

MECHANICAL PROPERTIES OF ENVIRONMENTALLY FRIENDLY GREEN CONCRETE MADE WITH NATURAL AND RECYCLED FINE AGGREGATES

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ABSTRACT: Extensive research efforts have been undertaken in the past to utilize several kinds of recycled fine aggregates to produce environmentally friendly and more sustainable concrete. In Thailand, various types of bricks, including fired clay hollow, fired clay solid, and hydraulically pressed cement-clay bricks, are manufactured for constructing low-rise buildings. There is an urgent requirement to employ recycled fine aggregates made from these bricks to mitigate the disposal and demolition waste generated by the brick industry. At present, the utilization of waste bricks of Thailand's origin as fine aggregates in concrete is yet to be investigated. Three types of fine recycled brick aggregates were utilized to create sustainable concrete. The recycled fine brick aggregates were substituted for natural fine aggregates at proportions of 0%, 10%, and 20% to formulate the concrete mixes. Furthermore, three distinct types of tests—compression, splitting, and flexural tests—were conducted to evaluate the mechanical properties of the concrete. The compressive and splitting tensile strengths increased with the replacement ratio of recycled aggregates. Notably, up to 51% and 80% improvements in the compressive and splitting tensile strength were observed, corresponding to 20% replacement proportions, respectively. However, the flexural strengths exhibited were attributed to the type of waste brick, with a maximum improvement of up to 22%. Moreover, the water absorption tendency was reduced by incorporating recycled fine aggregates in concrete. The current work aimed only at examining the strengths of recycled brick aggregate concrete. Therefore, future works are recommended to investigate the complete stress vs. strain constitutive relationships of this concrete as well as its flowability.

Keywords: Recycled fine aggregate, Compressive strength, Flexural strength, Water absorption, Brick.

1. INTRODUCTION

The generation of construction and demolition waste (CDW) resulting from the demolition of older buildings and the deterioration of existing constructions is being expedited by the rapid process of urbanization [1–4]. Additionally, the consumption of non-renewable resources is on the rise due to the considerable growth of the construction industry. In 2020, Thailand produced around 2.58 million cubic meters of ready-mixed concrete materials [5]. Forecasts suggest that global concrete demand is poised to reach approximately 18 billion tons per year by 2050 [6], with an average concrete consumption of approximately three tons per capita per year [7]. This points towards significantly utilizing natural resources, particularly coarse and fine aggregates, leading to their speedy exhaustion [8]. Considering sustainability, it is crucial to tackle this swift depletion of natural resources, necessitating effective solutions.

Extensive efforts have been made to explore the recycling of aggregates in concrete production. Past studies have shown that incorporating

recycled aggregates into concrete production can compromise the properties of the concrete [9–11]. However, Previous research has proposed that recycled aggregates impact on the mechanical characteristics of concrete in a diverse range of ways.

Kumar and Deoliya [12] reported a reduction of 16% and 7% in compressive strength and tensile strength, respectively, when 100% of natural fine aggregates were substituted with recycled fine aggregates. On the contrary, studies by Pedro et al. [13] reported a reduction of 4%-12% and 24% in compressive and tensile strength, respectively, when 100% of natural fine aggregates were replaced with recycled fine aggregates. Dang et al. [14] observed an opposite trend observing an increased compressive strength with the use of recycled fine brick aggregates. The varying findings regarding compressive strength, where some studies report increases while others indicate the opposite trend, underscore the necessity for careful attention in designing concrete with recycled aggregates. Specifically, the use of recycled bricks as fine aggregates has yielded

conflicting results. Hence, it is imperative to delve deeper into this realm through further experimentation.

The present research focuses on recycling bricks as a partial replacement for natural fine aggregates. This approach is motivated by the fact that a substantial quota of the yearly construction waste consists of bricks. It is documented that the volume of clay brick waste produced annually is escalating in a geometric progression [13]. An approximate calculation suggests that China generates around 400 million tons of brick waste annually, constituting up to 45% of the overall construction waste generated [14].

