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EXPLORING STRENGTH CONVERSION FACTORS OF RECYCLED AGGREGATE CONCRETE SOURCED FROM PILE CAP

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ABSTRACT

This study investigates the compressive strength development and strength conversion factors (SCFs) for Recycled Aggregate Concrete (RAC) using coarse aggregates sourced from three different demolition sites in Rajshahi, Bangladesh: RUET, Varendra, and Meherchandi. The aim was to assess RAC performance against Natural Coarse Aggregate (NCA) concrete and to develop SCFs across varying specimen sizes and shapes 100 mm cube, 150 mm cube, 100×200 mm cylinder, and 150×300 mm cylinder at 7, 14, and 28 days of curing. Experimental results revealed that although RAC showed comparable or higher strength at early curing stages in some cases, it lagged behind NCA at 28 days, particularly for RUET-sourced RCA. Meherchandi RCA achieved the highest cube strength, while Varendra RCA performed best in cylindrical specimens. SCFs were found to be variable, influenced by mortar content, specimen geometry, and curing age, with values ranging from 0.86 to 1.42. Scanning Electron Microscopy (SEM) analysis confirmed that the Interfacial Transition Zone (ITZ) in RAC was more porous and micro-cracked compared to NCA, explaining its reduced long-term strength. The findings highlight the need for customized SCFs when using RAC and underscore the potential of properly selected RCA in structural applications.

Keywords: *Recycle Aggregate Concrete, Strength Conversion Factor, Shape and Size Effect, Pile Cap, Interfacial Transition Zone.*

1. INTRODUCTION

Concrete is the backbone of modern construction used everywhere due to its strength and durability. However, this comes at a significant cost to our planet. The production of cement, a key ingredient in concrete is a major source of carbon dioxide (CO_2) emissions. As noted by (Kim et al., 2022) producing just one cubic meter of concrete can release between 189 and 266 kg of CO_2. At the same time, our cities are generating massive amounts of construction and demolition waste, which piles up in landfills. This creates a twin challenge: reducing the environmental footprint of new construction and managing the waste from old structures. A promising solution to both problems is Recycled Aggregate Concrete (RAC). By crushing demolition waste into Recycled Coarse Aggregates (RCA), we can replace natural aggregates in new concrete. This approach conserves natural resources and reduces landfill waste. Researchers like (Khan & Ali, 2022) have highlighted the great potential of using such waste materials to create more sustainable concrete with a lower environmental impact.
Despite its clear benefits, RAC has one major hurdle preventing its widespread use, it often has lower compressive strength than conventional concrete. Studies including those by (Fonseca et al., 2011), have shown that this is mainly because the recycled aggregates are more porous and have old mortar attached to them. This leads to a weaker Interfacial Transition Zone (ITZ) the microscopic boundary where the aggregate piece meets the cement paste. (Poon et al., 2004) used advanced imaging to show that this zone in RAC is typically more porous and micro-cracked, which explains the reduction in strength. Furthermore, measuring the strength of concrete is not as straightforward as it seems. The result you get depends heavily on the size and shape of the test specimen. For example, a cube will usually show a higher strength than a cylinder made from the same concrete, and larger specimens tend to show lower strength than smaller ones, as explained by (Tokyay & Özdemir, 1997). To compare results fairly engineers use Strength Conversion Factors (SCFs). While reliable SCFs are well established for normal concrete, these factors cannot be directly applied to RAC due to its fundamentally different aggregate characteristics. The variable quality of recycled aggregates means these factors need to be specifically determined for RAC. (Reddy et al., 2019) pointed out that these conversion factors for RAC can vary based on the mix and the specimen size. This brings us to the core problem. Although the need for specific SCFs for RAC is known, there is a lack of detailed studies that develop these factors for recycled aggregates from specific local sources. The properties of RCA can change dramatically depending on where the demolition waste came from. A conversion factor developed for one type of RCA might not work for another. Therefore, to confidently use RAC in structural projects, we need localized studies that connect the strength performance of local RCA to standardized conversion factors.

