Suitability of Recycled Aggregates for Application in Structural Concrete: Experimental Study

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Received 05 October 2024; Accepted 22 December 2024

Abstract

Demolition wastes have been increasing day by day as the age-old concrete structures are to be replaced for a new one. In order to reduce the impact of this demolished concrete in nature, recycling it as coarse aggregates appearsto be a highly sustainable option. Recycled aggregates comprise crushed, graded inorganic particles processed from the materials that have been used in the construction and demolition debris. The aim of this project is to determine the suitability of recycled aggregates for application in structural concrete in terms of strength and serviceability criteria. The initial questions concerning the strength of aggregate and workability enhancement aredue to the associated mortar content. Few tests were conducted on the properties of the new aggregate, such as specific gravity, water absorption, and aggregate crushing

Journal of Graphic Era University, Vol. 13_1, 139–154.
doi: 10.13052/jgeu0975-1416.1317

value. Properties of concrete such as compression strength, splitting tensile strength, flexural strength, and modulus of elasticity were found out. Finally, the application of recycled coarse aggregates in pavement construction was studied. A brief comparison of the cost efficiency was also evaluated.

Keywords: Recycled aggregate, cement concrete, compressive strength, flexure strength.

1 Introduction

Utilization of the demolition waste from old concrete structures in new civil infrastructure development has been an emerging area of interest. Exercising recycled aggregates in construction has been found to be beneficial for environmental protection and cost-efficiency. Such waste products are processed and used as alternative aggregate for structural concrete [1]. Concrete manufactured by using such recycled concrete aggregate is termed as Recycled Aggregate Concrete (RAC) [2].

More than 3 billion tonnes of raw materials are annually manufactured around the world in construction projects, and a comparable volume of waste materials is produced due to the partial to complete demolition of obsolete civil infrastructures [3]. Effective disposal of the solid waste is challenging unless they can be suitably reused. It is important to evaluate whether these waste products possess the essential engineering properties necessary for structural applications, including density, gradation, strength and stiffness parameters, endurance and resilience, etc. [4]. This evaluation necessitates adequate testing and processing of these materials for optimal utilization of existing resources.

Studies in relevant fields have commenced well before the year 2000, wherein the retained moisture in RAC had been investigated [5]. A laboratory-based study on porosity of RAC was conducted [6]. Assessment of the strength of RAC by means of toughness and soundness test results was performed earlier [7]. Studies on the durability and moisture conditioning of fresh and hardened RAC were also carried out [8, 9]. The principle of 3R, namely, reduce, reuse, and recycle, was studied for RAC in China [10]. Theoretical and experimental investigations on the time-dependent drying shrinkage model for RAC were developed [11]. A brief review on the sustainable use of recycled construction waste products in pavement construction projects has been performed [12].

Despite these significant contributions, a clear research gap remains in comparing the structural performance of RAC versus natural aggregates (NAC), specifically in terms of compressive, flexural, and tensile strengths and cost-efficiency in concrete applications. This study aims to address this gap by systematically investigating the compressive, split tensile, and flexural strengths of RAC compared to NAC, with a focus on cost-effectiveness and optimal application in structural concrete.

2 Objective And Methodology

The primary objective of this investigation is to assess the suitability of recycled coarse aggregates obtained from demolished concrete structures and to analyze the structural properties of concrete made of such recycled aggregates by conducting a series of laboratory tests. Comparison of the RAC with conventional concrete made up of natural aggregates has also been aimed to be conducted.

In this study, mixes were designed for both concretes prepared with waste materials used as recycled coarse aggregates and normal coarse aggregates. To ensure comprehensive testing, we included a specific number of samples for each concrete mix. A total of 12 samples per mix type were tested, with four samples each for compressive strength, split tensile strength, and flexural strength. For RAC, the waste products were manually crushed and machine-washed. Concrete mixes for each aggregate type were prepared for M20, M25, and M30 proportions, and the following properties were determined: compressive strength, split tensile strength, flexural strength, and modulus of elasticity.