The present study investigates the mechanical properties and water absorption of concrete fabricated with recycled brick aggregates. To achieve this, three types of bricks were considered, mainly as fired clay solid bricks (Type A), fired clay hollow bricks (Type B), and hydraulically compressed clay interlocking bricks (Type C). Moreover, fine aggregates from natural recycled concrete aggregates were also considered making a total of four recycled fine aggregate types.

2. RESEARCH SIGNIFICANCE

Previous research has shown that massive amounts of construction waste are being produced each year, with bricks as a notable component. Though some studies have used recycled brick aggregates as a substitute for natural fine aggregates in concrete, the characteristics of resulting concrete have been shown to be widespread. Thus, the need to further explore the behavior of recycled aggregate concrete is emphasized. The present study partially replaces natural fine aggregates with recycled brick aggregates obtained from three different types of bricks. Moreover, authors compared the response of concrete made with three different types of recycled fine brick aggregates that adds to the novelty of this study.

3. METHODOLOGY

3.1. Test Matrix

In this study, a total of 108 specimens were produced, categorized into five groups, each utilizing four distinct types of aggregates. The recycled fine aggregates were sourced from fired clay bricks (Type A), fired clay hollow bricks (Type B), hydraulically compressed clay interlocking bricks (Type C), and Demolished Recycled Concrete (DRC). Furthermore, except for the control group, each of these five groups was subdivided into two subgroups, and within each subgroup, there were 12 specimens designed

for four different types of tests: compression, splitting, flexural, and water absorption. Each of the five groups included two cylinder-type specimens, one flexural prism-type specimen, and one cube-type specimen. A total of three specimens were tested for each specimen type and their average results are reported. A systematic nomenclature consisting of three components was adopted for identification. The initial digit represented the group number, followed by characters denoting the recycled fine aggregate types and concluding with a numerical value indicating the replacement ratio. Table 1 summarizes specimen details. Fig.1 shows different types of aggregates used. Local river sand was used as natural fine aggregates.

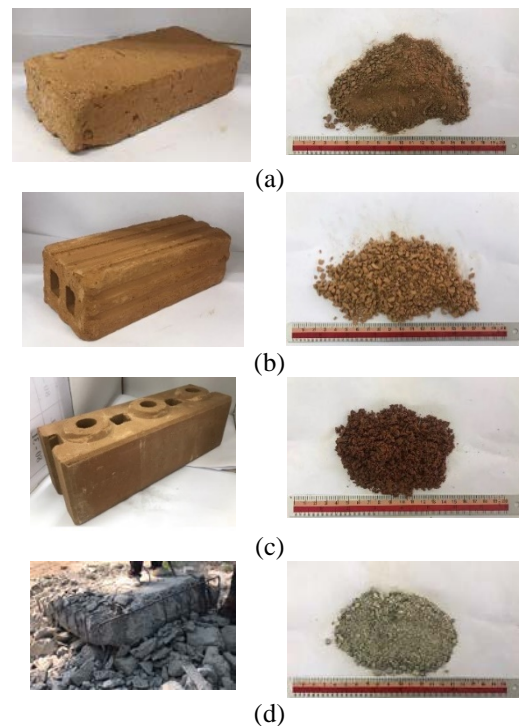


Fig. 1. Types of fine aggregates used in this study (a) fired clay solid bricks, (b) fired clay hollow bricks, (c) hydraulically compressed clay interlocking bricks, and (d) recycled concrete aggregates

3.2. Material Properties

The mechanical properties of bricks were assessed according to the guidelines outlined in ASTM C1314-21 and ASTM C140/C140M-22a [15,16]. Table 2 presents the calculated characteristics of bricks. Each type of brick and concrete was sourced locally, and a brick crusher machine was utilized to crush them. After crushing and screening, the size of aggregates ranged from 4.75 mm to 75 microns. Replacement ratios of 10% and 20% for natural fine aggregates were used in this work. The concrete mix proportions

are detailed in Table 3. Laboratory conditions were employed for the mixing of Recycled Concrete Aggregates (RCA) and Recycled Brick Aggregates (RBA) to prepare the specimens. Steel molds were used for crafting these specimens, with each mold being filled with concrete and uniformly compacted through vibration, as depicted in Figure (3). After a duration of 24 hours, the concrete specimens were extracted from the molds and subjected to curing under ambient conditions for the subsequent 27 days, aimed at achieving the concrete's 28-day strength. The slump of concrete was recorded at 73 mm.