To address this need, our study investigates the compressive strength and develops strength conversion factors for RAC using coarse aggregates sourced from three different demolition sites in Rajshahi, Bangladesh. The main goals of this project are:

- To evaluate the compressive strength behavior of Recycled Aggregate Concrete (RAC) compared to natural aggregate concrete.
- To develop strength conversion factors for different specimen shapes and sizes using RAC sourced from local pile caps.

By providing this crucial data, our research aims to support the reliable use of local recycled aggregates in structural concrete, helping to make the construction industry in Bangladesh more sustainable.

2. METHODOLOGY

The experimental investigation was carried out to evaluate the compressive strength behavior of Recycled Aggregate Concrete (RAC) and to develop strength conversion factors considering different specimen shapes and sizes. For this study, the concrete mix was designed as M20-grade concrete with the mix ratio of 1:1.5:3 for cement: fine aggregate: coarse aggregate. A concrete mix with w/c ratio of 0.5 was prepared. The fresh concrete exhibited a slump of 1.6 inches. Natural Coarse Aggregate

(NCA) was used as a control, while Recycled Coarse Aggregates (RCA) were collected from three different sources: RUET campus, Varendra construction site, and Meherchandi demolition area. These aggregates were characterized for key physical properties such as bulk density, specific gravity, water absorption, and mortar content. A uniform mix design with a constant water–cement ratio of 0.45 was adopted for all concrete types, and full replacement of NCA with RCA was implemented in each case. Concrete specimens were cast in four distinct geometries: 100 mm cube, 150 mm cube, 100×200 mm cylinder, and 150×300 mm cylinder, and each specimen type was tested at three curing ages 7, 14, and 28 days to evaluate strength development over time. All specimens were cured under water and tested for compressive strength using a digital compression testing machine following ASTM and BS standards. Strength conversion factors (SCFs) were calculated by taking the ratio of RAC strength to NCA strength for each geometry and age group, and both arithmetic and geometric means were used to generalize the SCFs. In addition, microstructural analysis using Scanning Electron Microscopy (SEM) was performed on selected samples to assess the quality of the interfacial transition zone (ITZ) and to identify porosity, microcracks, and bonding characteristics that influence the compressive performance of RAC.

Figure 1: Sample making process

2.1 Material Properties investigation:

2.1.1 Cement: For this study, Ordinary Portland Cement (OPC) was used from the Seven Rings brand, which is a widely recognized cement supplier. The cement is classified as CEM-1, 52.5 N, and conforms to the standards outlined in BDS EN 197-1:2003, ASTM C150, Type 1. This type of OPC is commonly used for general-purpose concrete and is characterized by its high strength and versatility.

2.2.1 Fine Aggregate: In this study, locally available Domar sand was used as the fine aggregate in both Recycled Aggregate Concrete (RAC) and Natural Coarse Aggregate Concrete (NCA). Fine aggregates, which pass through a 4.75 mm sieve, enhance workability and fill voids between coarse particles to form a dense mix. Domar sand is recognized for its consistency and suitability in concrete production. The fineness modulus, ranging from 1.92 to 3.66, indicates its particle size distribution and influences both strength and workability.The Domar sand in this study had an FM of **2.53**, indicating a moderately fine texture suitable for concrete with good workability and strength.

2.2.2 Gradation: Gradation refers to the distribution of particle sizes within a fine aggregate sample. A well graded fine aggregate has a balanced distribution of coarse and fine particles, ensuring better packing and reducing voids in the mix. Domar sand was tested for gradation, and its particle size distribution followed the standard specifications for fine aggregates.The curve appears to have a relatively smooth distribution across a range of sieve sizes, suggesting that the aggregate is well-graded.