3 Experimentations

Recycling is the act of processing the used material for use in creating new products. The materials used and testing details are described in this section.

3.1 Materials

Both the RAC and NAC are used in this study for comparison. Recycled aggregate is mainly obtained by demolished obsolete concrete structures, including buildings and bridges. They are available in bulk quantities from local sites and procured at cheap costs. Recycling of concrete involves

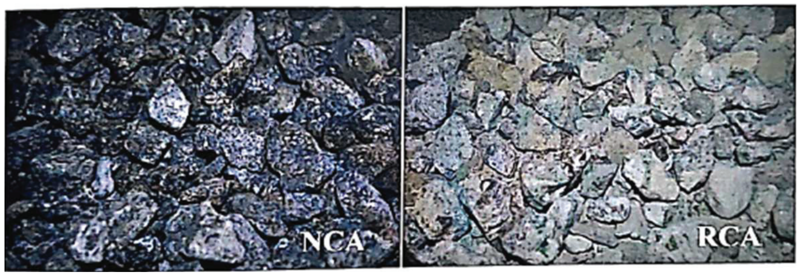

Figure 1 Photographs of natural and recycled coarse aggregates used

breaking, removing, and crushing existing concrete into a material with a specified size and quality. The recycled aggregates may be either manually crushed with the help of a hammer or machine crushed, which is particularly applicable when aggregates are composed of rock fragments.

For bulk works, it is not easy to dismantle the concrete manually, so crushers are used for this purpose. After crushing, the aggregates were sieved manually following an appropriate code of practice to ensure well grading of aggregates.

Natural aggregates used for manufacturing NAC are obtained by crushing the naturally available rocks to the required size, and they are obtained at all standard sizes. The natural and recycled aggregates have much difference in properties, which are discussed later. Photographic views of the aggregates are shown in Figure 1.

3.2 Physical Properties

The specific gravities of aggregates have been determined following the standard procedure [13]. The specific gravities of different coarse aggregates are listed in Table 1 below.

Table 1 Specific gravity of coarse aggregates

Category	Type		Specific Gravity
Recycled aggregate	Manually crushed	Unwashed	2.67
		Washed	2.67
	Machine crushed		2.35
Natural aggregate	–		2.73

Sieve analysis of the coarse aggregates has been carried out using the procedure recommended [14]. The sieve sizes adopted were 25 mm, 20 mm,

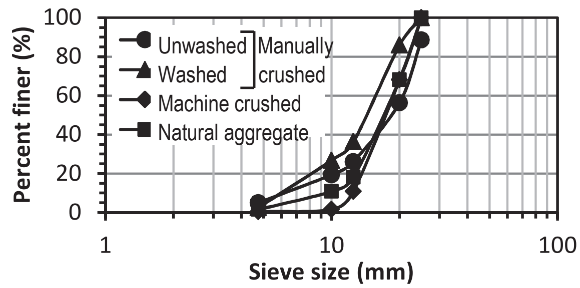

Figure 2 Particle size distributions of different coarse aggregates.

12.5 mm, 10 mm, and 4.75 mm. The particle size distribution curves are depicted in Figure 2.

3.3 Mix Proportions

The process of selecting suitable proportions of different ingredients in a concrete having specific characteristic strengths with the objective of producing a concrete of the required strength, durability, and workability is termed the concrete mix design. Herein, the standard code of practice has been followed [15]. The design mix adopted is presented in Table 2 below.

Table 2 Concrete mix design

				Ratio of Ingredients by Weight			
Coarse Aggregate			Concrete Grade	C	FA	CA	W
Recycled	Manually crushed	Un-washed	M20	1	1.85	3.47	0.5
			M25	1	1.71	3.21	0.5
			M30	1	1.37	2.69	0.45
		Washed	M20	1	1.85	3.47	0.5
			M25	1	1.71	3.21	0.5
			M30	1	1.37	2.69	0.45
	Machine crushed		M20	1	1.85	3.05	0.5
			M25	1	1.71	2.82	0.5
			M30	1	1.37	2.33	0.45
Natural			M20	1	1.85	3.55	0.5
			M25	1	1.71	3.28	0.5
			M30	1	1.37	2.7	0.45

Notations: C = Cement; FA = Fine Aggregate; CA = Coarse Aggregate; W = Water.
Note: To enhance the bond the admixture used was Pidicrete CF204 manufactured by Pidilite, added at a rate of 250ml per 50 kg of cement.