3.3. Specimen Details and Preparation

In this work, standard concrete cylinders of 100 mm diameter and 200 mm height were used to evaluate compressive performance and splitting tension of reference concrete. Flexural beam specimens measured 100 mm in height, 100 mm in width, and 500mm in length. Water absorption cubes were sized at 150 mm x 150 mm. The dimensional details of the test specimens are visually presented in Figure 2.

Table 1. Test matrix

Name	Target Concrete Strength (MPa)	Recycled Aggregate Origin	Number of Specimens			
			Compression	Splitting	Flexural	Water Absorption
1-CON	15	Natural aggregates	3	3	3	3
2-RBA10	15	Fired clay solid bricks	3	3	3	3
2-RBA20	15	Fired clay solid bricks	3	3	3	3
3-RBB10	15	Fired clay hollow bricks	3	3	3	3
3-RBB20	15	Fired clay hollow bricks	3	3	3	3
4-RBC10	15	Hydraulic cement-clay bricks	3	3	3	3
4-RBC20	15	Hydraulic cement-clay bricks	3	3	3	3
5-DRC10	15	Recycled concrete	3	3	3	3
5-DRC20	15	Recycled concrete	3	3	3	3

Table 2. Properties of recycled bricks

Property	Type of Brick		
	Type A	Type B	Type C
Density (kg/m ³)	120	140	145
Compressive Strength (MPa)	3.14	8.10	6.26
Water Absorption (%)	22.00	13.10	12.30

Table 3. Concrete mix proportions

Component	Amount (kg/m ³)
Cement (kg/m ³)	417
Fine Aggregates (kg/m ³)	970
Coarse Aggregates (kg/m ³)	832
Water (kg/m ³)	250

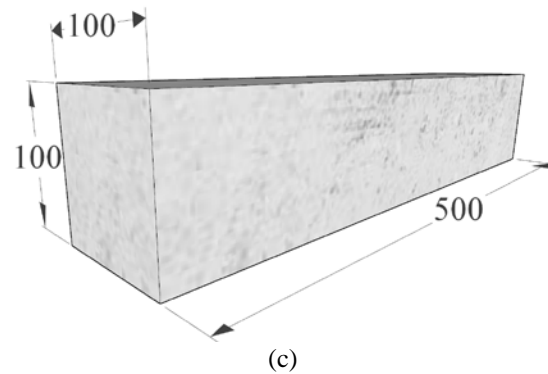


Fig 2. Details of test specimens (a & b) splitting and compression, (c) flexural, and (d) water absorption

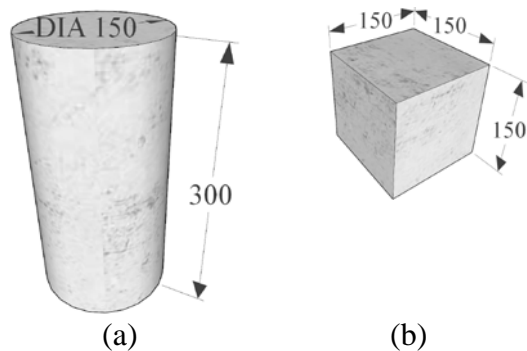


Fig. 3 Concrete casting in molds

3.4. Instrumentation and Test Setup

For the compression tests, each cylinder underwent incremental loading using a Universal Testing Machine (UTM), with care taken to ensure even load distribution by refining the top and bottom surfaces of the cylinders. Monitoring of axial deformation was accomplished using two pre-calibrated Linear Variable Differential Transducers (LVDTs) affixed vertically to the UTM's loading component.

Specimens were horizontally positioned in splitting tests, and a deformed steel bar was affixed to the top of each specimen. Similarly, flexural specimens were placed inside UTM, and a load cell with a capacity of 10 tons was used to monitor the applied load. Vertical deformation was gauged using LVDTs, aided by steel plates affixed at the midpoint of each specimen's length. The mechanical configurations of these test setups are depicted in Fig. 4. The loading rate was 50 kN/s.