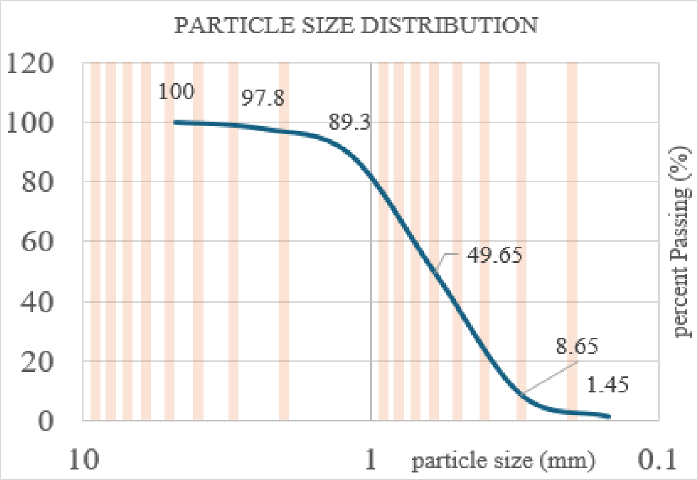

Figure 2: Particle Size Distribution Curve of Fine Aggregate

2.1.4 Specific Gravity of Coarse aggregates: Specific Gravity is the ratio of the density of a material to the density of water and is a key property for evaluating aggregates. It indicates the density of the material and helps determine the proportions for concrete mix design. Studies suggest that the specific gravity of NCA is usually around 2.60 to 2.75 and The specific gravity of RCA typically falls within the range of 2.30 to 2.60. Some studies have reported values as low as 2.14 (Nafis et al. 2017; Sahare et al. 2024). Our experiments show the specific of NCA is 2.88 and RCA ranges from 2.19 to 2.24, the variation is due to source variation shown in table 2.1.

2.1.5 Water Absorption: Water absorption refers to the amount of water an aggregate can absorb when immersed for 24 hours, expressed as a percentage of its dry mass. This property significantly influences the workability, strength, and water-to-cement ratio in the concrete mix. Water absorption is a crucial property of aggregates, particularly Recycled Coarse Aggregate (RCA), which tends to absorb more water than Natural Coarse Aggregate (NCA). (Joseph et al., 2015) highlighted that RCA can have water absorption values as high as 10%, which significantly impacts the water-to-cement (w/c) ratio in concrete mixes. In our experiment we found the water absorption of NCA was 1.65% and RCA ranges from 7.76% to 9.62% shown in table 2.1.

Table 2.1: Specific Gravity of coarse aggregate

Sample	Submerged Weight, W1 (g)	Surface Dry Weight, W2 (g)	Oven Dry Weight, W3 (g)	Specific Gravity	Water absorption (%)
NCA	1296	1969	1937	2.88	1.65
RCA (RUET)	1231	2086	1903	2.23	9.62
RCA (Varendra)	1215	2094	1926	2.19	8.72
RCA (Meherchandi)	1203	2054	1906	2.24	7.76

2.1.6 Bulk density: Bulk density is the mass of an aggregate per unit volume, including the voids between particles. It's a key property that influences the workability and strength of a concrete mix design.Since bulk density depends on how tightly the aggregate is packed,This study measured both the loose and dense bulk densities of the coarse aggregate shown in table 2.2.

Table 2.2: Bulk Density of coarse aggregate

Sample	Loose Bulk Density (kg/m³)	Compacted Bulk Density (kg/m³)
NCA	1499.46	1699.34
RCA (Varendra)	1536.9	1558.09
RCA (Meherchandi)	1272.74	1445.78
RCA (RUET)	1281.92	1428.83

2.1.7 Mortar Content: The mortar content in Recycled Coarse Aggregate (RCA) significantly affects the strength and workability of Recycled Aggregate Concrete (RAC). It refers to the old cement paste attached to the aggregate surface, which weakens the concrete when present in excess. Acid treatment helps reduce this mortar content, improving adhesion and enhancing both compressive and tensile strength described by (Alyaseen et al., 2021)**.** The acid emulsion test is used to determine the mortar content in Recycled Coarse Aggregate (RCA) by dissolving the calcium carbonate in the old mortar attached to the aggregates. A solution of 37% Hydrochloric acid and water in a 10:1 ratio is prepared, and the RCA is immersed in the solution for 24 hours. After immersion, the aggregates are thoroughly washed, oven-dried for 24 hours, and the difference in weight between the original and cleaned aggregates is measured. The mortar content is then calculated as a percentage of the original RCA mass shown in table 2.3.

