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The Utilisation of Recycled Concrete Aggregate as Partial Sand Replacement in Wall Panel Production

Amir Khomeiny Ruslan[1], Noorsuhada Md Nor[1,*], Muhammad Syaqif Hazim Kamar[1], Muhamad Yusri Zainal[2], Soffian Noor Mat Saliah[1], Sarina Ismail[2], Azmi Ibrahim[3]

[1]School of Civil Engineering, College of Engineering, Universiti Teknologi MARA, Cawangan Pulau Pinang, Pulau Pinang, Malaysia
[2]Pusat Kecemerlangan Kejuruteraan dan Teknologi JKR (CREaTE), Alor Gajah, Melaka, Malaysia
[3]School of Civil Engineering, College of Engineering, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia

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Abstract Recently, extensive research within the concrete industry has been devoted to a sustainable approach by using concrete waste as a natural aggregate replacement. The reason is that the volumes of building-related waste generated nowadays are becoming a significant threat to the environment but they may be used as a useful material in the construction industry. Hence, this study aims to investigate the effects of using recycled concrete aggregates as a partial fine aggregate replacement in mortar cubes and wall panels. Mortar cubes and wall panels sized 70.7 mm x 70.7 mm x 70.7 mm and 1000 mm x 300 mm x 100 mm, respectively, were prepared. The recycled concrete aggregate was mixed into the mortar at percentages of 0%, 50% and 100% of the total mortar volume and designated as 0RCA, 50RCA and 100RCA, respectively. The samples of both the mortar cubes and wall panels were assessed under a compressive strength test. The cubes samples were tested at the ages of 3 days, 14 days and 28 days. Meanwhile, the wall panels were compressively loaded for more than 28 days. It was found that the 0RCA mortar cubes represented the highest compressive strength compared to the other 50RCA and 100RCA samples by 46.6% and 38.8%, respectively. The 50RCA wall panels represented the highest ultimate load of 203.26 kN with strength effectiveness of 179.75% compared to 0RCA and 50RCA wall panels. This indicates that recycled concrete aggregates can be a useful material in the production of wall panels.

Keywords Recycled Concrete Aggregate, Compressive Strength, Wall Panel, Mortar

1. Introduction

Concrete is a widely utilised material worldwide, which is extensively used in civil engineering construction, commercial construction, military projects and in many other contexts. Concrete members are extensively utilised in most countries for structural forms, which have many building applications, from low-rise houses to high-rise multi-storey buildings [1]. Natural resources comprise most of the materials used in concrete building. This has become a major concern that many researchers claim. For instance, Shaban et al. [2] and Tam et al. [3] stated that the world aggregate production increased by 58% in ten years, which was expected to increase to 60 billion tons in 2030 [2, 3]. Recently, many investigations focused on the reusability of concrete waste as aggregate [4–9]. This waste has become an alternative material in the construction industry to reduce the dependency on the use of natural resources. At the same time, it would decrease the accumulation of construction waste disposed in landfill and conserve the environment [5–7].

Recycled concrete aggregate is mainly made from demolition waste, which primarily consists of aggregate and cement. Recycled concrete aggregate is also inhomogeneous and less dense than natural aggregate, and there is a weak interfacial transition zone developed between the mortar and the aggregate [4]. Corinaldesi et al. [10] reported that the volume of residual mortar covers the recycled concrete aggregate in the range of 25% to 60%, depending on the aggregate size. Gomez-Soberon [11] claimed that the recycled concrete aggregate is porous, which makes its water absorption range of 3% to 10% higher compared to that of natural aggregate, which is 1 to 5%. Evangelista et al. [12] discovered that when compared to natural aggregate, the application quality of recycled aggregate is lowered owing to the existence of porous mortar, a weak interfacial transition zone, angular form, and rough texture. As a result, it is typically not recommended for use in structural concrete.

Recently, the use of recycled concrete aggregate has been extensively reported by Nedeljkovic ́et al. [13]. They came to the conclusion that the physico-chemical properties of recycled concrete aggregate have an impact on the performance of hardened concrete. In the meanwhile, the demand of construction industry for cement can be minimized. Performance of concrete, on the other hand, is yet uncertain and depends on a variety of factors. Attri et al. [14] used recycled concrete aggregate to produce concrete paver blocks. They found that coarse recycled concrete aggregate can replace up to 45% of the natural concrete aggregate. Meanwhile, fine recycled concrete aggregate can replace up to 40% of the river sand without having a significant impact on the paver block properties. Recycled concrete aggregate has been used by Rahal and Elsayed [15 Y. Y. Kim, K. M. Lee, J. W. Bang, and S. J. Kwon (2014) Effect of W/C Ratio on Durability and Porosity in Cement Mortar with Constant Cement Amount, Advances in Materials Science and Engineering, Vol. 2014.] to produce beams, in various ranges of 0% to 100%. They found that beams containing recycled aggregate concrete have 12% higher normalised shear strength than beams with natural aggregate.

