American Journal of Construction and Building Materials
2026, Vol. 10, No. 2, pp. 54–61
https://doi.org/10.11648/j.ajcbm.20261002.12

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Research Article

An Experimental Study on the Compressive Strength of Recycled Stone Aggregate Concrete

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Abstract

The volume of construction and demolition (C&D) waste generated worldwide continues to rise sharply, which undermines efforts to meet long-term sustainability targets. Converting demolished concrete into aggregate offers a practical route to limit landfill disposal and preserve natural raw materials. In Bangladesh, crushed brick chips are the conventional coarse aggregate for concrete, whereas demolished substructure elements such as pile caps usually contain stone chips and can therefore supply stone-based recycled concrete aggregate (RCA) of high strength. In this work, natural coarse aggregate (NCA) was substituted with stone-based RCA at levels of 0%, 20%, 40%, 60%, 80%, and 100%, and the resulting recycled aggregate concrete (RAC) was examined. The aim was to identify an acceptable RCA substitution level that does not impair concrete performance. Six batches of cylindrical specimens (100 mm × 200 mm) were prepared with a mix proportion of 1: 1.1: 3.1, designed following the British Standard method, and a constant w/c ratio of 0.50. Tests on the coarse aggregates indicated that the collected RCA was of better quality than the brick-based NCA, with a higher SSD unit weight (1493 kg/m^3 versus 1338 kg/m^3) and a much lower water absorption (10.32% versus 23.16%). Consequently, compressive strength rose progressively with RCA content up to 80% substitution, where it exceeded that of the control mix by 47%. At full (100%) substitution, the gain over the control dropped to 33.8%. This decline is linked to the larger quantity of old mortar attached to the aggregate surface, which produces a weaker interfacial transition zone (ITZ).

Keywords

Recycled Coarse Aggregate, Natural Coarse Concrete, Stone Chips, Brick Chips, Concrete

1. Introduction

1.1. Background

Solid waste management is widely regarded as one of the major environmental challenges of the present era, and considerable research effort has been directed toward new methods of limiting the amount of waste sent for disposal. The construction sector is a particularly large contributor, because the erection and demolition of buildings produce substantial quantities of structural debris. Worldwide, roughly 600 million tons of Construction and Demolition (C&D) debris were estimated to have been generated in 2018; concrete accounted for 67.5% of this debris, a larger share than any other material, followed by asphalt concrete at 17.8%. The building industry

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Received: 30 September 2026; **Accepted:** 13 October 2026; **Published:** 28 October 2026

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is a leading source of solid waste in nearly every country, and in North America C&D debris represents about 25–40% of the total waste stream, varying by region [1]. In mainland China alone, the annual output of waste concrete is estimated at approximately 200 million tons [2]. Recycling this material can markedly lower the demand for virgin natural resources, and processing demolished concrete into recycled concrete aggregate is arguably the most effective means of reducing the solid waste landfilled globally each year. A standardized procedure is therefore needed for collecting demolished concrete and converting it into recycled coarse aggregates (RCA) suitable for recycled aggregate concrete (RAC) and other uses. Since the characteristics of the original concrete differ with its type and geographic origin, the composition of RCA also varies, and these differences in turn affect the properties of the recycled concrete. Establishing an acceptable level of RCA replacement for NCA across different applications thus requires extensive investigation of both RCA and RAC, together with detailed assessment of the long-term performance of RAC. Although several barriers still limit the wider adoption of RCA and RAC, continued research can help to overcome them. Ultimately, the recycling of demolished concrete can make an important contribution to long-term environmental targets and to more effective solid waste management worldwide.

Past studies on RCA include:

Levy and Helene (2004) reported that concrete made with recycled aggregate derived from old masonry, at replacement levels of 20%, 50%, and 100% and with the same water–cement ratio of 0.5, could reach the same 28-day compressive strength (20–40 MPa) as concrete made with natural aggregate. They further observed that at 20% replacement, the recycled concrete matched, and in some cases outperformed, the concrete containing only natural aggregate with respect to workability, water absorption, and compacting factor [3]. Ajdukiewicz and Kliszczewicz (2002) demonstrated that recycled aggregate concrete (RAC) can achieve a higher compressive strength than its parent concrete. To reach adequate workability, however, the w/c ratio must be adjusted, although the required change in water content is relatively minor [4]. Park et al. (2004) found that compressive strength declined once the recycled aggregate content exceeded 50%, based on replacement levels of 0%, 50%, and 100% [5]. Etxeberria et al. (2007) reported a 20–25% reduction in 28-day compressive strength when the coarse aggregate was fully (100%) replaced with recycled aggregate at an effective w/c ratio of 0.50. At a w/c ratio of 0.55, mixes with 0% and 25% replacement reached equal strength. Mixes with 50% and 100% replacement attained that same strength only when the cement content was raised by 6% and 8.3%, respectively, and the w/c ratio was lowered to 0.52 and 0.50, respectively [6]. Bołtryk and Małaszkiewicz tested mixes in which 0%, 25%, 50%, and 75% of the NCA was substituted with RCA, using water–cement ratios of 0.45, 0.47, 0.49, and 0.51, respectively; the aggregate gradation was also varied with the substitution level. At 28 days, the mixes with 25% and 75% RCA gave the highest compressive strength, whereas at 90 days the maximum strength was recorded for the 0% and 75% mixes, a notable and somewhat unexpected result [7]. Li et al. likewise observed that compressive strength generally fell as the w/c ratio increased; the 50% replacement mix was the only exception, showing a rise in compressive strength at a higher w/c ratio [8]. Karunaratne and Kariapper (2013) found that concrete with 50% of the NCA replaced by RCA developed a compressive strength comparable to that of concrete without RCA. Their study evaluated the properties of recycled aggregate and the suitability of recycled aggregate concrete relative to natural aggregate concrete (NAC), using an M30 mix design and a w/c ratio of 0.56, and identified 50% as the allowable replacement level [9]. Zhou and Chen (2017) examined two types of RCA, namely recycled crushed rock aggregate (RCRA) and recycled pebble aggregate (RPA), with w/c ratios of 0.49 and 0.47 for the corresponding concretes (RCRC and RPC). NCA was replaced by RCA by weight from 0% to 100% in 10% increments. Concrete with 70% RCA gained more strength than that with 50% RCA, whereas the 100% mix showed a smaller gain. The authors attributed this to a lower effective w/c ratio at higher replacement levels, since recycled aggregate absorbs more water than natural aggregate; at 70% replacement, the mix reached an optimum with improved packing density and aggregate interlock compared with the 50% mix. These findings also underline the value of location-specific studies: because many variables govern the properties of RCA, results interpreted without regard to local conditions may mislead the reader [10]. Mohammed et al. (2014) studied the strength of concrete made with recycled brick aggregate obtained from 33 demolished buildings of different ages, testing more than 700 cylinder specimens at 7, 14, and 28 days. The mixes used full (100%) replacement and w/c ratios of 0.45 and 0.55. The recycled aggregate concrete developed strengths of 20.7–31 MPa, and no significant change in compressive strength was observed for coarse aggregate replacement of up to 50%. At a w/c ratio of 0.45, the recycled aggregate performed somewhat better than the virgin first-class brick aggregate commonly used in Bangladesh. This study likewise emphasizes that local context must be considered, as numerous variables influence the properties of RCA [11]. Guo et al. investigated several physical properties of recycled aggregate (RA) recovered from demolished concrete pavements, using replacement levels of 0%, 25%, 50%, and 75% and a w/c ratio of 0.3. The recycled pervious concrete (RPC) achieved a higher compressive strength than natural pervious concrete (NPC), possibly because the rough texture of the recycled aggregate improves the bond between the aggregate and the cement mortar [12]. Safiuddin et al. examined the influence of RCA on the fresh and hardened properties of concrete, using a w/c ratio of 0.6 and testing specimens at 7 and 28 days. RCA had little effect on compressive strength, as concretes with and without RCA reached similar values; the exception was the mix with 100% RCA, which was weaker than the control concrete. The limited effect of RCA was attributed to improved interfacial bonding and interlocking, since RCA particles are more angular and have a rougher sur-

face texture than NCA [13]. Khan et al. (2019) studied the structural behavior of RAC beams in which 0%, 30%, 50%, 70%, and 100% of the NCA was replaced with RCA at a water–cement ratio of 0.43. Strength increased at 70% replacement relative to 50% but decreased again at 100%. This trend was attributed to the lower effective w/c ratio caused by the higher water absorption of RCA, with the 70% mix representing an optimum in terms of packing density and interfacial bond [14].