Table 2.3: Mortar content test of RCA

Acid Emulsion (Mortar Content) Test Results			
Sample	Initial Weight (g)	Final Weight (g)	Mortar Content (%)
RCA (RUET)	500	363	27.4
RCA (Varendra)	500	376	24.8
RCA (Meherchandi)	500	362	27.6

3. RESULT AND DISCUSSION

3.1 Strength Development: The compressive strength development of both cylindrical and cube specimens revealed distinct trends between Natural Coarse Aggregate (NCA) and Recycled Coarse Aggregate (RCA) concretes across curing ages. For cube specimens, at 28 days, the highest strength was observed for NCA (33.8 MPa for 100 mm cubes), while among RCA samples, Meherchandi RCA exhibited the highest strength (25.18 MPa), followed by Varendra (24.29 MPa) and RUET (22.53 MPa) shown in figure 3.1 and 3.2. Strength gain over time was evident in all specimens, but

RCA mixes showed comparatively slower development due to the presence of old mortar, higher porosity, and weaker interfacial transition zones (ITZ). At early ages (7 and 14 days), Meherchandi samples performed notably well, possibly due to lower water absorption and relatively better-quality recycled aggregates. In cube specimens, RAC showed comparable or slightly higher early strength (7 & 14 days) than NCA in some cases, especially for Meherchandi source. However, at 28 days, all RAC samples exhibited notably lower strength (by 26–32%) than NCA, indicating slower long-term strength development.

