Mechanical Properties of Recycled Aggregate Concrete with Industrial Waste Ash

Uruya Weesakul
Thammasat University Research Unit in Climate Change and Sustainability, Department of Civil Engineering, Faculty of Engineering, Thammasat School of Engineering, Thammasat University Rangsit Campus, Thailand
wuruya@engr.tu.ac.th

Thant Paing Htun
Thammasat School of Engineering, Thammasat University, Thailand
thant.pai@dome.tu.ac.th

Ali Ejaz
National Institute of Transportation, National University of Sciences and Technology (NUST), Islamabad, Pakistan
enggaliejax@gmail.com

Phromphat Thansirichaisree
Thammasat Research Unit in Infrastructure Inspection and Monitoring, Repair and Strengthening (IIMRAS), Faculty of Engineering, Thammasat School of Engineering, Thammasat University Rangsit Campus, Klong Luang, Pathumthani, Thailand
ckrisada@engr.tu.ac.th (corresponding author)

Qudeer Hussain
Civil Engineering Department, Kasem Bunding University, Thailand
ebbadat@hotmail.com

Received: 8 August 2024 | Revised: 27 August 2024 | Accepted: 4 September 2024

 DOI: https://doi.org/10.48084/etasr.8671

ABSTRACT

This study investigates the performance of concrete incorporating various recycled fine aggregates, including recycled brick aggregates, Fly Ash (FA), and Sugar Cane Bagasse Ash (SCBA). The test results showed that the mechanical properties were adversely affected when utilizing recycled brick or concrete aggregates, whereas FA or SCBA enhanced them. The water absorption potential of recycled bricks was proportional to the reduction in mechanical properties. FA and SCBA enhanced compressive strength and increased flexural strength up to 175.72% and 225.51%, respectively, at 20% replacement. The inclusion of recycled brick and concrete aggregates raised water absorption, while FA and SCBA significantly lowered it, improving the overall performance.

Keywords-fly ash; recyled aggregate; recycled bricks; fine aggregate

I. INTRODUCTION

Concrete is a fundamental building material extensively utilized in engineering developments. In 2021, China's concrete production amounted to 3.07 billion m^3, marking an increase of approximately 5.54% from 2020 [1]. Construction waste is primarily managed through dumping and landfilling, which leads to significant environmental issues [2, 3]. Approximately 35% of international construction and demolition waste is not disposed properly [4]. By crushing these materials, recycled aggregates can be produced and used to partly or fully substitute Natural Aggregate (NA) in the production of Recycled Brick Aggregate Concrete (ReBAC) [5]. This approach helps conserve natural reserves, decreases the need for landfill place, and supports the green production of building materials [6]. Concurrently, it could effectively contribute to achieving carbon peak and carbon neutrality goals [7, 8].

Prior investigations have indicated that the inclusion of recycled aggregates can compromise concrete properties [8-10]. Nevertheless, the effect of recycled aggregates on the mechanical properties of concrete has been argued with some disagreement. The quantitative decline in mechanical properties is inconsistent across various studies. Authors in [9] observed a reduction of 16% in compressive strength and 7% in tensile strength when 100% of Natural Fine Aggregate (NFA) was replaced with recycled fine aggregate. Conversely, authors in [10] stated a decrease of 4%-12% in compressive strength and 24% in tensile strength under the same conditions. These discrepancies highlight the need for further investigation to ensure the proper design of concrete utilizing recycled aggregates.

The current research focuses on recycling bricks as a partly substitution of NFA. This approach is driven by the fact that a substantial portion of annual construction waste is comprised of bricks. The volume of clay brick waste produced annually is increasing exponentially [11, 12]. Estimates indicate that China generates approximately 400 million tons of brick waste annually, contributing to 45% of the entire construction waste produced [13, 14]. Three categories of bricks were considered: fired clay solid bricks (RBA), fired clay hollow bricks (RBB), and hydraulically compressed clay interlocking bricks (RBC). Additionally, the results are compared with those from concrete made using partial replacements of NFA aggregate with Recycled Concrete Aggregate (RCA), Fly Ash (FA), and Sugar Cane Bagasse Ash (SCBA).

