RECYCLED AGGREGATE CONCRETE (RAC): A VIABLE SOLUTION FOR SUSTAINABLE CONSTRUCTION

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Abstract- *Construction activities are booming in and around the cities with development and modernization. As a result of these constructions, natural aggregates are being extracted. Simultaneously, there is a significant amount of construction and demolition waste (CDW) generated due to the demolition of structures either due to the structure attaining service life or fashion and the ongoing trend of reconstruction. Therefore, recycling coarse aggregate from CDW in concrete is one of the sustainable solutions to prevent a serious threat to the environment due to the extraction of virgin aggregates and landfilling. This paper presents the results of a study undertaken to examine the influence of recycled concrete aggregate on the properties of new concrete and its life cycle cost (LCC) analysis. It is clear from the test that the strength of RAC is much lowered than natural aggregate concrete (NAC). In order to achieve the optimum strength, the natural aggregate is replaced by recycled aggregate within a range of 0% to 100%, in intervals of 10%. Additionally, to enhance its strength further, reinforcing RAC with new and recycled polypropylene (PP) fiber is done in percentages ranging from 0.25% to 2% by weight of cement with an interval of 0.25%. For analysis, compression, and split tensile strength tests were performed at the end of 28 days of the curing period. The result revealed that 40% replacement of natural aggregate with recycled aggregate achieves the ideal percentage replacement without compromising the strength. Moreover, incorporating 1.5% of new PP fiber or 1.25% of recycled PP fiber in the RAC provides optimum strength. For LCC analysis, the initial investment cost, operations, and maintenance cost, and salvage cost of all the alternatives are compared. Through this analysis, it was determined that the LCC of concrete manufactured using recycled aggregate as concrete ingredients is the lowest. Consequently, incorporating recycled aggregates in concrete production reduces the LCC compared to using natural aggregates.*

Keywords-recycled aggregate concrete, natural aggregate concrete, construction and demolition waste, Polypropylene fiber, life cycled cost analysis.

1. INTRODUCTION

Due to rapid construction activities, a huge volume of CDW is generated which leads to serious environmental pollution including a disposal problem [1]. CDW consists of the debris generated during infrastructure construction, renovation, and demolition. Globally CDW production of about 2 to 3 billion tons per year was estimated of which 30 to 40% was concrete [2]. As per the European Commission (EU), annually 531 million tons of CDW materials were produced by the construction industry, which is approximately 25% of the total waste materials that exist in the world [3]. China alone contributes about 2300 million tons of CDW annually [4]. In urban areas of Bhutan with 60394 households, about 57.7% of the households have houses built with concrete [5]. During demolition, this leads to the generation of a huge volume of CDW at the end of service life. Using CDW as aggregate can reduce the extraction of natural virgin aggregates and the problem of landfilling. Therefore, many countries are opting for recycling CDW for useful products and a country like Denmark has reached a 90% recycling rate [6]. However, in comparison to NAC, the strength and other properties of RAC were found satisfactory [7]. Therefore, reinforcing with fibers such as polypropylene fiber helps in filling up of gap or increasing its strength up to a certain level.

Polypropylene (PP) fibers are one of the cheapest fibers compared to other fibers such as steel, glass, and synthetics and are also abundantly available. PP fibers were found to increase the impact strength of RAC and they possess very high tensile strength with low modulus of elasticity and higher elongation [8]. Polypropylene has the properties such as low heat resistance, excellent chemical resistance, and living hinge capability, and is cheap and easy to produce. Therefore, it is very feasible to use polypropylene-reinforced RAC to maximize its strength [9]. In this paper, two types of polypropylene fibers were used namely factory-manufactured new PP fibers and PP fibers which are threaded manually from PP waste.

Replacing a certain portion of natural aggregate with recycled aggregates can not only reduce CDW generation but also conserve the extraction of natural resources. It was concluded that partial replacement (0-50%) of natural aggregate by recycled aggregate results in an optimum strength value that can be adopted without much variation of its strength, particularly compressive strength [10]. The increasing cost of landfill coupled with the increase in aggregate production requirement for construction has made the use of recycled aggregate to partially replace natural aggregate more economical and environmentally advantageous [11].