This review found that the utilisation of recycled concrete aggregate in the construction of wall panels is currently limited. Hence, this article presents the use of recycled concrete aggregate in the production of wall panels as a partial fine aggregate replacement.

2. Materials and Methods

The process flow of this study, the aim of which was to determine the effect of using recycled concrete aggregate as a partially fine aggregate replacement in the production of wall panels, is presented in Figure 1. The process started with the material preparation of recycled concrete aggregate, natural fine aggregate, cement and water. This was followed by the sample preparation of both the mortar cubes and the wall panels. The compressive strength tests were then conducted on the hardened mortar cubes and wall panels. The compressive strength, stress, maximum load and deflection were then identified. Finally, the effects of using recycled concrete aggregate as a partial fine aggregate replacement in the production of mortar cubes and wall panels were examined.

Table 1. Designations and percentages of the recycled concrete aggregate in the mortar mix

Designations	Recycled concrete aggregate (%)	Natural aggregate (%)
0RCA	0	100
50RCA	50	50
100RCA	100	0

2.1. Preparation of Material

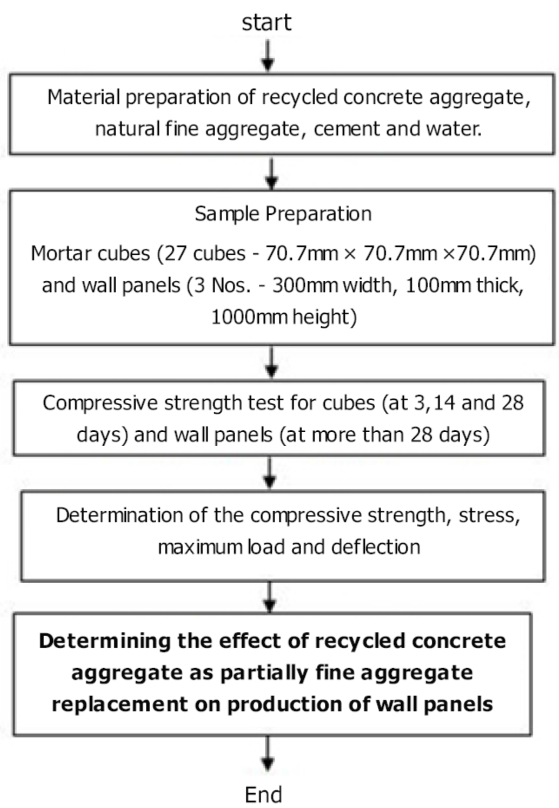

Figure 1. Process flow of the determination the effect of recycled concrete aggregate as partially fine aggregate replacement in mortar

The recycled concrete aggregate was utilised in place of some of the fine aggregate in the mortar mix. Three proportions of mortar mix design were used, as presented in Table 1. The first mix was 0% recycled concrete aggregate with 100% natural fine aggregate, designated as 0RCA. The second mix was 50% recycled concrete aggregate and 50% natural fine aggregate, designated as 50RCA.

The third mix was 100% recycled concrete aggregate and 0% natural fine aggregate, designated as 100RCA. The percentage of the recycled concrete aggregate was based on the total mortar volume. A constant water-cement ratio of 1.0 was used to produce the mortar containing the recycled concrete aggregate. Meanwhile, the water-cement ratio of 0.5 was utilised to produce 0RCA. Different water-cement ratios were utilized for production of the mortar. In this case a quantity of water needs to be added to the mortar mix containing RCA so that the water-cement ratio becomes 1.0. It is done to ensure that the good workability of fresh mortar can be achieved [16].

The recycled concrete aggregate was prepared by collecting the concrete cubes to be tested from a batching plant. Figure 2 shows the process of crushing the tested concrete cubes. A hacker was used to reduce the size of the tested concrete cubes to a range of 60 mm to 80 mm in length.

A sledgehammer was then used to crush the tested concrete cubes into smaller pieces. An abrasion machine was used to reduce the recycled concrete aggregate into fine aggregate. For natural fine aggregate, river sand was used.

Figure 2. Crushing proses for making recycled concrete aggregates

Based on Figure 3, it can be inferred that the recycled concrete aggregates were reduced to various sizes during the process of crushing and sieving, which gives particle size distribution of recycled concrete aggregate that were comparable to non-RCA aggregate. Both aggregates were classified as medium graded slightly silty gravelly sand.