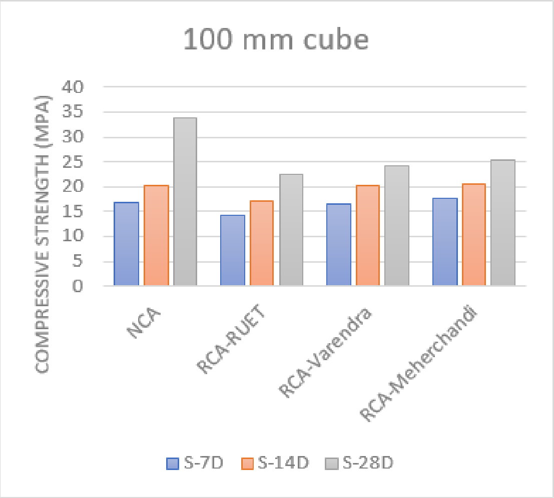

Figure 3.1: Graphical analysis of 100 mm cube sample

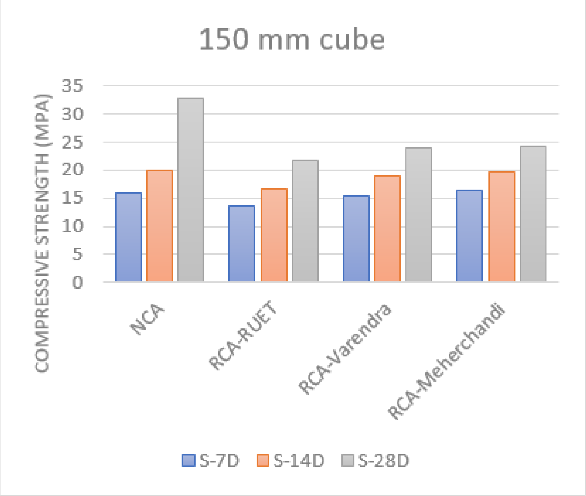

Figure 3.2: Graphical analysis of 150 mm cube sample

For cylindrical specimens, although all RCA samples showed lower strength compared to NCA (which reached 25.68 MPa in 100×200 mm cylinders at 28 days), Meherchandi RCA provided the highest strength among the recycled mixes (21.87 MPa), followed by Varendra (21.57 MPa) and RUET (20.71 MPa). A similar trend was found in 150×300 mm cylinders, where Meherchandi RCA again surpassed others shown in figure 3.3 and 3.4. These results confirm that specimen geometry influences compressive strength values cubes generally reported higher strength than cylinders. Across all samples, RCA concretes exhibited 20–30% lower strength than NCA at 28 days, but performance varied significantly by RCA source .

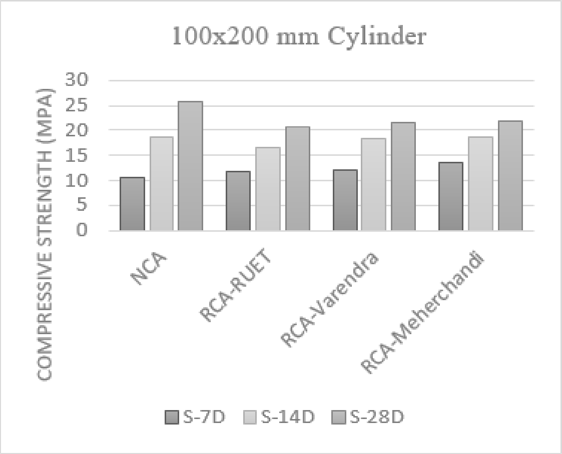

Figure 3.3: Graphical Analysis of Ø100x200 mm Cylinder

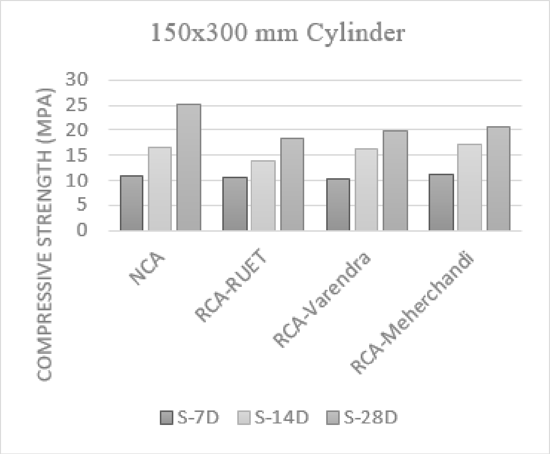

Figure 3.4: Graphical Analysis Ø150x300 mm Cylinder

The compressive strength decreases with increasing specimen size and changes shape from cube to cylinder, reflecting size and shape effects on strength measurement. Cubes generally show higher strength than cylinders due to more uniform stress distribution and reduced stress concentrations showed in table 3.1.

Table 3.1: Comparison of strength

Sample	**150 Cube**	**100 Cube**	**100x200 cyl**	**150x300 cyl**
	28Days	28Days	28Days	28Days
NCA	32.88	33.80	25.68	25.09
RCA-RUET	21.63	22.535	20.71	18.4
RCA-Varendra	23.89	24.29	21.57	19.87
RCA-Meherchandi	24.19	25.18	21.87	20.75

3.2 Strength Conversion Factors:

Strength Conversion Factors (SCFs) were developed to enable reliable comparison of compressive strengths across different specimen shapes and sizes for Recycled Aggregate Concrete (RAC) shown in figure 3.5 and table 3.2.