Concrete is a brittle, composite material that is strong in compression and weak in tension. The tensile strength of plain concrete is about 10% of its compressive strength and cracking occurs when the concrete tensile stress is produced from the externally applied loads [12]. It was found that the use of short uniform fibers in concrete is one approach to mitigate the cracking and increase the tensile straining capacity. The introduction of polypropylene fibers in concrete affects its properties both in the fresh and hardened state. In a fresh state, it may reduce workability, slow down the rate of bleeding, and increase the set times for the concrete. However, in the hardened state, polypropylene fibers act as crack arrestors [13]. Many researchers have found that the addition of fiber results in an increase in its strength up to a certain percentage and then a decrease [14]. This is due to a decrease in workability with an increase in the percentage of fiber with respect to the weight of cement.

Life cycle cost (LCC) analysis is an important methodology when assessing the sustainability of a process or product [15]. It is used for highlighting the part of a product or process's life cycle that can contribute to the most economic load. For successful completion of the life cycle cost analysis, the initial investment cost, operations cost, maintenance, and repair cost, and replacement and salvage cost of all the alternatives involved in the project must be compared [16].

Therefore, due to the problem associated with the generation of construction and demolition waste and the filling of a landfill, this paper aims to determine the mechanical properties of NAC and RAC reinforced with PP fibers to check the reusability of recycled concrete as an aggregate.

2. METHODOLOGY

The project's aims and objectives were pursued through the implementation of the sequence of methods shown in Fig. 1.

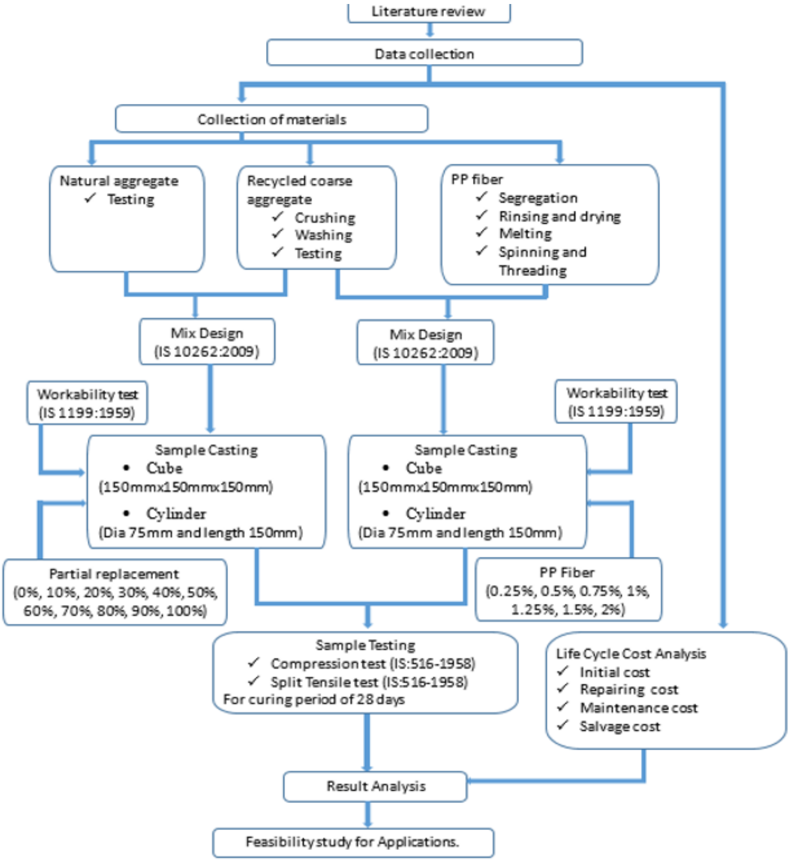

Fig. 1. Methodology chart

2.1. Material Used

Pozzolana Portland Cement (PPC) of grade 33 conforming to IS: 8112-1989 with the specific gravity of 3 was used. The fine Aggregate used was the natural sand locally extracted from river bed and was graded under zone III conforming to IS: 383-1970. It's determined specific gravity was 2.59% while water absorption measured 2.23%.

The locally available beams of the old concrete structure were utilized to extract recycled coarse aggregate. To conform to the required 20 mm sizes, the recycled concrete aggregate underwent mechanical breaking by hammer, in accordance with IS: 383-1970. The properties of natural and recycled coarse aggregate are given in Table 1.