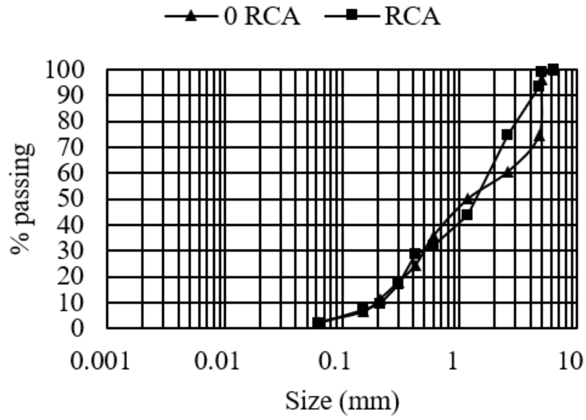

Figure 3. Sieve analysis of 0RCA and RCA aggregates

2.2. Preparation of Cubes and Wall Panels

For the preparation of the mortar cubes and wall panels, the same proportion was used, as presented in Table 1. The sample designated as 0RCA was prepared with a mortar mix design of 1: 0: 4 for fine aggregate: recycled concrete aggregate: cement. Meanwhile, for sample 50RCA, the mortar mix design was 1: 2: 2 for natural fine aggregate: recycled concrete aggregate: cement. A proportion of 0: 1: 4 for fine aggregate: recycled concrete aggregate: cement was prepared for sample 100RCA. For each proportion, all the materials were mixed and cast. For the fresh mortar, the flowability tests for each mix were conducted. It is to have good workability of the fresh mortar [17]. For the 0RCA and mixture containing RCA, the water cement ratio of 0.5 and 1.0 were utilized, respectively. The mortar cubes were cured until the ages of either 3, 14 or 28 days. The curing process for the wall panels was carried out by covering the wall with thick sacks and watering it until wet three times a day, once each in the morning, afternoon and evening.

Wall panels with a size of 300 mm wide, 100 mm thick and 1000 mm in height were cast vertically in order to maintain their stability. Figure 4 shows the size of the prepared wall panels.

2.3. Compressive Strength of Cubes and Wall Panels

Table 2 depicts the number of mortar cubes prepared in order to determine their compressive strength at the ages of 3, 14 and 28 days. There was a total of 27 mortar cubes prepared. For the analysis, the average compressive strength was identified for each mortar cube age.

For the wall panels, a total of three samples were prepared. They were tested at the age of more than 28 days [17, 18], as the optimum strength of the wall is reached after this time. A compressive uniformly distributed load was applied on top of the wall, which had been erected vertically, as shown in Figure 5. The load was applied to the wall panels until failure. The same load rate of 0.01 mm/min was utilised throughout the testing of all the wall panels.

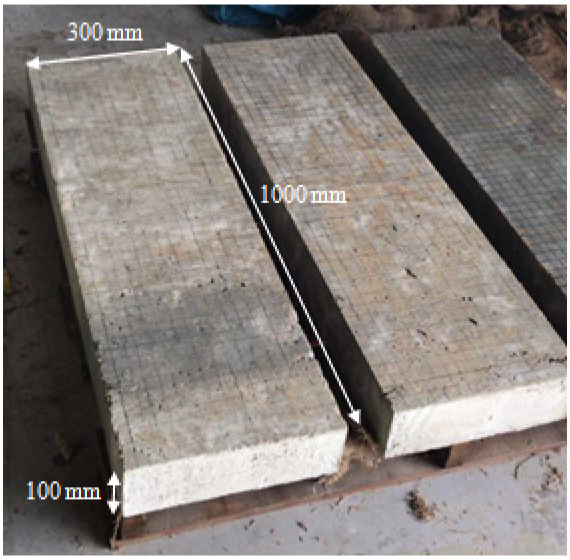

Figure 4. Dimension of the wall panel

Linear vertical displacement transducers (LVDTs) were applied at selected locations, as shown in Figure 5. The LVDTs were applied to determine the deflection of the wall at these locations. Three LVDTs (LVDTs 1 – 3) were located at mid-height of the wall and one LVDT (LVDT4) was located at 250 mm from the base of the wall, as shown in Figure 5. A data acquisition system was used to store the data collected from the tests.

Table 2. Number of mortar cubes at respective days

Type of mortar	Days		
	3	14	28
0RCA	3	3	3
50RCA	3	3	3
100RCA	3	3	3

2.4. Analyses

All the data collected from the data acquisition system were analysed. The compressive strength of the cubes was determined at 3, 14 and 28 days. The strength effectiveness of recycled concrete aggregate was determined as a partially fine aggregate in mortar.