- **SCF_1** converts strength from 150×300 mm cylinders to 150 mm cubes. The values ranged from 1.16 to 1.52 depending on curing age and RCA source, with an arithmetic mean of 1.42 at 7 days, decreasing to about 1.18 at 28 days. This indicates that cube specimens consistently show higher compressive strength than larger cylinders, especially at early ages.
- **SCF_2** converts strength from 150 mm cubes to 100 mm cubes. The values were close to unity, ranging from 1.02 to 1.07, with a slight decrease over curing time (mean of about 1.06 at 7 days to 1.03 at 28 days), and suggesting minimal size effect between these cube dimensions.
- **SCF_3** converts strength from 150×300 mm cylinders to 100×200 mm cylinders. The SCF_3 values ranged from 0.82 to 0.95, increasing with curing age (mean increasing from 0.86 at 7 days to 0.92 at 28 days), showing smaller cylinders tend to have higher strength due to reduced size and shape effects.

Table 3.2: Strength Conversion Factors

SCF_1 for converting 150x300 mm cylindrical Strength to 150 mm cubic strength = (cube / cyl)									
Sample	Sc-7D	Sc-14D	Sc-28D	Scy-7D	Scy-14D	Scy-28D	SCF_1-7D	SCF_1-14D	SCF_1-28D
RCA-RUET	13.63	16.77	21.63	10.7	14.005	18.4	1.27	1.20	1.18
RCA-Varind	15.52	18.97	23.89	10.21	16.14	19.87	1.52	1.18	1.20
RCA-Meherchandi	16.38	19.83	24.19	11.1	17.08	20.75	1.48	1.16	1.17
Arithmetic Mean (AM)							1.42	1.18	1.18
Geometric Mean (GM)							1.42	1.18	1.18

SCF_2 for converting 150 mm cubic Strength to 100 mm cubic strength= (100 cube /150 cube)									
Sample	Sc-150-7D	Sc150-14D	Sc-150-28D	Sc-100-7D	Sc-100-14D	Sc-100-28D	SCF_2-7D	SCF_2-14D	SCF_2-28D
RCA-RUET	13.63	16.77	21.63	14.2	17.16	22.535	1.04	1.02	1.04
RCA-Varibnd	15.52	18.97	23.89	16.42	20.24	24.29	1.06	1.07	1.02
RCA-Meherchandi	16.38	19.825	24.19	17.605	20.565	25.18	1.07	1.04	1.04
Arithmetic Mean (AM)							1.06	1.04	1.03
Geometric Mean (GM)							1.06	1.04	1.03

SCF_3 for converting 100x200 mm cylindrical Strength to 150x300 mm cubic strength= (100 mm cyl / 150 mm cyl)									
Sample	Scy-100-	Scy-	Scy-100-	Scy-150-	Scy-150-	Scy-150-	SCF_3-	SCF_3-	SCF_3-

	7D	100-14D	28D	7D	14D	28D	7D	14D	28D
RCA-RUET	11.7	16.505	20.71	10.7	14.005	18.4	0.91	0.85	0.89
RCA-Varind	12.21	18.355	21.57	10.21	16.14	19.87	0.84	0.88	0.92
RCA-Meherchandi	13.52	18.59	21.87	11.1	17.08	20.75	0.82	0.92	0.95
Arithmetic Mean (AM)							0.86	0.88	0.92
Geometric Mean (GM)							0.86	0.88	0.92

These **SCFs** highlight the importance of specimen geometry and curing age when interpreting RAC strength results and provide practical conversion parameters for structural design and quality control .