3.4 Physical Tests of Concrete

In order to examine the physical properties of concrete cast with recycled and natural aggregates, a few standard tests have been performed following the recommended specifications. The details are given in Table 3 below.

Table 3 Physical tests of concrete

Test	Code of Practice
Compression	[16]
Split Tension	[17]
Flexure	[16]
Stiffness: Modulus of Elasticity	[16]

Few photographic views of the tests are shown in Figure 3.

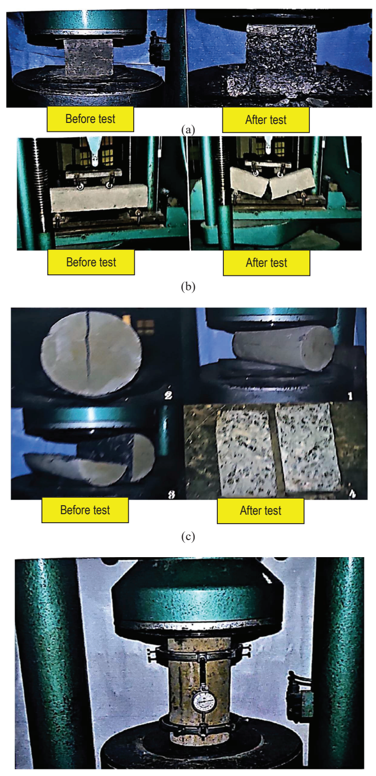

Figure 3 Different tests for concrete: (a) Compressive, (b) Split tensile, (c) Flexure, and (d) Modulus of elasticity.

4 Results And Discussion

The results obtained from the field and laboratory investigations have been summarized in this section, together with appropriate analysis and interpretations. The parameters studied are consistent with Table 3 above.

4.1 Compressive Strength

The compressive strengths of concrete cubes cast with different types of recycled coarse aggregates and natural aggregates are shown in Figure 4. Additional analysis has been provided to clarify the performance of machine-crushed aggregates. Machine-crushing is hypothesized to induce degradation in aggregate quality, potentially resulting in lower compressive strengths as indicated in the data. The impact of such degradation on structural performance is discussed further below.

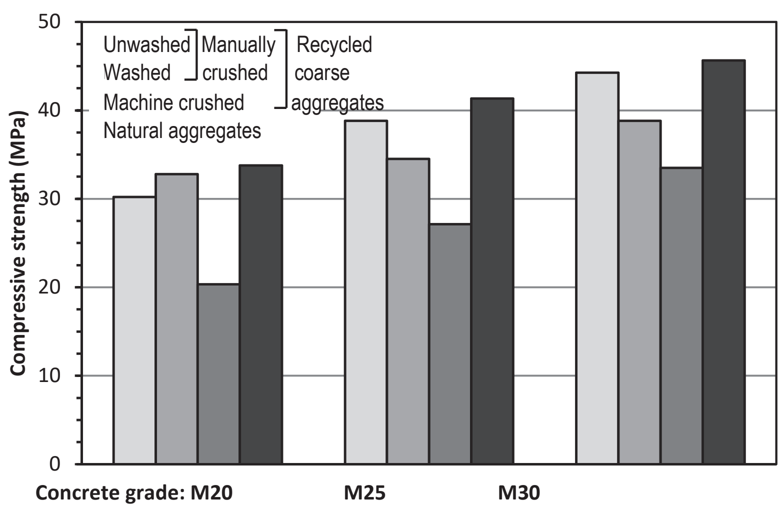

Figure 4 Compressive strength of concrete with various coarse aggregates.