For the wall panels, the relationship between the load and the deflection was performed to identify the ultimate load of each wall panel. The strength effectiveness test of the application of the recycled concrete aggregate as partially fine aggregate in the mortar mix used in wall panel production was performed.

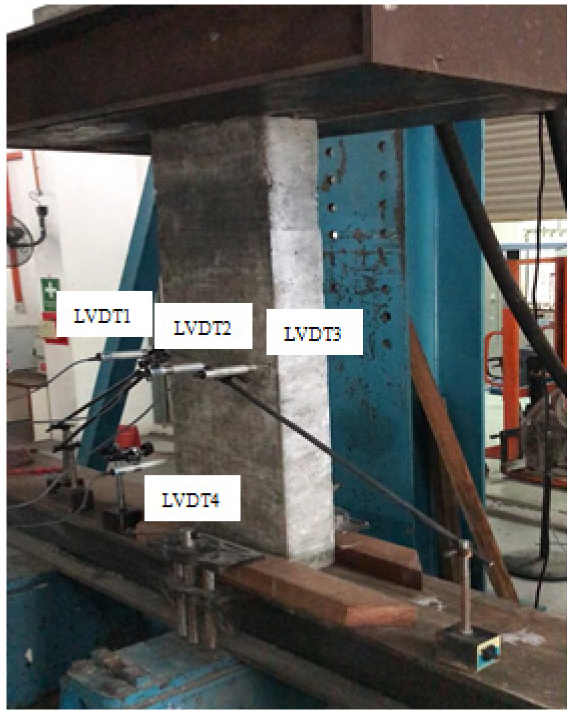

Figure 5. Test set-up of the wall panel

3. Results and Discussion

3.1. Workability of the Fresh Mortar

Figure 6 presents the results from the flow table tests for the 0RCA, 50RCA and 100RCA samples used in this study. The greatest diameter spread was recorded on 50RCA, with an average spread of 51 cm, while the lowest was recorded on 0RCA, with an average spread of 45 cm. The percentage of flowability for 0RCA, 50RCA and 100RCA were 80%, 105.3% and 92%, respectively. The value of flow test was in the range of 0 to 150%, indicating the high workability of the concrete mortar.

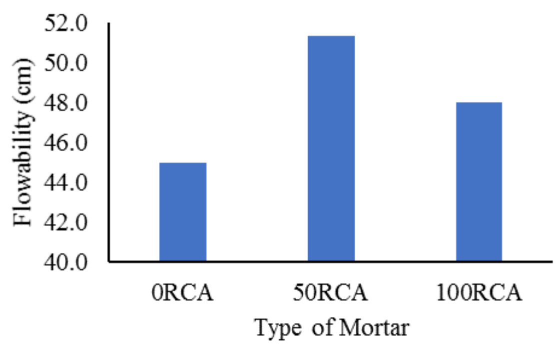

Figure 6. Flowability of the fresh mortar

3.2. Density of the Mortar Cubes

The results of the bulk density of the 0RCA, 50RCA and 100RCA samples are shown in Figure 7. The bulk density of all samples increased, with concrete age of 3 days corresponding to the lowest bulk density and the age of 28 days corresponding to the highest bulk density. The bulk density of normal concrete aggregate (0RCA) ranges from 2,136 to 2,178 kg/m^3 and it was observed that the bulk density of 50RCA and 100RCA was between 1,934 and 2133 kg/m^3. The bulk density of the mortar containing RCA was lower than that of the mortar containing no RCA. Table 3 presents the reduction in bulk density of 0RCA in comparison with that of 100RCA. Three-day old recycled concrete aggregate gave the highest reduction (9.46%) in bulk density while the 28-day old recycled concrete aggregate gave the lowest reduction (8.36%) in bulk density.

The bulk density of 0RCA aged 28 days was approximately 2178.6 kg/m^3 while the bulk densities of 50RCA and 100RCA of the same age were 2,133.1 kg/m^3 and 1,996.4 kg/m^3, respectively. The corresponding unit weights of 50RCA and 100RCA were approximately 20.9 kN/m^3 and 19.6 kN/m^3, respectively. The unit weight of the recycled concrete aggregate was considerably lower than the nominal value of 24 kN/m^3, which was in accordance with BS 8110 [19] for the traditional normal weight of concrete. This suggests that 50RCA and 100RCA were considered to have a lower self-weight than traditional concrete. The bulk density of recycled concrete aggregate was found to be less than that of natural sand aggregate, which was attributed to its lower specific gravity and bulk density [20].