II. RESEARCH SIGNIFICANCE

Although some studies have utilized recycled brick aggregates as a substitute for NFA in concrete, the properties of the resulting concrete have shown considerable variation. This underscores the need to further examine the behavior of recycled aggregate concrete. The present study replaces NFA in concrete with recycled brick aggregates derived from three different types of bricks. Additionally, FA and SCBA, both pozzolanic in nature, are used as partial replacements to study and compare their effects with those of recycled brick aggregates.

III. EXPERIMENTAL FRAMEWORK

A. *Test Specimens Details*

In this study, the mechanical characteristics of concrete made by replacing NFA with 10% and 20% of recycled brick and concrete aggregates are explored. NFA was replaced with 10% or 20% of RBA, RBB, RBC, RCA, FA, and SCBA. Table I lists the specimens tested for mechanical properties and water absorption. Three specimens were tested from each category and the results were average. The target compressive strength was 15 MPa. The decision to use 10% and 20% replacement ratios for recycled brick and concrete aggregates was taken based on by prior studies and industry norms. These specific percentages allow for a meaningful evaluation of the mechanical properties while still achieving environmental benefits by reducing the reliance on NA. Other ratios were considered, but initial testing revealed that higher replacement levels would lead to a significant decline in concrete strength, making them impractical for most applications. The selected ratios strike a balance between sustainability and structural integrity.

TABLE I. DETAILS OF TESTED SPECIMENS

ID	Recycle aggregate origin	Replacement (%)
Con	Natural	0
RBA10	Fired clay solid brick	10
RBA20	Fired clay solid brick	20
RBB10	Fired clay hollow brick	10
RBB20	Fired clay hollow brick	20
RBC10	Cement clay interlocking brick	10
RBC20	Cement clay interlocking brick	20
DRC10	Demolished recycled concrete	10
DRC20	Demolished recycled concrete	20
FA10	Fly ash	10
FA20	Fly ash	20
SCBA10	Sugarcane bagasse ash	10
SCBA20	Sugarcane bagasse ash	20

B. *Material Properties*

The test matrix utilized recycled concrete from demolished buildings and three different types of building bricks. The first two types of bricks were composed of clay (solid and hollow), while the third type was a hydraulically compressed cement clay interlocking brick, as illustrated in Figure 1. Each type of brick and concrete was locally acquired, and a crusher machine was utilized to crush them. The crushed bricks were screened to standard fine aggregate sizes. The grading for all mix designs was kept constant to determine the grading of fine aggregates. A standard sieve set with minimum of 0.15 mm and maximum of 5 mm was utilized. The mechanical properties of the bricks were determined through compressive strength and water absorption tests, as shown in Table II. Table III presents the physical and mechanical properties of the RCAs, which were determined in accordance with ASTM C128-07a.

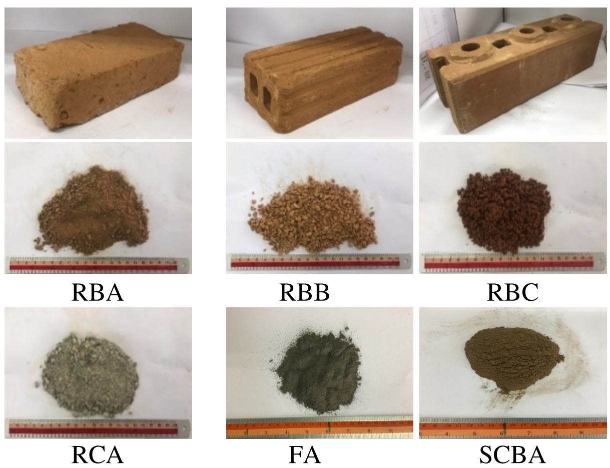

Fig. 1. Various fine aggregate types used.

C. *Specimen Details*

In this work, cylinders of 150 mm and 300 mm diameter and height, respectively, were used to measure the compressive strength and splitting tension of concrete. The dimensions of the flexural beam specimens were 100 mm in height and width, and 500 mm in length. The water absorption test cubes edge was 150 mm. Dimension details of the test specimens are graphically shown in Figure 2.