4.2 Split Tensile Strength

The split tensile capacity of the concrete member is determined by laboratory testing, and the split tensile strength is evaluated from the following correlation [17]:

$$f_{st} = \frac{2P_u^t}{\pi DL} \tag{1}$$

where, f_{st} is the split tensile strength, P_u^t is the ultimate tensile load, and D and L are the initial diameter and length of the concrete member, respectively.

The values of split tensile strength of concrete specimens with recycled and natural coarse aggregates are portrayed in Figure 5.

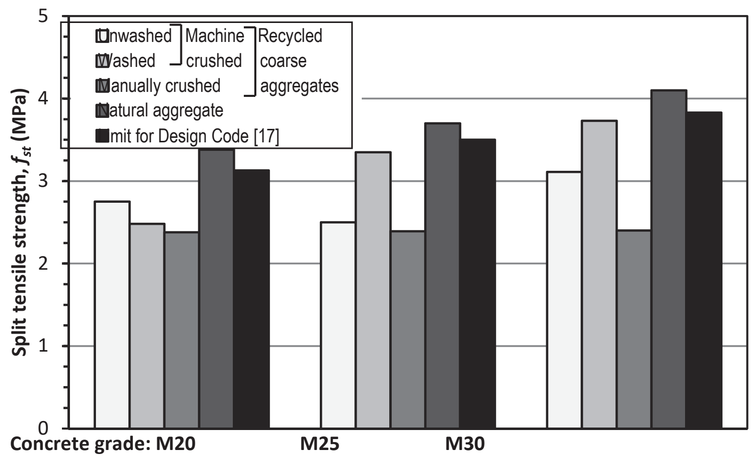

Figure 5 Split tensile strength of concrete with various coarse aggregates.

As observed, the split tensile strength of concrete with natural coarse aggregates consistently surpassed that of recycled aggregates. This result is attributed to potentially higher moisture absorption and residual micro-cracks in recycled aggregates, which are discussed later in the Analysis and Interpretation section.

4.3 Flexural Strength

According to the Indian Standard Code of Practice [18], the flexure strength of concrete may be estimated from its characteristic strength using the following correlation:

$$f_f = 5700\sqrt{f_{ck}} \quad [in\ MPa] \tag{2}$$

where f_f is the flexural strength and f_{ck} is the characteristic compressive strength of concrete.

From the test data, the flexural strength is evaluated using the following expression [17]:

$$f_f = \frac{P_u^f L}{bd^2} \tag{3}$$

where P_u^f is the ultimate flexural load, *L*, *b*, and *d* are the length, width, and depth of the concrete specimen, respectively.

The values of flexural strength of concrete specimens with recycled and natural coarse aggregates are portrayed in Figure 6. To strengthen our findings, we incorporated a comparative analysis with similar studies from existing literature, which highlights the distinct behaviour of RAC in flexural applications compared to NAC. As observed, the flexural strengths of concrete for both recycled and natural coarse aggregates exceed the minimum prescribed limits as per design code [18]. Also, for M20 grade of concrete, the washed manually crushed aggregate exhibited better value compared to natural aggregate, while the M25 and M30 concretes exhibited all aggregates to show close values.

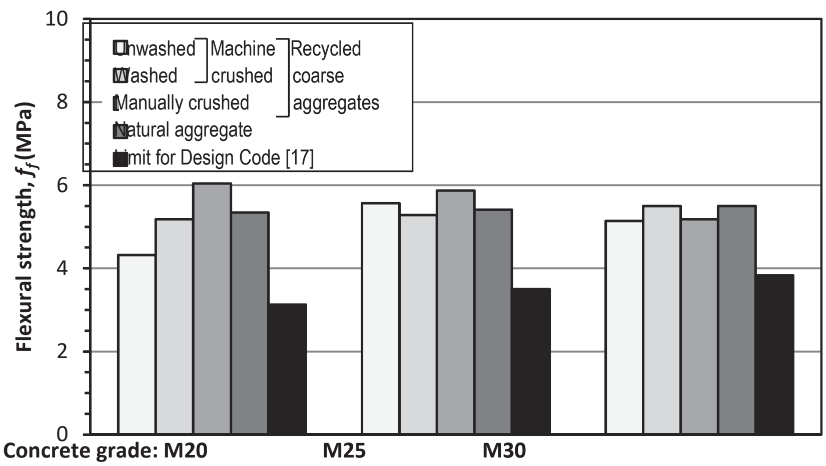

Figure 6 Flexural strength of concrete with various coarse aggregates.