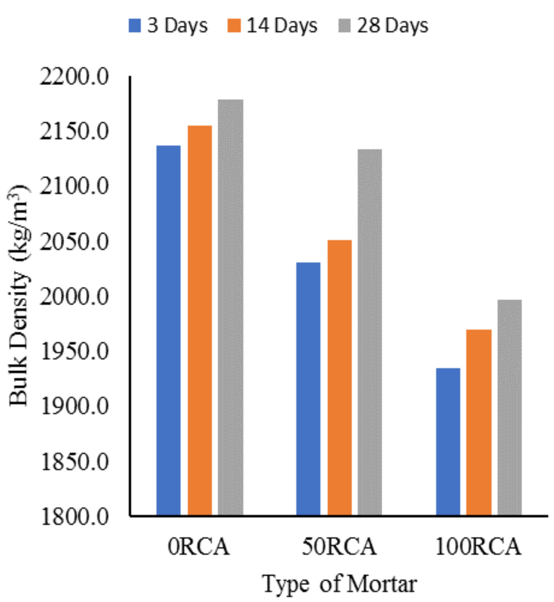

Figure 7. Bulk density of the mortar cubes

Table 3. Percentage reduction of the bulk density of the mortar cubes

Type of mortar	Days		
	3	14	28
	Density (kg/m^3)		
0RCA	2136.6	2154.3	2178.6
50RCA	2030.7	2050.5	2133.1
100RCA	1934.5	1969.2	1996.4
Reduction in bulk density (%)	9.46	8.59	8.36

3.3. Compressive Strength of the Cubes

The experiment conducted to determine the effect of recycled concrete aggregate on compressive strength was thoroughly analysed. Table 4 presents the compressive strength results for the 0RCA, 50RCA and 100RCA test cubes at 3, 14 and 28 days.

Figure 8 depicts the variation in compressive strength that occurs depending on the type of mortar used: 0RCA, 50RCA and 100RCA. It should be noted from this figure that the strength of the 0RCA grade of mortar increased as the number of testing days increased for this grade. However, at 28 days, the strength of 50RCA mortar decreased significantly compared to 14 days. The decrease in strength could be a result of a decrease in the adhesion or bond strength between the recycled concrete aggregate and the cement paste. The addition of recycled concrete aggregate, which contains microscopic waste concrete particles, increases the porosity of concrete [21].

At 28 days of age, similar variations in compressive strength were observed for 100RCA, which demonstrated a 15% increase in compressive strength. When recycled concrete aggregate was used in place of natural fine aggregate, the compressive strength of the mortar varied. These findings corroborate previous research [22 - 25]. The results indicate that recycled concrete aggregate is unsuitable for medium and high strength concrete applications (40 MPa – 60 MPa), but is more practical for low-strength structure and non-load bearing wall [23]. It can be affirmed by the percentage reduction of mortar containing recycled concrete aggregate as partial and fully sand replacement (Table 5). It is found that 50% of the recycled concrete aggregate reduce the strength of the mortar to 47.15%, 38.16% and 46.6% for 3 days, 14 days and 28 days, respectively. However, the use of recycled concrete aggregate as sand replacement reduces the strength of 30.46%, 26.44% and 38.8% at 3days, 14 days and 28 days, respectively.

Table 4. Compressive strength of the mortar cubes at 3, 14 and 28 days

Type of mortar	Avg. 3-day Compressive strength (MPa)	Avg. 14-day Compressive strength (MPa)	Avg. 28-day Compressive strength (MPa)
0RCA	6.96	11.61	12.1
50RCA	4.73	7.18	6.46
100RCA	4.84	8.54	7.41

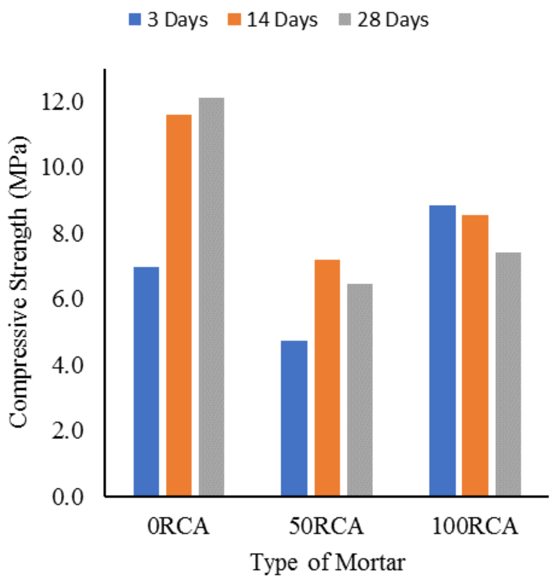

Figure 8. Compressive strength of the mortar cubes

Table 5. Percentage reduction of compressive strength of the mortar cubes at 3, 14 and 28 days