TABLE II. MECHANICAL PROPERTIES OF BRICKS

Types	Density (kg/m^3)	Compressive strength (MPa)	Water absorption (%)
RBA	1200	3.14	22
RBB	1400	8.10	13.10
RBC	1450	6.26	12.30

TABLE III. PROPERTIES OF FINE AGGREGATES

Property	NA	RBA	RBB	RBC	DRC	FA	SCBA
Bulk specific gravity (kg/m^3)	2.27	2.40	2.44	2.30	2.28	1.99	1.59
Water absorption (%)	0.44	1.47	0.6	0.94	2.44	0.51	0.65

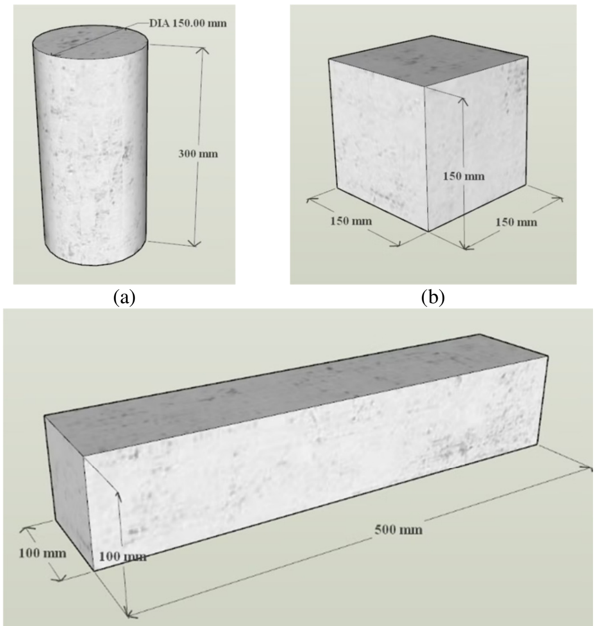

Fig. 2. Specimen details for: (a) compression and split tensile testing, (b) water absorption testing, and (c) flexural testing.

D. Test Setup

For compression testing, each cylinder was subjected to a load using a Universal Testing Machine (UTM). To ensure even load distribution, the top and bottom surfaces of each cylinder were meticulously cleaned and smoothed, as shown in Figure 3(a). For the splitting test, the cylinder specimens were laid horizontally, and a deformed steel bar was attached at the top of the specimen along a height of 200 mm. The load was applied using the UTM machine, as depicted in Figure 3(b). The flexural test prisms, each 500 mm in length, were set up in the flexural test equipment, as shown in Figure 3(c). A 10-ton load cell was placed at the top of the specimens. The 150 mm cubes underwent the water absorption test according to ASTM-C-642-06.

(a)

(b)

(c)

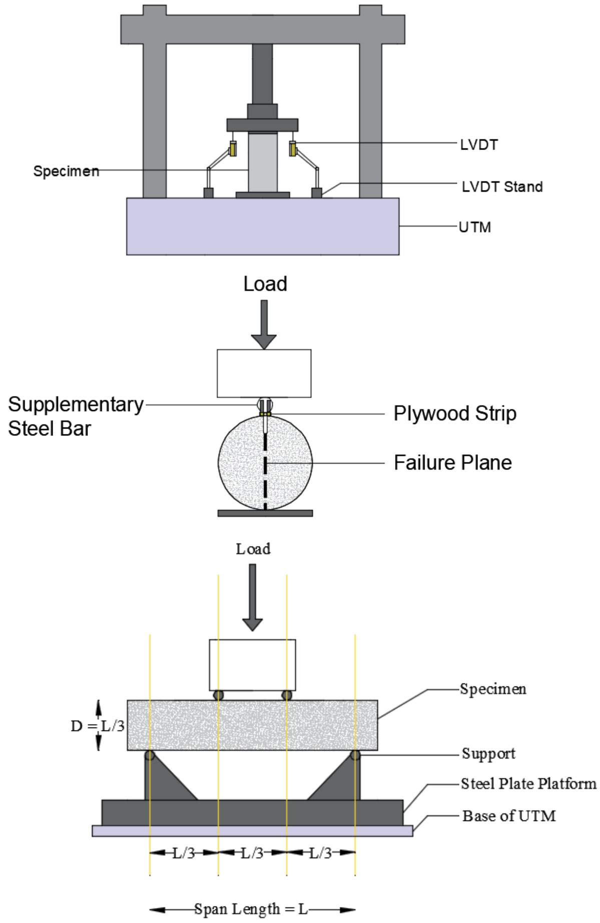

Fig. 3. Test configuration for (a) compressive, (b) tensile, and (c) flexural loads.