TABLE 1. Physical properties of the aggregate

Property	Natural Aggregate	Recycled Aggregate
Specific Gravity	2.63	2.37
Water Absorption (%)	0.93	5.6
Fineness Modulus	7.3	7.28
Abrasion Value (%)	26.11	32.225
Impact Value (%)	12.56	18.07
Crushing Value (%)	19.56	25.89

Polypropylene wastes were gathered and processed to obtain recycled PP fibers, while newly manufactured polypropylene fibers from the factory were used. The properties of both types of fibers are given in Table 2. The recycled and new PP fiber are shown in Fig. 2 and Fig. 3 respectively.

TABLE 2. Properties of the fibres

Properties	New PP fibers	Recycled PP fibers
Length	20mm	About 20mm
Thickness	60 microns	169-630.4 microns

Fig. 2. Recycled PP fibers

Fig. 3. New PP fibers

2.2. Mix Proportion

The reference concrete mix for M25 in the study was established using natural aggregates. Prior to determining the mix proportion, a trial mix was conducted. For the natural aggregate, the mix proportion selected was 1: 1.36: 2.57 (Cement: Fine Aggregate: Coarse Aggregate), while for the recycled concrete aggregate, the mix proportion chosen was 1: 1.36: 2.31(Cement: Fine Aggregate: Coarse Aggregate). These proportion were derived by considering the properties of the materials to be used, adhering to the guidelines specified in IS 10262:2009 and IS 456-2000. The same water-cement ratio was maintained for whole samples.

2.3. Preparation of Specimen

The study includes the casting at two stages. Firstly, the casting of natural aggregate concrete samples and casting of concrete samples with partial replacement of natural coarse aggregate by recycled coarse aggregates of varying percentages with intervals of 10% from 0% up to complete replacement as shown in Fig. 4. Before the casting, the recycled coarse aggregates were soaked for 24 hours to lower the excessive water absorption during the mixing [17]. Secondly, the casting of samples of recycled aggregate concrete with the addition of polypropylene fiber of varying percentages with intervals of 0.25% from 0% to 2% replacement as shown in Fig. 5. The slump test for each set of casting was done to check the workability conforming to IS 1199:1959. The specimens were cured for 28 days, to determine their strength.

Fig. 4. NAC sample preparation

Fig. 5. RAC with PP fibres sample preparation

2.4. Testing of the Specimen

In accordance to IS 516:1958, concrete cubes with dimension of 150mmX150mmX150mm and cylinders with a diameter of 100mm and a height of 200mm were casted as shown in Fig. 6 and Fig. 7 respectively. For this study, a total of 162 samples were casted. This included sixty-six samples consisting of three each for concrete cube and cylinder with eleven varying percentages of replacement for natural coarse aggregate by recycled coarse aggregate. Once the optimal replacement was determined, additional samples were casted by adding new PP fiber at varying intervals of 0.25% by weight of cement added. This resulted in forty-eight samples comprising three each for cube and cylinder with eight varying percentages. Similarly, for another set of forty-eight samples, recycled PP fiber was used instead of new PP fiber. The cubes and cylinders sample were casted for comparative analysis of compressive strength and split tensile respectively for both NAC and RAC. The compaction of the samples was achieved using the mechanical vibrator.

After 24 hours from its casting, the samples were removed from the molds. The samples were kept in the water tank for 28 days of curing. After the required period, the samples were taken out and allowed to dry for 30 minutes, then, the specimens are allowed for testing.

Fig. 6. Concrete cubes casting for compression test

Fig. 7. concrete cylinder casting for tensile test

3. RESULT AND DISCUSSION

3.1. Partial replacement of Natural Aggregate (NA) by Recycled Concrete Aggregate (RCA)

From the obtained values of compressive strength, no significant variation is observed during the partial replacement of NA by RCA. With an increase in replacement, the compressive strength decreases gradually. Up to 40% replacement with RA, a linear decrease in strength is observed and then a sudden decrease in strength continues. Fig. 8 and Fig. 9 show the cube compressive test and cylinders split tensile test results respectively for partial replacement of NA by RCA in concrete production from 0% to 100% with 10% variations. Up to 40% replacement, the compressive strength was found to be higher than that of overall average strength as shown in Table 3. Therefore, 40% replacement was taken as the optimum percentage of replacement that can be done without compromising its strength significantly.