Type of mortar	Percentage Reduction For 3-day (%)	Percentage Reduction For 14-day (%)	Percentage Reduction For 28-day (%)
50RCA	47.15	38.16	46.6
100RCA	30.46	26.44	38.8

3.4. Mechanical Performance of the Wall Panels

Figure 9 presents the relationship between the load and deflection for 0RCA, 50RCA and 100RCA wall panels after the load was applied. From the quasi-static load to failure, the maximum load of 0RCA, 50RCA and 100RCA was found to be 72.46 kN, 203.26 kN and 155.90 kN, respectively. It is found that deflection of the 100RCA is higher compared to other wall panels with the value of 7.1 mm. The smallest deflection is found to be with the panels with inclusion of 50% of the recycled concrete aggregate as partial sand replacement.

Meanwhile, Table 6 presents the compressive strength and strength effectiveness of the wall panels. The strength effectiveness of 50RCA and 100RCA were 179.75% and 115%, respectively. The maximum compressive stress for 0RCA, 50RCA and 100RCA wall panels were observed at 2.42 MPa, 6.77 MPa and 5.2 MPa, respectively. The maximum wall deformations for 0RCA, 50RCA and 100RCA wall panels were recorded at 5.2 mm, 4.9 mm, and 6.9 mm, respectively.

Figure 10 shows the relationship between load and deflection for all wall panels. In this figure, the deflection was captured by the LVDT located at the edge at mid-span of the wall panel (LVDT3) and designated as Def 3. The deflection of 0RCA and 100RCA walls panels exhibited significant patterns where the deflection was linear at initial stage prior the crack of the wall started to appear. This indicated the wall panel resistance toward the deflections at the elastic staged. When the crack of the wall becomes larger, the deflection of the wall becomes more intense with small increment of load until the wall failed at ultimate load. There are 83% in terms of deflection different between 0RCA and 100RCA wall panels when the panel started to deflect beyond the deflection linearity of the wall panels.

Meanwhile, Figures 11 to 13 show the relationship between load and deflection with respect to time for all wall panels. The load ranges before the time to failure of the walls was different for each sample. Among the three sample types, 50RCA was able to cater for the highest loading. The findings proved that 50RCA and the natural aggregates proportionate ratio increased the maximum load of the wall panel [24]. This happened due to the balanced presence of the coarse aggregates. The combination of 50% RCA and 50% natural sand results in a novel type of mortar, as the fine gravel from the crushed recycled concrete aggregate increases the mortar's compressive strength. Additionally, the presence of the additive in the recycled concrete aggregate may improve material bonding [7].

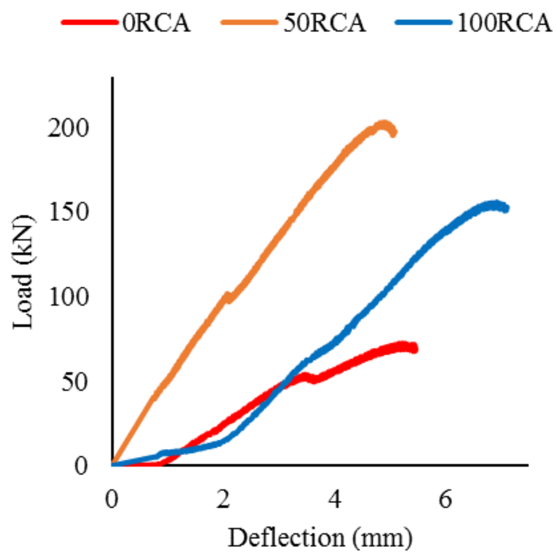

Figure 9. The relationship between load and deformation for wall panels

The longest time for durability was demonstrated by the 100RCA wall panel mix at 4260 s. The 100RCA wall panel took a longer time to fail than the 0RCA and 50RCA. While natural sand is effective at filling the void created by compressive strength, its durability is inferior to that of the fine aggregates in recycled concrete aggregate. The increased proportion of fine gravel in the recycled concrete aggregate also contributed to the time required for the 100RCA wall panel to fail being the longest, as gravel had a good durability profile. The range of time to failure for the wall panel mix with the presence of sand was between 3060 s and 3300 s. The 0RCA wall panel had a lower loading value, which meant it was the fastest to fail. The addition of recycled concrete aggregate in the mix design for a wall panel improved its durability and strength [8].