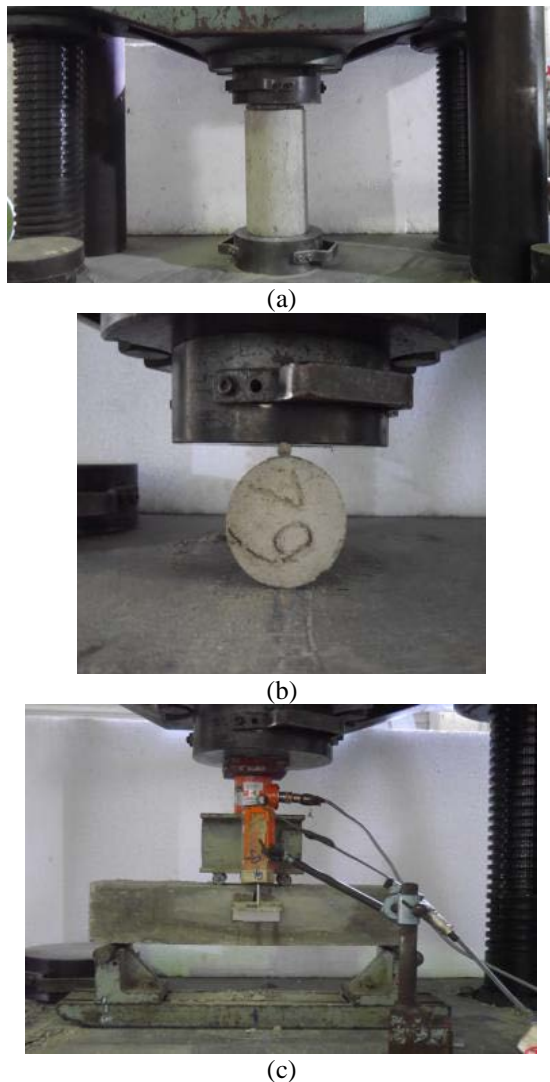


Fig 4. Test setups (a) compression, (b) splitting tensile, and (c) flexural test

4. EXPERIMENTAL RESULTS

A comparison in mechanical properties of control and experimental concrete was made in the present study and Table 4 summarizes experimental results of all tests. It is noteworthy that the values in Table 4 are average values of three specimens representing each specimen type and test.

4.1. Compressive Strength

The comparison of compressive strength of all mix types is graphically shown in Fig. 5. A general trend is observed in Fig. 5, i.e., the inclusion of recycled aggregates to substitute fine aggregates enhanced the compressive strength. In addition, this enhancement was proportional to the replacement ratio, i.e., the increase in compressive strength was more pronounced for the 20% replacement ratio than the 10% replacement ratio. For instance, Specimen 2-RBA10 and Specimen 2-RBA20 had compressive strengths of 12.99 MPa and 17.07 MPa, respectively. This corresponds to a 51% and 99% enhancement as compared to the control specimen. The positive grading of bricks and the pozzolanic reaction facilitated by the incorporation of super fine aggregate brick powder contributed to the enhancement of the cement paste and aggregate transition zone [17].

Another important observation in Fig. 5 is related to the comparison of the performance of specimens with different recycled bricks. Notably, specimens constructed with Type B bricks had the highest improvement, followed by Type A and Type C bricks, respectively. This can be ascribed to the microstructural properties of the resulting concrete and morphological characteristics of recycled fine aggregates [14]. Lastly, the inclusion of recycled concrete aggregates as 10% and 20% replacement of natural fine aggregates also imparted improvements of 26% and 51% in compressive strength, respectively. It is important to note that the water-to-cement ratio was kept constant in this study. But this parameter has been found to influence the mechanical properties of concrete made with recycled fine brick aggregates [14]. Consequently, the future works must also extend this study by modifying the water-to-cement ratios.

4.2. Splitting Tensile Strength

The comparison of splitting tensile strength of all mix types is graphically shown in Fig. 6. A typical tendency observed in Fig. 6 is that the splitting tensile strength increased by the substitution of natural fine aggregates with recycled aggregates.