4.4 Modulus of Elasticity

After the code of practice [18], the modulus of elasticity (E_c) is given by,

$$E_c = 5000\sqrt{f_{ck}} \quad [in\ MPa] \tag{4}$$

In this investigation, the secant modulus of elasticity at the specified stress level corresponding to one-third cube compression strength of concrete has been considered. The Young's modulus of elasticity values was determined by subjecting the cylinder specimens to axial compression are portrayed in Figure 7.

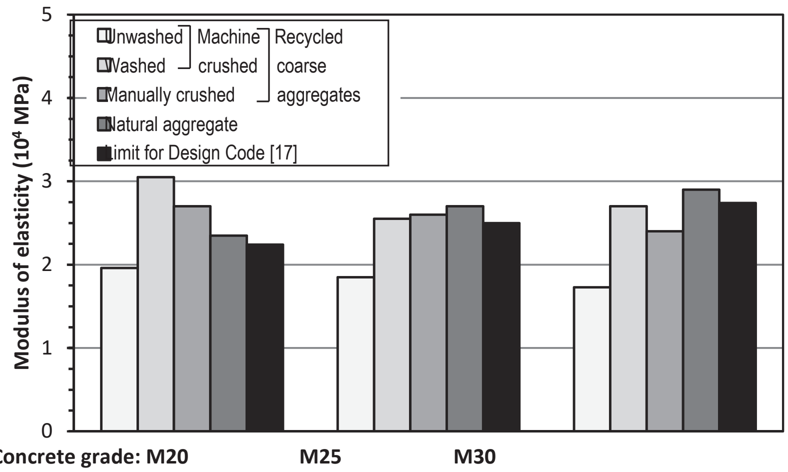

Figure 7 Modulus of elasticity of concrete with various coarse aggregates.

As observed, the values of modulus of elasticity for natural coarse aggregates are slightly higher than the values prescribed in the standard practice code. In the case of M20 grade concrete, the washed manually crushed and machine crushed aggregates exhibited significantly higher values than the natural aggregates, whereas the relevant values for the unwashed manually crushed aggregates are sufficiently low. For M25 grade of concrete, the relevant values for washed manually crushed aggregates are higher than the prescribed values as per the code of practice, but slightly lower than that of the natural aggregates. In the case of M30 concrete grade, the values for both manual and machine crushed aggregates are lower than those of the practice code.

4.5 Analysis and Interpretation

As observed, the strength and stiffness of concrete with natural coarse aggregates exceed those of recycled coarse aggregates. The strengths of concrete with manually crushed recycled aggregates are closer to those of natural aggregates, while machine-crushed aggregates show greater deviations. This is likely because natural aggregates are derived directly from rocks, which contributes to the higher strengths of concrete, while recycled products are derived from dismantled structural components that have already deteriorated due to prolonged environmental exposure and loading-unloading cycles.

Additionally, machine crushing likely degraded the strength of recycled aggregates further due to impact loading [19, 20].

5 Cost Efficiency Assessment

Apart from safety and serviceability, cost efficiency is one of the fundamental goals of any major project, particularly for public utility civil infrastructures. In the present study, the relative costs of construction with recycled aggregates have been compared with those of natural aggregates. A detailed breakdown of material costs has been provided, covering the cost of recycled versus natural aggregates, processing expenses, and potential savings. Materials required for 1 m^3 of concrete were obtained from mix designs, and the material costs for RAC and NAC were collected locally and standardized. Specifically, the costs of manually crushed recycled aggregates, machine-crushed recycled aggregates, and natural aggregates were evaluated individually, including labour, transportation, and processing costs for each type. The ratio of total costs for concrete with manually crushed RAC to NAC was estimated at 1: 0.884, while for machine-crushed, unwashed RAC, the value was found to be 1: 1.09. This analysis highlights the potential for cost savings when using manually processed recycled aggregates, whereas machine-crushed unwashed aggregates show a slight cost increase compared to natural aggregates.