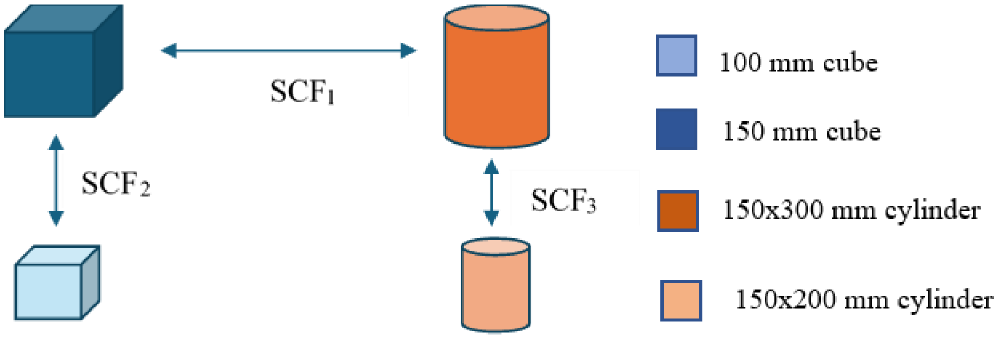

Figure 3.5: Flowchart of SCF

3.3 Microstructural Evaluation

The ITZ is denser and stronger due to better bonding between natural aggregates and cement paste, leading to higher mechanical strength shown in Figure 3.6. Hydration products are uniformly distributed, enhancing durability. The Interfacial Transition Zone (ITZ) in concrete containing recycled aggregates is generally more porous and weaker due to the presence of residual mortar on the aggregates. This results in the formation of microcracks and a reduction in bond strength, as shown in Figure 3.7. Irregular hydration and a compromised ITZ may lead to increased permeability and diminished long-term durability. Ettringite formation, a typical aspect of the cement hydration process, occurs when sulphate and aluminate ions react to form a crystalline mineral. Although ettringite formation generally facilitates early strength development, excessive or delayed formation can cause cracking and expansion, known as Delayed Ettringite Formation (DEF). The presence of ettringite in concrete at 28 days suggests a slower strength development in recycled aggregate concrete. This is supported by our results, which demonstrate that the compressive strength of recycled aggregate concrete is lower compared to that of natural aggregate concrete.