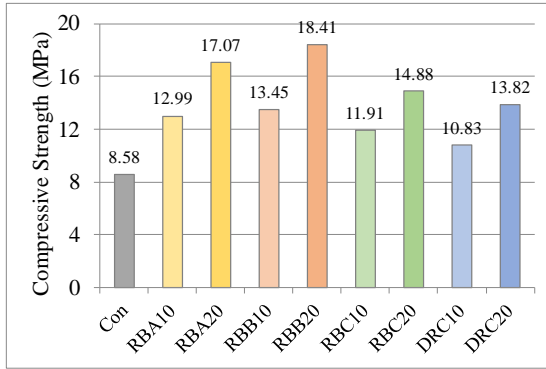


Fig 5. Comparison of compressive strength

Generally, a higher improvement was observed by increasing the replacement ratio from 10% to 20%.

Table 4 Summary of experimental results

Name	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Flexural Strength (MPa)	Strength	Water Absorption (%)
1-CON	8.58	4.25	2.43		7.56
2-RBA10	12.99	4.18	1.99		6.24
2-RBA20	17.07	4.63	1.99		6.77
3-RBB10	13.45	5.88	2.97		6.84
3-RBB20	18.41	7.64	2.55		6.30
4-RBC10	11.91	4.90	2.22		6.73
4-RBC20	14.88	6.20	1.90		6.23
5-DRC10	10.83	6.26	2.92		6.03
5-DRC20	13.82	7.50	2.55		6.75

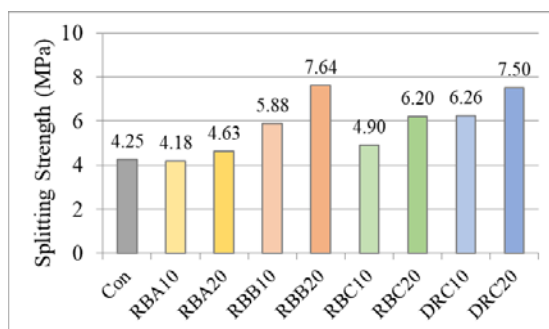


Fig 6. Comparison of splitting tensile strength

4.3. Flexural Strength

The comparison of splitting tensile strength of all mix types is graphically shown in Fig. 7. Contrary to the trends observed for compressive and splitting strengths, a higher replacement ratio resulted in lower improvement in flexural strength. Related to the flexural strength of the control specimen, i.e., 2.43 MPa, specimens constructed with recycled aggregates of Type A and Type C had lower flexural strengths. At the same time, the

These results are similar to the results of compressive strength and acknowledge the general trend of splitting tensile strength improvement as a function of concrete compressive strength. It is further noted that the highest splitting tensile strength improvement was observed for Type B bricks, analogous to compressive strength. Though the tensile strength was improved, the tensile ductility, which is a desired property of the concrete under tension, is not guaranteed. The future works must study the complete tensile stress vs. strain relations to investigate the effects of recycled fine brick aggregates on the tensile behavior of the resulting concrete.

flexural strength of specimens with Type B and recycled concrete aggregates was generally higher than the flexural strength of the control specimen. This, again, can be ascribed to the highest compressive strength of Type B bricks among all brick types used in the present study. Nonetheless, the authors acknowledge that there is a further need to study and explore this peculiar trend in flexural strength.

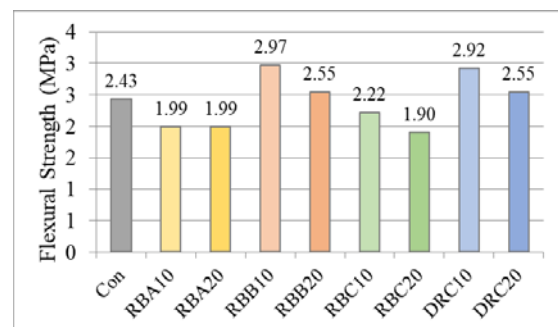


Fig 7. Comparison of flexural strength

4.4. Water Absorption

The comparison of water absorption of all mix types is graphically shown in Fig. 8. Generally, concrete with recycled brick fine aggregate resulted in lower water absorption capacities than concrete with natural aggregate concrete. No clear trend in the difference between the water absorption capacities of concrete with different replacement ratios could be observed. The recycled bricks were not over-dried before crushing to fine aggregates. The water absorbed within the pores and adhered to the surface might have reduced the water absorption capacity of the recycled concrete. A similar inference can be extended to the case of recycled concrete aggregates.