Over the past few decades, RA has gained wider acceptance as sources of NA become scarcer and landfill space diminishes. Reusing processed demolition waste is therefore a more sustainable option that can lower both construction costs and the consumption of natural resources, and the ready availability of recycled aggregate can further encourage its uptake. Available statistics show that very large quantities of demolished concrete are produced every year, posing a serious risk of environmental pollution. Greater public awareness of this issue is needed, together with wider acceptance of RA as a substitute for natural aggregate. Previous experimental work and expert opinion broadly agree that demolished concrete can serve as an environmentally friendly RA. Nevertheless, certain factors must be evaluated before RA is used for a particular project or purpose; for example, the demolished concrete may require treatment or processing to remove impurities or to improve aggregate properties. Some researchers have reported that RA, whether processed or unprocessed, can outperform natural aggregate. Because the properties of RA vary between sites and countries, material from a specific source should be tested beforehand to identify all factors that may affect the fresh and hardened concrete. Properties such as workability, compressive strength, tensile strength, and density can be controlled by adjusting the w/c ratio and the level of NA replacement with RA. However, some RA behaviors do not follow the expected trends, and further detailed investigation is required to explain these unusual characteristics of RAC. Given its suitability, sustainability, and environmental benefits, RAC is likely to be widely adopted over the coming decades.

1.2. Objectives

This paper's objectives therefore include:

1) To utilize demolished concrete as recycled concrete aggregate (RCA) in support of environmental sustainability while limiting any loss of strength.
2) To assess how different levels of RCA substitution for natural coarse aggregate (NCA) influence the strength of concrete.
3) To identify an optimum and dependable RCA replacement level by comparing the present results with those of earlier studies.
4) To examine how RCA content affects the water–cement ratio, density, and compressive strength of recycled aggregate concrete (RAC).

2. Methodology

2.1. Specimen Details

To achieve the objectives of this study, concrete was produced with different RCA proportions, and six mix batches were prepared as outlined in the test plan (Table 1). The number of specimens cast for each level of NCA replacement with RCA is given in the table.

Table 1. *Test Plan.*

	Number of Specimens					
w/c	**0%**	**20%**	**40%**	**60%**	**80%**	**100%**
0.50	3	3	3	3	3	3

2.2. Materials

Portland Composite Cement (PCC) served as the binder in all concrete mixes (Figure 1a), with an assumed unit weight of 1440 kg/m^3 (typical value for composite cement). Locally sourced quartzite river sand finer than 5 mm was used as fine aggregate (Figure 1b), with an assumed unit weight of 1440 kg/m^3 (typical value for river sand). Crushed brick chips, the natural coarse aggregate (NCA) used in every mix, were obtained from local suppliers with a maximum size of 1 inch (Figure 1c). The recycled aggregate consisted of waste stone-chip concrete recovered from the demolished pile cap of an existing structure. These concrete pieces were broken down manually and mechanically to produce coarse aggregate with a maximum size of about 1 inch (Figure 1d).



Figure 1. *Materials (a) Cement (b) River Sand (c) Natural Coarse Aggregate (NCA) & (d) Recycled Coarse Aggregate (RCA).*

2.3. Aggregate Properties

Aggregate properties strongly govern the quality and behavior of concrete. Accordingly, the necessary aggregate tests were conducted at the start of the study to understand and explain how RCA affects concrete performance. Sieve analysis and fineness modulus tests were carried out on both coarse aggregates (NCA and RCA) in accordance with ASTM C136-96A. The sieve analysis establishes the particle size distribution of each aggregate and allows their uniformity and similarity to be compared. As Figure 2 shows, the gradations of NCA and RCA used in each batch were broadly comparable. Both curves, however, indicate that NCA contained a slightly larger proportion of finer particles than RCA, because the demolished concrete was not crushed into very small fragments during RCA production.