IV. EXPERIMENTAL RESULTS

A. Compressive Strength

The compressive strength of specimens can be seen in Figure 4. A reduction was shown in all cases with the exception of FA and SCBA. The maximum reduction was observed in the case of RBA10. Another important observation is that the increase in replacement ratio from 10% to 20% reduced the compressive strength in all cases of recycled brick and concrete aggregates. The inclusion of FA and SCBA enhanced the compressive strength. However, the compressive strength did not show significant alteration by changing the replacement ratio of SCBA. Similar observations were also reported by the authors in [15], who replaced NFA with SCBA with various replacement ratios. It was noted that the compressive strength was enhanced at 10% substitution by SCBA, but it slightly reduced when the replacement ratio increased to 20%. It should be noted that the decrease in compressive strength with increase in replacement ratio is documented in [16, 17]. The decrease was found to depend on the type of recycled brick.

B. Split Tensile Strength

The splitting tensile strength of specimens can be seen in Figure 5. Except for FA and SCBA, the splitting tensile strength decreased in all cases, with RBA10 exhibiting maximum reduction. Another important observation is that increasing the replacement ratio from 10% to 20% reduced the splitting tensile strength further for all types of recycled brick and concrete aggregates. The splitting tensile strength showed significant enhancement by increasing the replacement ratio of SCBA. It is noteworthy that the decrease in splitting tensile strength with an increased replacement ratio is well-documented [18]. In this study, the highest reduction in splitting tensile strength was observed for RBA, followed by RBB and RBC. For 20% replacement ratio, the reduction in split tensile strength ranged from -5.95% to -41.68%. For the 10% replacement ratio, this variation ranged from +2.01% to -40.10%.

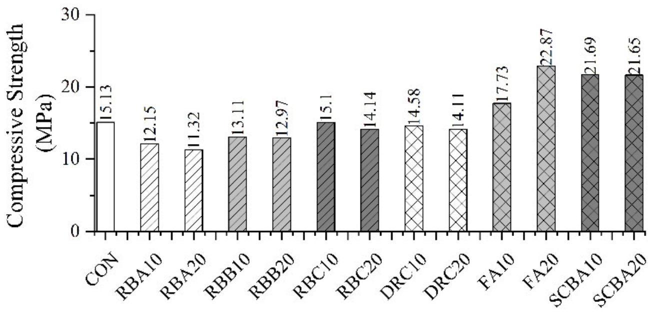

Fig. 4. Compressive strength result comparison.

C. Flexural Strength

The comparison of flexural strength is observed in Figure 6. The flexural strength demonstrated a reduction in the case of recycled brick and concrete aggregates. Again, the maximum reduction in flexural strength was reported for RBA bricks, followed by RBB, and RBC. The increase in replacement ratio reduced the flexural strength further of recycled brick and concrete aggregates. On the contrary, the increase in replacement ratios of FA and SCBA further enhanced the flexural strength. At 10% and 20% replacement ratios, the flexural strength of FA-based concrete was 135.80% and 175.72% greater than the control mix, respectively. Similarly, the same enhancement for SCBA-based concrete was 202.88% and 225.51%, respectively.

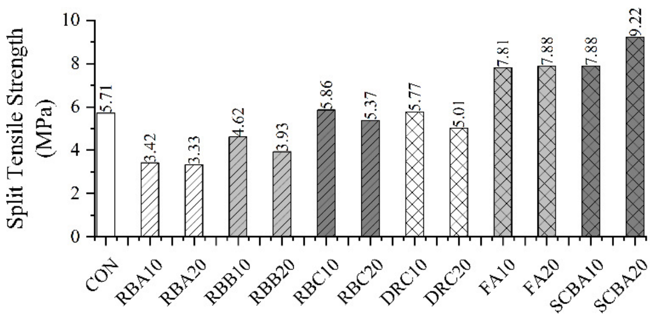

Fig. 5. Split tensile strength result comparison.

For 10% replacement ratio, the decrease in flexural strength of recycled brick-based concrete ranged from -4.53% to -26.34%. This reduction for the 20% replacement was further enhanced and ranged from -8.64% to -37.29%. This reduction in flexural strength is attributed to the issue that the inclusion of recycled aggregates decreases the content of hydration products, leading to a decrease in the flexural strength of concrete [19]. The reduction in flexural strength by the incorporation of recycled brick aggregates has been reported in [20, 21]. In [22], NFA was replaced with FA with replacement ratios ranging from 10% to 40%. It was noted that the inclusion of FA had a positive influence on flexural strength.