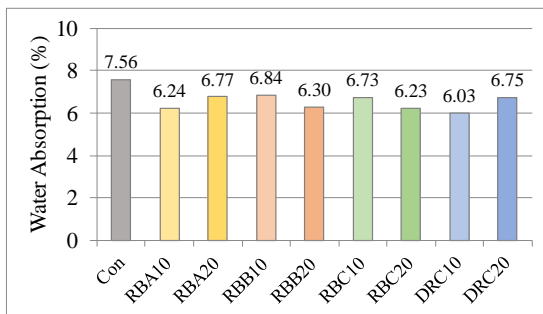


Fig 8. Comparison of water absorption

4.5. Failure Modes

The established failure modes of concrete specimens in compression, flexure, and splitting are widely recognized. This section delves into the effect of various water types on the physical behavior of concrete, with a specific focus on its compressive, flexural, and splitting tensile properties. Fig. 9 illustrates the failure modes in compression, revealing that all specimens exhibited typical behavior characterized by concrete crushing and longitudinal splitting of cylinders. The propagation of splitting cracks occurred throughout the entire length of the specimens, and notably, the failure patterns closely resembled each other. Additionally, some specimens also demonstrated diagonal shear cracking. Similarly, Fig. 10 displays the flexure failure modes, wherein all specimens demonstrated splitting perpendicular to the longitudinal axis of the beams. Moving to the splitting failure modes depicted in Fig. 11, it is evident that a uniform failure pattern emerged across all specimens. Overall, the different aggregate types did not significantly influence the concrete's failure modes under compression, flexure, and splitting.