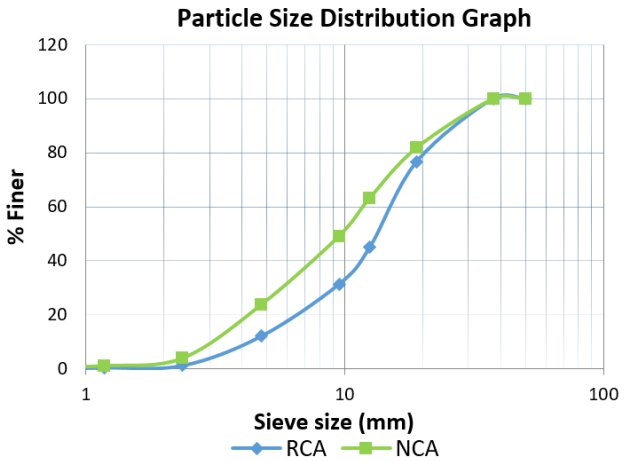


Figure 2. *Comparison of particle size distribution between RCA & NCA.*

Specific gravity and water absorption of the coarse aggregates were determined according to ASTM C127-88, and bulk density (unit weight) was measured following ASTM C29/C 29M-97. The resulting physical properties are summarized in Table 2. Unit weight is a key parameter because it reflects how closely aggregate particles pack within a given volume; it is also required to calculate the quantity of each aggregate in a concrete mix. Previous work has shown that the amount and quality of adhered old mortar govern the unit weight and water absorption of RCA. In most cases, the saturated surface dry (SSD) density of RCA is lower than that of NCA because the old mortar is itself of low density. In the present study, however, Table 2 indicates that the RCA had a higher unit weight than the NCA. This agrees with the observation that RCA derived from high-strength concrete is denser than RCA derived from low-strength concrete. Because the RCA originated from a pile cap, its parent coarse aggregate was stone chips, which typically possess a higher unit weight and specific gravity than brick chips (NCA). Water absorption is closely linked to unit weight, with denser aggregate absorbing less water. The higher unit weight of the RCA therefore accounts for its lower absorption, whereas the lighter NCA absorbs considerably more water owing to its greater porosity.

Table 2. *Physical Properties of Coarse Aggregate.*

PROPERTIES	RCA	NCA
Unit weight (kg/m^3)	1353.33	1086.67
SSD Unit weight (kg/m^3)	1493.03	1338.32
Bulk Sp. Gr. (OD)	2.214	1.696
Bulk Sp. Gr. (SSD)	2.443	2.089
Apparent Sp. Gr.	2.87	2.794
Absorption (%)	10.323	23.158
% Voids	38.75	35.8

2.4. Sampling, Mixing, and Curing

Cylindrical molds 100 mm in diameter and 200 mm in length were used to cast the specimens. Specimen preparation and curing followed ASTM C31/C31M-19; the specimens were removed from the molds 24 hours after casting and then cured in a water tank for 28 days. A mix proportion of 1: 1.1: 3.1 (cement: fine aggregate: coarse aggregate) was adopted based on the British Standard method which target (which target strength was nearly 15 MPa), with a water–cement ratio of 0.50. This w/c ratio was chosen on the basis of earlier studies and the favorable performance reported for recycled aggregate. The mixing and curing procedures are illustrated in Figure 3a & 3b.



(a) (b)

Figure 3. *(a) Mixing & (b) Curing.*

2.5. Compressive Strength Test

Following 28 days of curing, the compressive strength of every mix was determined with a Universal Testing Machine (UTM) in accordance with ASTM C39/C39M-01, as illustrated in Figure 4.



(a) (b)

Figure 4. *(a) Before crushing, (b) After crushing.*

3. Results & Discussion

Table 3 presents the compressive strength results, which varied with the level of NCA replacement by RCA (0%, 20%, 40%, 60%, 80%, and 100%).

Table 3. *Compressive strength & hardened concrete cylinder unit wt. results.*

RCA%	No.	Stress (MPa)	Avg. (MPa)	Wt. (kg)	Vol. (m^3)	Unit Wt. (kg/m^3)
	1	7.4		3.33	0.00157	2121.02
0%	2	7.15	7.19	3.31	0.00157	2108.28
	3	7.03		3.32	0.00157	2114.65
	1	8.88		3.45	0.00157	2197.45
20%	2	9.87	9.87	3.49	0.00157	2222.93
	3	10.85		3.43	0.00157	2184.71
	1	9.25		3.52	0.00157	2242.04
40%	2	11.35	10.20	3.54	0.00157	2254.78
	3	9.99		3.52	0.00157	2242.04
	1	11.59		3.49	0.00157	2222.93
60%	2	8.14	10.36	3.54	0.00157	2254.78
	3	11.35		3.52	0.00157	2242.04
	1	10.98		3.54	0.00157	2254.78
80%	2	10.61	10.57	3.63	0.00157	2312.10
	3	10.11		3.59	0.00157	2286.62
	1	9		3.65	0.00157	2324.84
100%	2	8.63	9.62	3.69	0.00157	2350.32
	3	11.22		3.63	0.00157	2312.10

Figure 5 shows that the compressive strength of the concrete cylinders rose as the RCA content increased up to 80%, but fell when the NCA was fully (100%) replaced. The rising trend can most likely be attributed to the good quality of the crushed recycled stone aggregate, which also improved bonding within the concrete. Hence, the properties of the parent aggregate in the RCA had a major influence on the compressive strength of the specimens.

