes, the cracking patterns (e.g., position, number, spacing) on the CSA beams, however, were relatively similar to those on the CC beams. Due to the lower elastic modulus and tensile strength of CSA, flexural cracks formed closer together, thus reducing the spacing between near-neighbor cracks. The maximum spacing between cracks was 141 mm on the CC beams. Meanwhile, the maximum spacings between cracks on the CSA beams were 131, 133, 135, and 138 mm, corresponding to the CSA25, CSA50, CSA75, and CSA100 beams (see Fig. 7). These results were consistent with other reports [23,27]; they found that using recycled aggregates had a negligible effect on the bearing capacity of RC beams.

4.4 Ultimate flexural strength of the beams

The experimental and calculated results of the flexural strength are shown in Table 6. The measured flexural strength of the tested beams became greater than those calculated by current design codes, such as the Vietnamese standard TCVN 5574:2018 [29], American standard ACI 318-19[30], and European standard EC2 [31]. Compared with ACI 318-19 and EC2, TCVN 5574:2018 overestimated the flexural strength of the tested beams. As shown in Table 6, the ratio between the experimental and calculated flexural strength using TCVN 5574:2018 ranged from 1.11 to 1.21 for the CC beams and from 1.03 to 1.26 for the CSA beams. ACI 318 and EC2 underestimated the flexural strength. The results showed that the ratio between the experimental flexural strength and the calculated value was similar to that of TCVN 5574:2018.

Some studies have also shown that the ACI 318 and EC2 underestimated the flexural strength of RC beams in flexure compared to the experimental results obtained from recycled aggregate concrete beams. The experimental results and standard calculations of the flexural strength are similar to those of Yang et al. (2020) [32]. The experimental results and standard calculations of the flexural strength of ACI 318 and EC2 ranged from 1.04 to 1.28 and from 1.07 to 1.26, respectively. Zhang et al. (2021) [15] showed that the ratio between the experimental flexural strength and the calculated flexural strength of ACI 318 ranged from 1.13 to 1.23 when RCA replaced NCA. The test values calculated by ACI 318 range from 1.18 to 1.25 when 5% to 15% recycled brick was used in concrete beams [24]. The ACI 318 and EC2 underestimated the flexural capacity of RCA beams by 5% to 14% [28]. However, these results showed that the SA application in RC beams was reasonable since those CSA beams met the requirements for flexural behavior according to the current design codes, such as TCVN 5574:2018, ACI 318, and EC2. From these results, using SA to replace NCA in RC beams was possible since the experimental results showed higher values than the required values by the design codes mentioned above.

Table 6. Comparison of the tested and calculated flexural strength capacities of the beams

Specimen		$M_{u,exp}$ (kN.m)	$M_{u,TCVN}$ (kN.m)	$M_{u,exp}/M_{u,TCVN}$	$M_{u,ACI}$ (kN.m)	$M_{u,exp}/M_{u,ACI}$	$M_{u,EC2}$ (kN.m)	$M_{u,exp}/M_{u,ACI}$
CC	1	22.5	18.6	1.21	18.5	1.22	18.2	1.24
	2	20.5	18.5	1.11	18.4	1.12	18.1	1.13
CSA25	1	22.8	18.6	1.23	18.4	1.24	18.1	1.26
	2	20.3	18.5	1.10	18.3	1.11	18.1	1.13
	3	19.5	18.4	1.06	18.3	1.07	18.0	1.09
CSA50	1	20.7	18.2	1.13	18.0	1.15	17.7	1.17
	2	22.8	18.3	1.25	18.1	1.26	17.8	1.29
	3	21.2	18.5	1.14	18.3	1.16	18.0	1.17
CSA75	1	23.0	18.2	1.26	18.0	1.28	17.6	1.31
	2	22.2	18.3	1.21	18.1	1.22	17.8	1.25
	3	22.2	18.3	1.21	18.1	1.23	17.7	1.25
CSA100	1	21.8	18.3	1.20	18.0	1.21	17.7	1.23
	2	22.2	18.3	1.21	18.1	1.22	17.8	1.24
	3	18.8	18.2	1.03	18.0	1.04	17.7	1.07

5. CONCLUSIONS

This study used SA to replace NCA. Various experiments were carried out on the concrete specimens and the RC beam to assess the impact of the SA content in the concrete mixture on the flexural behavior of the tested beams. The main conclusions are as follows:

Overall, SA manufactured from WCF have the potential to partially replace NCA in the production of concrete and structural members.

The ultimate loads of CSA beams ranged from 83.5 kN to 89.7 kN (fluctuating approximately 2.42–4.41%) compared to CC beams (85.9 kN). The deflection of the tested beams was significantly affected by the SA content. The CSA100 beams show the maximum mid-span deflection of 35.5 mm on average, which increased by 44% compared to CC beams. This is directly related to the decrease sharply in the elastic modulus of the SA concrete.

The SA content in the concrete mixture significantly affected the cracking load of RC beams. The first cracks of CSA75 and CSA100 beams were reduced by 28% and 49% compared to CC beams. To ensure a minor decrease in the cracking load and stiffness of RC beams made with SA, it is recommended that a maximum of 50% SA content be used for replacing NCA. The failure mode and crack patterns of the tested beams were similar. However, more research is needed to capture the formation and opening of concrete cracks on the CSA beam under loading.

Based on a comparative study between the theoretical and experimental results from the flexural capacity of the tested beams, the current design codes, such as TCVN 5574:2018, ACI 318-19, and EC2, can be applied to estimate the maximum load of RC beams using SA.

The results showed the feasibility of using an appropriate SA content in concrete production. In future research, continue to study the recycling of other types of powder waste from CDW (e.g., masonry blocks, brick walls, mixed CDW) to produce SA and apply it to structures.

6. ACKNOWLEDGMENTS

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