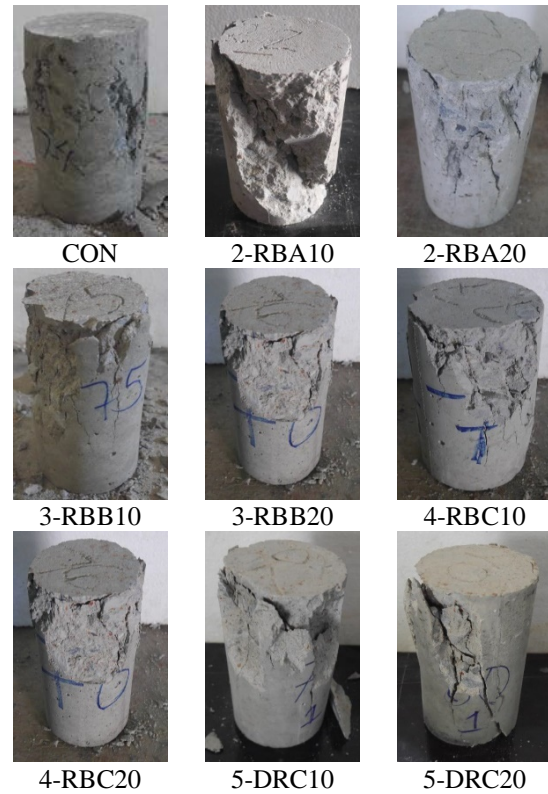


Fig 9. Failure modes in compression

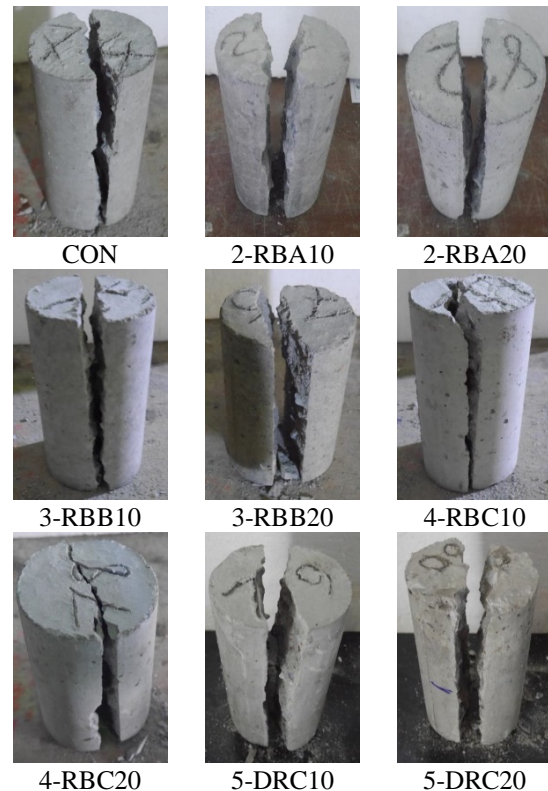


Fig 10. Failure modes in splitting

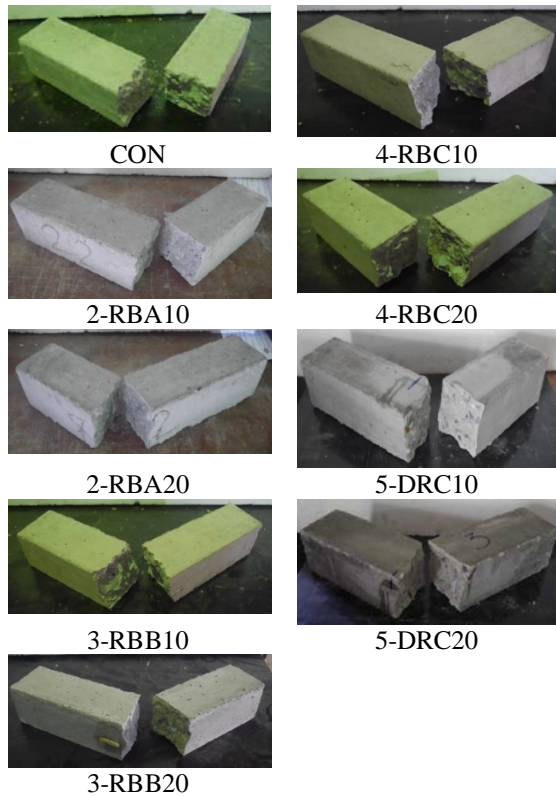


Fig 11. Failure modes in flexure

5. CONCLUSIONS

This study explored the impact of recycled fine aggregates sourced from bricks and concrete on mechanical properties and water absorption of concrete. Recycled brick aggregates were obtained from fired clay bricks (Type A), fired clay hollow bricks (Type B), hydraulically compressed clay interlocking bricks (Type C), and Demolished Recycled Concrete (DRC). The following conclusions can be listed based on experimental observations.

1. The outcomes of recycled fine aggregate concrete substantiate that an escalation in the proportion of recycled aggregates results in a corresponding rise in compressive strength. This phenomenon can be ascribed to the pozzolanic reaction and the absorption of water by the fine brick aggregate powder, which contribute to the cement's hydration process. Furthermore, these positive effects can be traced back to the favorable mechanical and durability properties inherent to the origin of the bricks used in the mix. Though the positive effects were observed related to compressive and tensile strength, the effect on flowability and ductility of the concrete needs to be investigated.
2. Among the four distinct aggregate types, the brick exhibited the highest compressive

strength, reaching up to 18.41 MPa. Additionally, the hydraulically compressed cement-clay bricks displayed strength enhancement up to 14.88 MPa.

3. The improvement in compressive strength and splitting tensile was more pronounced as the replacement ratio of fine aggregates increased. This pattern remained consistent regardless of the type of recycled aggregates used.
4. The flexural strength was reduced, contrary to the compressive and splitting strengths, as the replacement ratio of recycled aggregates increased. It is noteworthy that both recycled brick and concrete aggregates had similar effects on modifying the mechanical properties of concrete.
5. A marginal decrease in the water absorption rate is observable across all recycled fine aggregates, while the absorption rate experiences an uptick with an increase in the replacement proportion for recycled brick and concrete aggregate.

6. ACKNOWLEDGMENTS

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