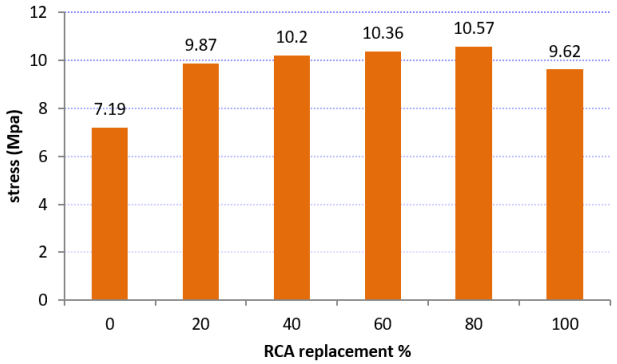


Figure 5. *Compressive strength graph.*

Table 3 also reports the unit weight of the hardened concrete cylinders, and Figure 6 plots compressive strength against this unit weight. Since hardened unit weight reflects both the degree of compaction and the unit weight of the coarse aggregate, it offers insight into their effect on strength. As Figure 6 shows, the compressive strength of recycled aggregate concrete (RAC) rises with increasing hardened density, a pattern consistent with the findings of Kumutha and Vijai [15]. For the 0.5 w/c ratio, the trend line shows a mild upward slope. Because cement, water, and aggregates differ in density, the overall density of concrete depends on the proportions of its constituents and on the compaction effort applied. Denser concrete usually contains fewer voids and therefore develops higher strength. Fewer voids also make the concrete less permeable to water and dissolved substances, which lowers water absorption and is expected to improve durability.

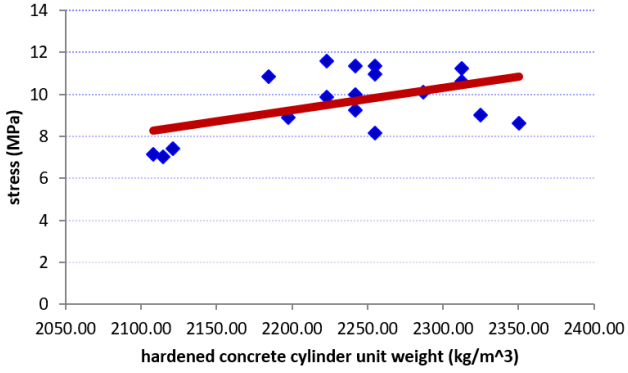


Figure 6. *Impact of compaction.*

These results show that compressive strength increased with the level of NCA replacement by RCA up to 80%. Several factors explain this behavior. A lower effective water–cement (w/c) ratio yields a denser matrix with fewer pores and hence higher strength. In addition, concrete strength is strongly governed by aggregate quality: the aggregate recovered from the demolished pile cap, whose parent aggregate was stone chips, is stronger than the aggregate typically obtained from demolished buildings, which raises the overall strength of the concrete. The strength gain from 0% to about 80% RCA can thus be attributed to better aggregate interlock, an internal curing effect, a reduced effective water–cement ratio, and a limited amount of old mortar. At 100% RCA, however, the large quantity of weak, porous adhered mortar, higher porosity, weaker interfacial transition zones, greater water absorption, and reduced stiffness of the aggregate skeleton become dominant, causing strength to decline. These findings indicate that recycled concrete aggregate can be used safely in concrete. RCA replacement of up to 50% is recommended for structural applications, and up to 80% may be used for non-structural applications. Full (100%) replacement is generally not advised because of the reduction in strength, unless suitable measures are adopted. Nonetheless, the 100% mix still outperformed the 0% mix, suggesting that full replacement may be feasible if the aggregate is appropriately treated. Safiuddin et al. likewise advised against 100% RCA, as it gave lower compressive strength than the control concrete [13]. Mohammed et al. also recommended replacing up to 50% of NCA with RCA [11], and Karunaratne and Kariapper proposed the same 50% limit [9]. In contrast, Zhou and Chen reported higher strength at 70% than at 50% replacement, which closely agrees with the present findings [10].