Table 6. Compressive strength and strength effectiveness of the wall panels

Type of wall	Compressive strength (MPa)	Strength effectiveness (%)
0RCA	2.42	-
50RCA	6.77	179.75
100RCA	5.20	115.00

Figure 10 shows the load-deflection relationship in relation to time for the wall panel of the 0RCA. This shows that when the load increased, the deflection on the wall panel increased. The deflection of the wall panel was 5.2 mm and the break point value for the deformation was 5.4 mm. Figure 11 shows the relationship between load, deflection and time for the 50RCA wall panel. The maximum deflection of the wall panel was 4.9 mm while the break point of the deflection was 5.1 mm. Figure 12 shows the load and deflection with respect to time for the 100RCA wall panel. The maximum deflection value was 6.9 mm while the break point was 7.1 mm.

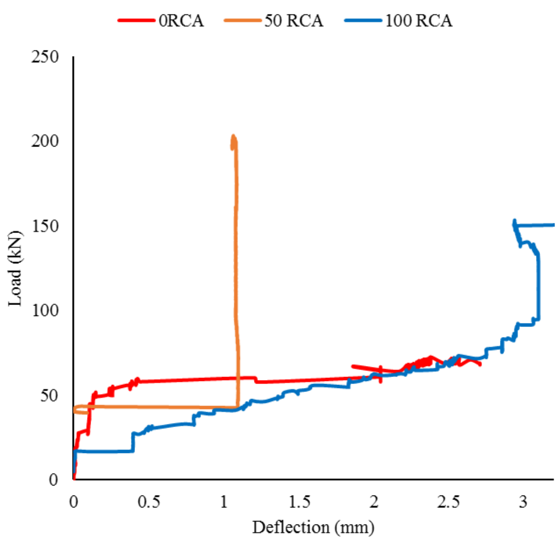

Figure 10. The relationship between load and deflection (Def 3) at mid-span of the wall panels.

Significantly different behaviour was observed for each sample depending on the different materials used. The deflection that occurred at the wall panel sample produced different values, which included the time the deflection happened. The highest deflection value came from the 0RCA wall panel at 6.9 mm. This shows that the behaviour of this wall panel in terms of deflection was higher, as this sample could resist the larger deflection due to the continuous loading that was applied. The maximum deflection value was also parallel with the highest loading value, which means the deflection occurred when a higher load was applied. The presence of the gravel aggregates and the amount of cement from the crushed recycled concrete aggregate enabled the 0RCA wall panel to resist a larger deflection compared to the 50RCA wall panel. This was due to the ability of the cement to bond together when it was mixed with the recycled concrete aggregate. It was evident that the deflection with the larger value could cater for the longest time until it reached the limit to fail at 7.1 mm. For the 50RCA wall panel, the loading value was high and the deflection that occurred at the wall panel was 4.9 mm. It started to fail at 5.1 mm. The 50RCA can cater for a high loading with the smallest deflection value but the time for the wall panel to fail was faster than that of the 100RCA wall panel due to the presence of 50% natural sand in the mix. The presence of the sand caused the combination of the material to become more fragile compared to that of the 100RCA wall panel. The bounding strength in the 50RCA was lower compared to 100RCA, the sample with the highest amount of cement, thus contributing to this wall panel having the longest time to failure.

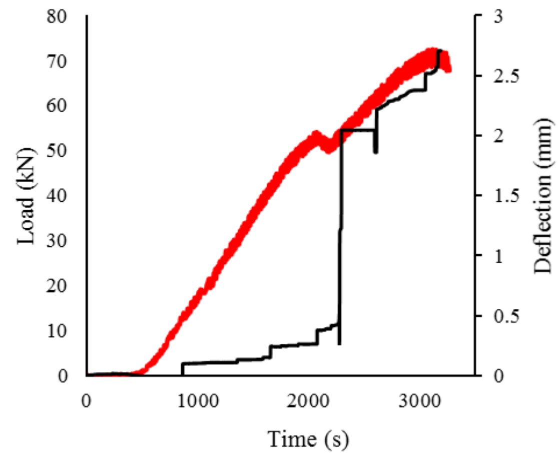

Figure 11. Load and deflection distribution with respect to time for wall panel 0RCA