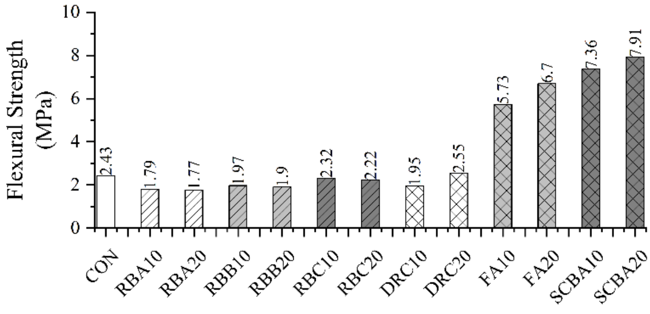

Fig. 6. Flexural strength result comparison.

D. Water Absorption

The comparison of water absorption ratios can be seen in Figure 7. Compared to the water absorption of the control mix, the mixes with recycled brick and concrete aggregates exhibited greater potential for water absorption. This can be attributed to their reduced mechanical properties, ascribed to the lower water quantity left for hydration. On the other hand, mixes with FA and SCBA demonstrated significantly lower water absorption than the control mix. The 10% and 20% replacement ratios of FA demonstrated lower water absorption ratios than control mix by 20.14% and 25.18%, respectively. SCBA-based mixtures at 10% and 20% demonstrated 30.57% and 40.04% reduced water absorption ratios than the control mix, respectively.

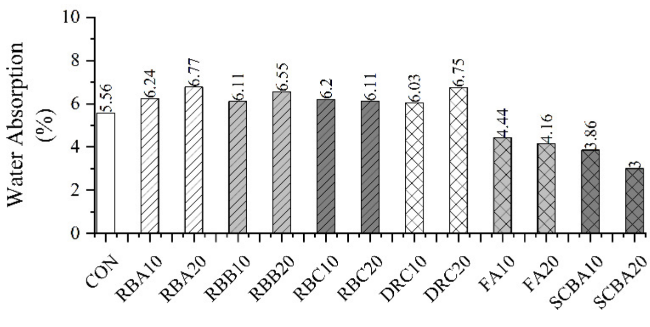

Fig. 7. Water absorption ratios result comparison.

E. Failure Modes

The established failure patterns of concrete specimens subjected to compression, flexure, and splitting are well-recognized. Figure 8 depicts the failure modes under compression, showing that all specimens displayed typical behavior characterized by concrete crushing and longitudinal splitting of cylinders.

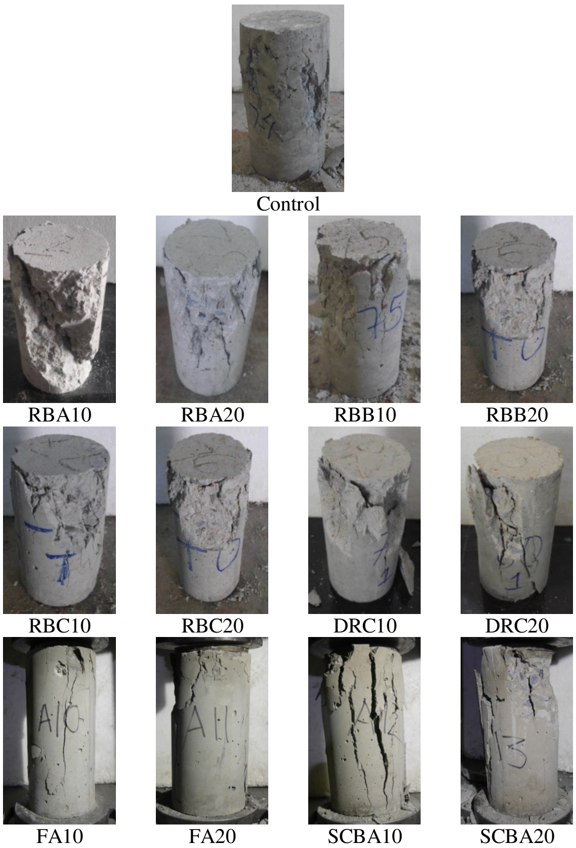

Fig. 8. Failures modes in compression.