6 Conclusions

The present research work was aimed at the utilization of recycled coarse aggregates derived from demolished obsolete concrete structures. The practical benefits of using such recycled materials in terms of strengths, stiffness, and cost-efficiency of concrete have been examined. The following conclusions can be drawn from the entire work:

- The compressive strengths of concrete are all higher than their relevant characteristic strengths prescribed by the code of practice, although concrete cast with recycled aggregates exhibited slightly lower values compared to those with natural aggregates.
- Split tensile strengths of concrete cast with natural aggregates are higher than the relevant prescribed values, whereas for recycled aggregates, the values were comparatively lower.

- Flexural strengths of concrete exceeded the prescribed values in all cases. Notably, concrete with recycled aggregates demonstrated higher flexural strength than those with natural aggregates, which indicates the suitability of RAC for certain structural applications.
- Differences in modulus of elasticity values for all concrete specimens were minimal. In most cases, the modulus values for recycled aggregates were comparable or higher than those for natural aggregates.
- Cost analysis indicates that the estimated cost of concrete with machine-crushed, unwashed recycled aggregates was slightly lower than that with natural coarse aggregates, suggesting potential cost savings.

In summary, the findings support the potential use of RAC in practical applications, especially non-load-bearing structures, pavements, and cost-sensitive construction projects. These applications align with the distinct structural behaviours observed in RAC, making it a viable and sustainable alternative for specific construction needs.

7 Limitations and Future Directives

This study establishes the viability of RAC for structural applications, yet several limitations highlight directions for future research:

- Material Variability
- Due to diverse sources, recycled aggregates exhibit inherent variability, affecting consistency in concrete properties. Improved quality control measures are essential for predictable large-scale applications. Future work should examine advanced sorting and treatment techniques to enhance aggregate uniformity.
- High-Strength Applications
- While the study supports RAC up to M30 grade, its performance in higher-strength applications remains untested. Further studies on RAC's suitability for higher-grade concrete could broaden its structural application range.
- Processing Impact
- Differences in aggregate crushing methods impact RAC strength. Future research could explore alternative crushing techniques to optimize aggregate quality with minimal resource intensiveness.
- Lifecycle and Environmental Analysis
- Preliminary results indicate RAC's cost benefits; however, comprehensive lifecycle and environmental impact analyses are needed to confirm RAC's sustainability on a larger scale.

- Durability Under Real-World Conditions
- Long-term RAC performance in varied environmental conditions, such as freeze-thaw cycles and chemical exposures, requires further investigation. Accelerated ageing tests could help predict RAC durability and structural integrity over time.
- By addressing these aspects, future research can enhance RAC's reliability and broaden its adoption in sustainable construction.

Acknowledgements

The authors thankfully acknowledge the laboratory, field-space and infrastructure facilities from North Eastern Regional Institute of Science & Technology to implement the entire program. The resource materials available at Regent Education and Research Foundation and Graphic Era Deemed to be University are also acknowledged.

Data Availability and Conflict of Interest Statements

All data are available in the paper. The authors declare that there is no conflict of interest.

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Sudip Basack received the bachelor's degree in civil engineering from Calcutta University in 1994, the master's and the doctor of philosophy degrees in civil engineering from Jadavpur University in 1996 and 2000, respectively. Later on he undertook post-doctoral study at University of Wollongong, Australia in the year of 2010. He has significant academic experience in India and overseas. More than 150 research publications have been authored/co-authored by him. He has successfully supervised more than 12 research students at masters and PhD levels, completed several Government sponsored R & D and consultancy projects. He has extensively travelled around the world, including USA, UK, Germany, Australia, New Zealand, Singapore, Malaysia, China, etc. His research areas include solid mechanics, concrete technology, geotechnical engineering, water resources, renewable energy, among others.