4. Conclusion

This paper studied the properties of concrete made with RCA and the following conclusions were deduced from the investigation:

Most previous researchers have recommended limiting RCA replacement to 20–25%. The present study, however, indicates that up to 50% replacement is suitable for structural applications, and up to 80% can be used safely in non-structural applications, provided that mix design, water content, and curing are properly controlled. At 100% RCA replacement, strength decreases because of the large quantity of weak, porous adhered old mortar, higher water absorption, greater porosity, the formation of multiple weak interfacial transition zones, and the reduced stiffness of the aggregate skeleton. Full replacement may nevertheless be achievable if the aggregate is suitably treated beforehand. Overall, RCA used within an optimum replacement range offers acceptable mechanical performance together with considerable environmental benefits, making it a sustainable substitute for natural aggregate. Before RA is adopted for structural concrete, however, its specific

characteristics should be evaluated experimentally, since the properties of recycled aggregate vary from site to site with the type and age of the source structures. Properties of RAC such as workability, compressive strength, tensile strength, and density can be tailored by adjusting the w/c ratio and the RCA replacement level.

Abbreviations

C&D	Construction and Demolition
RCA	Recycled Concrete/Coarse Aggregate
RAC	Recycled Aggregate Concrete
NCA	Natural Coarse Aggregate
NA	Natural Aggregate
RA	Recycled Aggregate
ITZ	Interfacial Transition Zone
PCC	Portland Composite Cement
SSD	Saturated Surface Dry
UTM	Universal Testing Machine
w/c	Water–cement Ratio

Author Contributions

Mahedi Hasan Shuvo: Data curation, Supervision

Md Johirul Islam Khan: Conceptualization, Methodology, Resources

Md Abdullah Al Mamun: Funding acquisition, Investigation, Project administration

Shamima Nasrin: Validation, Visualization

Md Shofiul Islam: Formal Analysis, Writing – original draft

Data Availability Statement

All data supporting the findings of this study are included in this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography



Mahedi Hasan Shuvo is a Lecturer in the Department of Civil and Environmental Engineering at Fareast International University, Bangladesh. He received his B. Sc. degree in Civil Engineering from the Islamic University of Technology (IUT), Bangladesh, in 2021. His research interests include structural engineering, seismic performance and resilience of structures, sustainable construction materials, and structural analysis and design. His current academic work focuses on sustainable and resilient structural systems and the application of advanced analytical approaches in civil engineering.



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Md Abdullah Al Mamun working as an Associate Professor in the Department of Civil and Environmental Engineering at Fareast International University, Bangladesh. He received his B. Sc. degree in Civil & Environmental Engineering from the University of Asia Pacific (UAP), Bangladesh, in 2005. He received his Master's in 2009 and Ph. D in 2013 from Hokkaido University, Japan on Concrete Technology. His research interests include durability of concrete in severe environment, sustainable durable material for built environment, structural engineering, repair and retrofitting of deteriorated concrete structures, development of high strength fiber reinforced concrete and recycling of aggregates. His current research work focuses on use of sustainable construction material in Bangladesh and modeling of constitutive laws of different construction materials. Dr. Mamun actively engages in organizing seminars, workshop and symposium on concrete technology. He is a member of Japan Concrete Institute (JCI), and Japan society of Civil Engineers (JSCE).



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Research Field

Mahedi Hasan Shuvo: Structural Engineering, Structural Sustainability, Concrete Technology, Sustainable Materials, Earthquake Engineering, Multi-hazard Resilience.

Md Johirul Islam Khan: Structural Analysis & Design, Seismic Analysis of Building, Sustainable Construction, Reinforced Fiber Concrete, Recycled Aggregate Concrete, and Geopolymer Concrete.

Md Abdullah Al Mamun: Concrete in Severe Environment, Recycling of Aggregates, Sustainable Concrete Construction, Constitutive Laws of High Performance Concrete, Utilization of Industrial by as Coarse Aggregate.

Shamima Nasrin: Geotechnical Engineering, Slope Stability, Soil Behavior and Characterization, Sustainable Geotechnical Practices, Environmental Engineering, Wastewater Treatment.

Md Shofiul Islam: Sustainable Construction Materials, Air Quality analysis, Traffic Engineering, Transport Planning, and Environmental Sustainability.