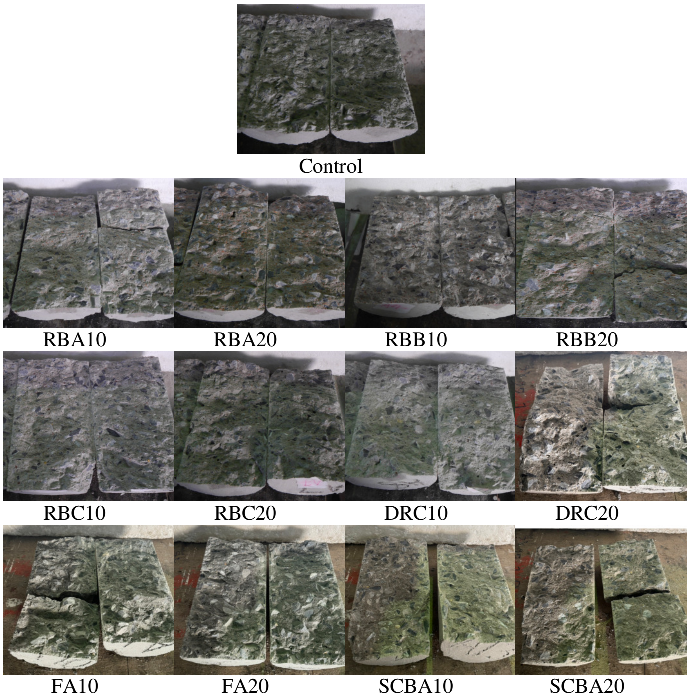

Fig. 9. Failures modes in split tension.

Cracks propagated along the full height of the samples, and the failure patterns were notably similar, as illustrated in Figure 9. Similarly, Figure 8 highlights the flexural failure modes, where all specimens exhibited splitting perpendicular to the beams' longitudinal axis. Figure 10 shows the splitting failure modes, indicating a consistent failure pattern across all specimens. The differences in mechanical performance among the recycled brick types (RBA, RBB, RBC) can be traced back to their varying physical characteristics. RBA, which is made from fired clay solid bricks, absorbed the most water and had the lowest compressive strength, resulting in weaker concrete. In contrast, RBB and RBC performed better due to their lower water absorption and higher intrinsic strength.

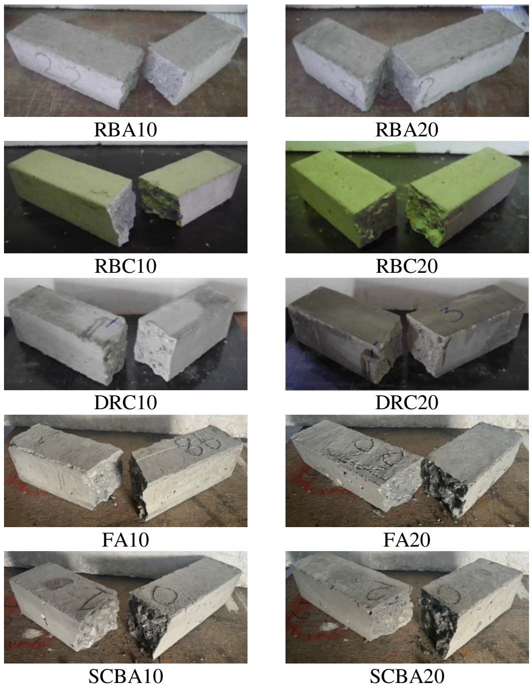

Fig. 10. Failures modes in flexure.

V. CONCLUSIONS

The study addresses the variability in concrete properties when recycled brick aggregate is used as a substitute of Natural Fine Aggregate (NFA). To better understand this, in this study, NFA was replaced with recycled brick aggregates derived from three different brick types. Additionally, the effects of partial replacements with Fly Ash (FA) and Sugar Cane Bagasse Ash (SCBA), both of which are pozzolanic materials, were examined to compare their impact with that of the recycled brick aggregates.