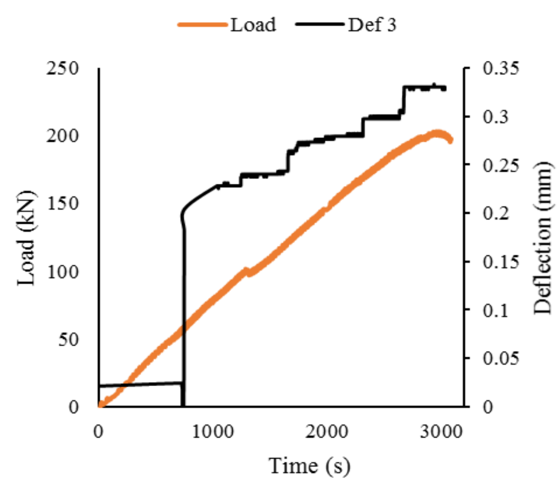

Figure 12. Load and deflection distribution with respect to time for wall panel 50RCA

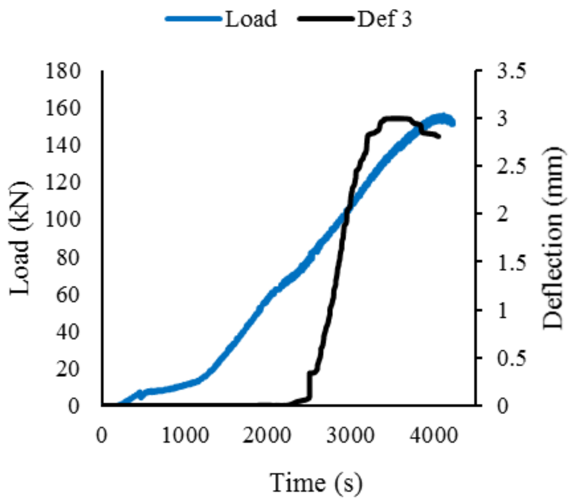

Figure 13. Load and deflection distribution with respect to time for wall panel 100RCA

Figure 14 shows the relationship between the strain with respect to the wall panel deflection. The ratio between maximum strain-deflection for 0RCA, 50RCA and 100RCA wall panels were 2.01, 4.64 and 0.71, respectively. The ratio shows that the 50 RCA wall panel has low buckling effect compared to that 0 RCA wall panel, and the 100 RCA wall panel has more tendency to deflect when the load was applied. The present of RCA has significant implications on the strain-deflection ratio, yet the optimum ratio of RCA to reflect the optimum strain-deflection relationship was not discovered in this study.

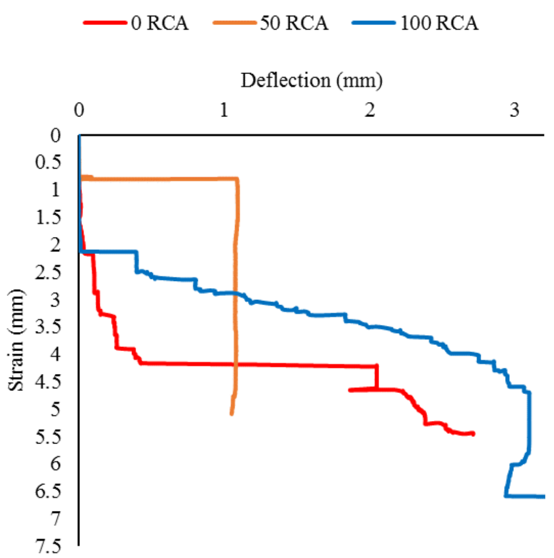

Figure 14. The relationship between strain and deflection of wall panels

4. Conclusions

This article discusses the effects of employing recycled concrete aggregates as part of the fine aggregate replacement for the creation of mortar cubes and wall panels. The compressive strength of the mortar cubes was determined at 3 days, 14 days and 28 days. Meanwhile, for the wall panel, the compressive strength was determined at the age of more than 28 days. In light of the findings, it is possible to conclude that:

i) It was found that the bulk densities of both 0RCA and 100RCA were lower than the range of normal weight concrete. The reduction in bulk density of the 100RCA, compared to the 0RCA bulk density, was 8% to 9%.
ii) At age 28 days, the 0RCA mortar cubes represent the highest compressive strength, compared to the 50RCA and 100RCA samples. However, recycled concrete aggregate at a proportion of 100% produces a greater compressive strength than recycled concrete aggregate at a percentage of 50%.
iii) The ultimate load for the 50RCA wall panel at 203.26 kN is higher than that of 0RCA and 100RCA.
iv) The 50RCA wall panel has 179.75% compressive strength effectiveness compared to 0RCA and 100RCA wall panels.
v) The smallest deflection is found to be with the panels with inclusion of 50% of the recycled concrete aggregate as partial sand replacement.

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