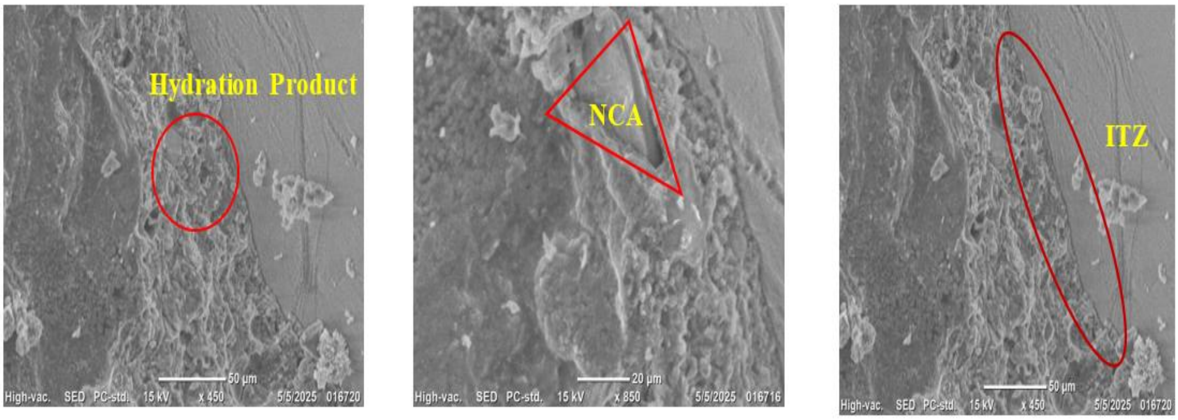

Figure 3.6: SEM analysis of NCA

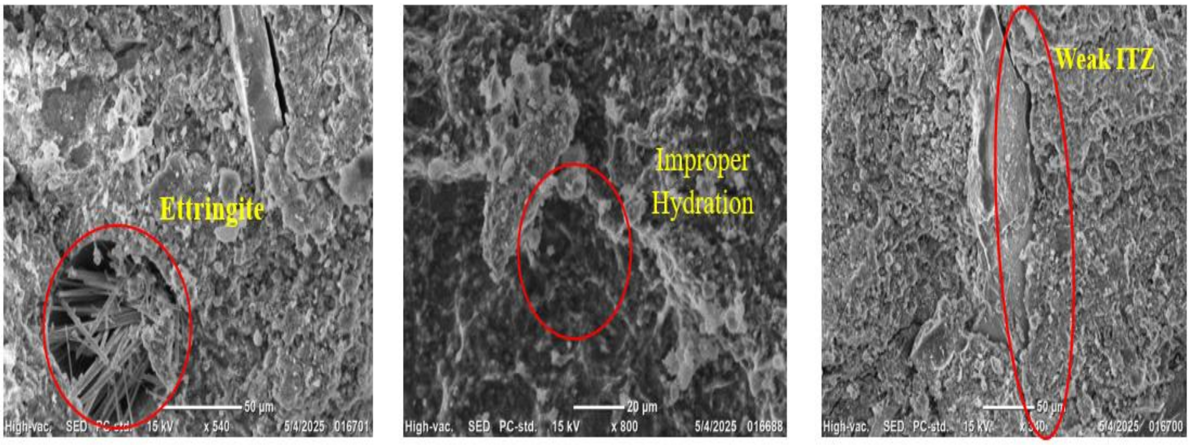

Figure 3.7: SEM analysis of RCA

4. CONCLUSIONS

This research comprehensively investigated the compressive strength development of Recycled Aggregate Concrete (RAC) obtained from three different sources RUET, Varendra, and Meherchandi and compared it with Natural Coarse Aggregate (NCA) concrete across different specimen shapes (cubes and cylinders) and sizes (100 mm and 150 mm cubes, 100×200 mm and 150×300 mm cylinders) at multiple curing ages (7, 14, and 28 days). The results consistently showed that RAC exhibits lower compressive strength than NCA, primarily due to the presence of residual mortar and higher porosity in recycled aggregates, which weakens the Interfacial Transition Zone (ITZ) as confirmed by SEM microstructural analysis. The study successfully developed three Strength Conversion Factors (SCFs) to standardize strength comparisons: SCF_1 converts 150×300 mm cylindrical strength to 150 mm cube strength, SCF_2 converts 150 mm cube strength to 100 mm cube strength, and SCF_3 converts 150×300 mm cylindrical strength to 100×200 mm cylindrical strength. These SCFs varied slightly with curing age but showed good consistency across the different RAC sources, with arithmetic mean values of approximately 1.18 for SCF_1 at 28 days, 1.03 for SCF_2, and 0.92 for SCF_3. These conversion factors enable reliable translation of compressive strength results between different specimen geometries and sizes, addressing a critical gap in the standardized testing of RAC. Strength development trends revealed that Meherchandi samples generally showed higher strengths among RACs in both cube and cylinder specimens, likely due to lower porosity and better aggregate quality, whereas Varendra samples showed comparatively higher cylinder strengths. The findings highlight the influence of source-specific aggregate properties on RAC performance, emphasizing the need to consider local material characteristics in design and testing. Overall, this research provides a valuable framework for interpreting RAC compressive strength data across different specimen types, improving the accuracy of strength assessments for structural applications. By establishing reliable conversion factors and linking microstructural observations to mechanical performance, the study supports the wider adoption of RAC as a sustainable construction material while ensuring structural safety and durability. Further research is recommended to explore the long-term durability characteristics of RAC under different environmental exposures and loading conditions. Investigations into optimizing mix designs and improving ITZ quality through innovative treatments or additives can enhance RAC performance. Additionally, extending the study to other mechanical properties such as tensile strength, modulus of elasticity, and fatigue behavior would provide a more comprehensive understanding. The development of more refined, probabilistic conversion models incorporating variability in recycled aggregate quality could further standardize RAC testing and design practices globally.

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DECLARATION OF USE OF AI

During the preparation of this work, the author(s) used an AI tool solely for the purpose of grammar checking and language enhancement to improve readability. No AI was used to generate, interpret, or analyze scientific content, nor was it involved in the research methodology or data processing. The author(s) have reviewed and edited all content and take full responsibility for the work's integrity.

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