- The compressive strength of concrete reduces with the incorporation of 10% recycled brick and concrete aggregates, with the most significant reduction observed when using recycled brick aggregates. Increasing the replacement ratio to 20% further diminished compressive strength across all types of recycled aggregates. However, the addition of FA and SCBA enhanced the compressive strength, with FA showing a more pronounced improvement as the replacement ratio increased.

- The decrease in compressive strength is influenced by the type of recycled brick used, with the highest reduction associated with RBA, followed by RBB and RBC. Additionally, water absorption characteristics align with the same order of recycled brick types.
- Using recycled brick and concrete aggregates reduces the splitting tensile and flexural strength of concrete, with the greatest reduction observed for RBA10. Increasing the replacement ratio from 10% to 20% further decreases these strengths. However, FA and SCBA improve both splitting tensile and flexural strengths, with FA showing increased benefits at higher replacement ratios. For FA-based concrete, flexural strength increased by up to 175.72% at 20% replacement, while SCBA-based concrete saw improvements of up to 225.51%.
- The inclusion of recycled brick and concrete aggregates increases water absorption due to their reduced mechanical properties. In contrast, FA and SCBA significantly decrease water absorption, enhancing the overall performance.

ACKNOWLEDGMENT

This study was supported by the Faculty of Engineering, Thammasat School of Engineering, Thammasat University (Contract No. 001/2566). Thanks are also extended to AIT for allowing the use of its supporting test facilities.

REFERENCES

[1] Y. Zeng, H. Guo, J. Lei, Y. Hu, and Z. Yang, "Study on the mechanical properties of recycled brick coarse aggregate concrete based on finite element modeling," *Journal of Building Engineering*, vol. 95, Oct. 2024, Art. no. 110110, https://doi.org/10.1016/j.jobe.2024.110110.

[2] C. Alexandridou, G. N. Angelopoulos, and F. A. Coutelieris, "Mechanical and durability performance of concrete produced with recycled aggregates from Greek construction and demolition waste plants," *Journal of Cleaner Production*, vol. 176, pp. 745–757, Mar. 2018, https://doi.org/10.1016/j.jclepro.2017.12.081.

[3] J. Xiao, Z. Ma, and T. Ding, "Reclamation chain of waste concrete: A case study of Shanghai," *Waste Management*, vol. 48, pp. 334–343, Feb. 2016, https://doi.org/10.1016/j.wasman.2015.09.018.

[4] K. Kabirifar, M. Mojtahedi, C. Wang, and V. W. Y. Tam, "Construction and demolition waste management contributing factors coupled with reduce, reuse, and recycle strategies for effective waste management: A review," *Journal of Cleaner Production*, vol. 263, Aug. 2020, Art. no. 121265, https://doi.org/10.1016/j.jclepro.2020.121265.

[5] E. Yooprasertchai, P. Saingam, Q. Hussain, K. Khan, A. Ejaz, and S. Suparp, "Development of stress-strain models for glass fiber reinforced polymer composites confined sustainable concrete made with natural and recycled aggregates," *Construction and Building Materials*, vol. 416, Feb. 2024, Art. no. 135097, https://doi.org/10.1016/j.conbuildmat.2024.135097.

[6] M. Shaaban, W. F. Edris, E. Odah, M. S. Ezz, and A. A.-K. A. Al-Sayed, "A Green Way of Producing High Strength Concrete Utilizing Recycled Concrete," *Civil Engineering Journal*, vol. 9, no. 10, pp. 2467–2485, Oct. 2023, https://doi.org/10.28991/CEJ-2023-09-10-08.

[7] B. Wang, L. Yan, Q. Fu, and B. Kasal, "A Comprehensive Review on Recycled Aggregate and Recycled Aggregate Concrete," *Resources, Conservation and Recycling*, vol. 171, Aug. 2021, Art. no. 105565, https://doi.org/10.1016/j.resconrec.2021.105565.

[8] A. Maqsoom, A. Mughees, H. Zahoor, A. Nawaz, and K. M. Mazher, "Extrinsic psychosocial stressors and workers' productivity: impact of employee age and industry experience," *Applied Economics*, vol. 52, no. 26, pp. 2807–2820, Jun. 2020, https://doi.org/10.1080/00036846.2019.1696936.

[9] G. S. Kumar and R. Deoliya, "Recycled cement and recycled fine aggregates as alternative resources of raw materials for sustainable cellular light weight flowable material," *Construction and Building Materials*, vol. 326, Apr. 2022, Art. no. 126878, https://doi.org/10.1016/j.conbuildmat.2022.126878.

[10] D. Pedro, J. de Brito, and L. Evangelista, "Structural concrete with simultaneous incorporation of fine and coarse recycled concrete aggregates: Mechanical, durability and long-term properties," *Construction and Building Materials*, vol. 154, pp. 294–309, Nov. 2017, https://doi.org/10.1016/j.conbuildmat.2017.07.215.

[11] L. Zhu and Z. Zhu, "Reuse of Clay Brick Waste in Mortar and Concrete," *Advances in Materials Science and Engineering*, vol. 2020, no. 1, 2020, Art. no. 6326178, https://doi.org/10.1155/2020/6326178.

[12] I. A. Rana, R. H. Lodhi, A. Zia, A. Jamshed, and A. Nawaz, "Three-step neural network approach for predicting monsoon flood preparedness and adaptation: Application in urban communities of Lahore, Pakistan," *Urban Climate*, vol. 45, Sep. 2022, Art. no. 101266, https://doi.org/10.1016/j.uclim.2022.101266.

[13] H. Li, L. Dong, Z. Jiang, X. Yang, and Z. Yang, "Study on utilization of red brick waste powder in the production of cement-based red decorative plaster for walls," *Journal of Cleaner Production*, vol. 133, pp. 1017–1026, Oct. 2016, https://doi.org/10.1016/j.jclepro.2016.05.149.

[14] I. A. Rana, S. Khaled, A. Jamshed, and A. Nawaz, "Social protection in disaster risk reduction and climate change adaptation: A bibliometric and thematic review," *Journal of Integrative Environmental Sciences*, vol. 19, no. 1, pp. 65–83, Dec. 2022, https://doi.org/10.1080/1943815X.2022.2108458.

[15] P. O. Modani and M. R. Vyawahare, "Utilization of Bagasse Ash as a Partial Replacement of Fine Aggregate in Concrete," *Procedia Engineering*, vol. 51, pp. 25–29, Jan. 2013, https://doi.org/10.1016/j.proeng.2013.01.007.

[16] K.-L. Lin, H.-H. Wu, J.-L. Shie, C.-L. Hwang, and A. Cheng, "Recycling waste brick from construction and demolition of buildings as pozzolanic materials," *Waste Management & Research*, vol. 28, no. 7, pp. 653–659, Jul. 2010, https://doi.org/10.1177/0734242X09358735.

[17] L. Zheng, Z. Ge, Z. Yao, and Z. Gao, "Mechanical Properties of Mortar with Recycled Clay-Brick-Powder," in *11th International Conference of Chinese Transportation Professionals*, Nanjing , China, Aug. 2011, pp. 3379–3388, https://doi.org/10.1061/41186(421)335.

[18] Y.-J. Kim, "Quality properties of self-consolidating concrete mixed with waste concrete powder," *Construction and Building Materials*, vol. 135, pp. 177–185, Mar. 2017, https://doi.org/10.1016/j.conbuildmat.2016.12.174.

[19] Q. Tang, Z. Ma, H. Wu, and W. Wang, "The utilization of eco-friendly recycled powder from concrete and brick waste in new concrete: A critical review," *Cement and Concrete Composites*, vol. 114, Nov. 2020, Art. no. 103807, https://doi.org/10.1016/j.cemconcomp.2020.103807.

[20] D.-J. Moon, H.-Y. Moon, and Y.-B. Kim, "Fundamental Properties of Mortar Containing Waste Concrete Powder," *Geosystem Engineering*, vol. 8, no. 4, pp. 95–100, Dec. 2005, https://doi.org/10.1080/12269328.2005.10541243.

[21] T. Pavlu and M. Sefflova, "Carbonation Resistance of Fine Aggregate Concrete with Partial Replacement of Cement," *Key Engineering Materials*, vol. 722, pp. 201–206, 2017, https://doi.org/10.4028/www.scientific.net/KEM.722.201.

[22] R. Siddique, "Effect of fine aggregate replacement with Class F fly ash on the mechanical properties of concrete," *Cement and Concrete Research*, vol. 33, no. 4, pp. 539–547, Apr. 2003, https://doi.org/10.1016/S0008-8846(02)01000-1.