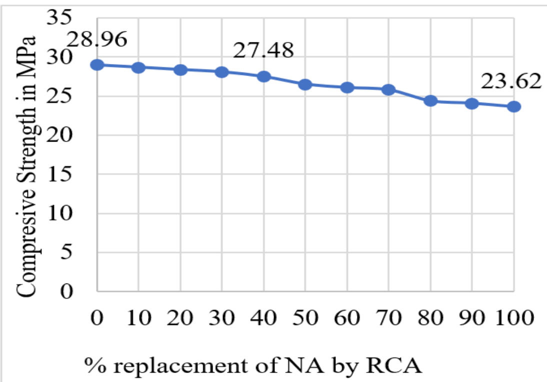

Fig. 8. Compressive strength test result for partial replacement of NA by RCA

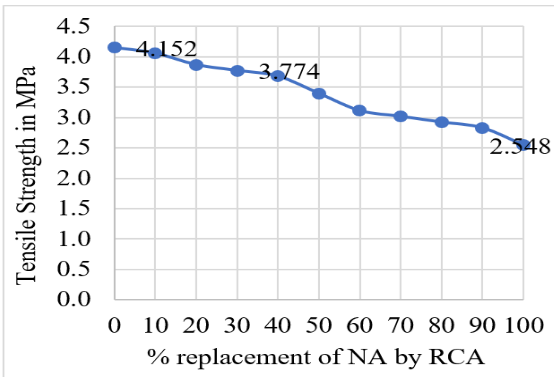

Fig. 9. Split test result for partial replacement of NA by RCA

TABLE 3. Partial replacement compression test

Replacement of NA by RA (%)	0(Ref. Mix)	10	20	30	40	50	60	70	80	90	100
Compressive Strength (MPa)	**28.96**	**28.67**	**28.37**	**28.08**	**27.48**	26.51	26.08	25.78	24.07	23.62	26.54
Average strength: **26.54**											

Although, concrete is meant for bearing the compressive load due to its brittle nature, the split tensile test is conducted since the tensile strength of concrete is one of the fundamental properties which influence the amount and size of cracking in structures. Concrete develops cracks when tensile forces exceed its tensile strength. The split tensile test also shows the same trend as of compressive test in reducing the strength with an increase in the replacement of NA by RCA.

3.2. Addition of Polypropylene (PP) fibers to RCA

The addition of PP fiber in recycled aggregate concrete (RAC) doesn't show much variation in compressive strength compared to NAC.

There is a gradual increase in compressive strength until it reaches the highest value of 28.37 MPa at 1.5% addition of new PP fibers by weight of cement and then it begins to decrease as shown in Fig. 10. Similarly, in the same figure, the highest strength of 27.56 MPa is achieved at 1.25% addition of recycled PP fibres to RAC by weight of cement. Fig. 11 shows the result of the split tensile test for two types of fibers reinforced concrete. The maximum tensile strength of 3.87 MPa and 3.49 MPa was obtained when there is the addition of 1.5% new and 1.25% recycled PP fibers were added respectively.

Both the compressive and tensile strength test data clearly show the addition of new PP fiber gives better strength compared to recycled PP fiber. However, there is no significant variation between them. Moreover, there was not much of a compressive strength variation between NAC (28.96 MPa) and 40% replacement of natural aggregate by RCA reinforced with 1.5% new (28.37 MPa) PP fibers in it.

3.3. Strength variation for difference types of concrete

The Fig. 12 and Fig. 13 shows the strength variation for different types of concrete. There was not much of strength variation among NAC, 40% replacement of NA by RCA, and 1.5% new and 1.25% recycled PP fibers reinforced concrete in terms of both compressive and tensile strength.

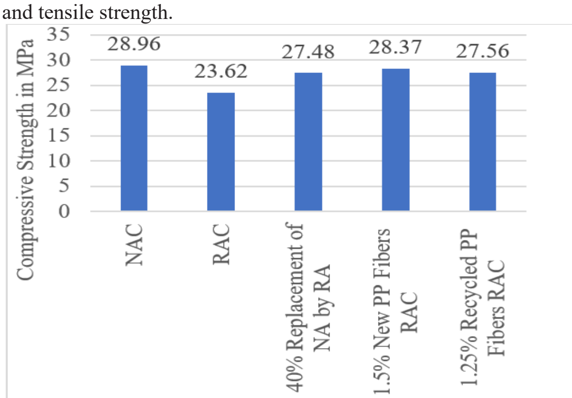

Fig. 12. Compressive strength for different types of concrete

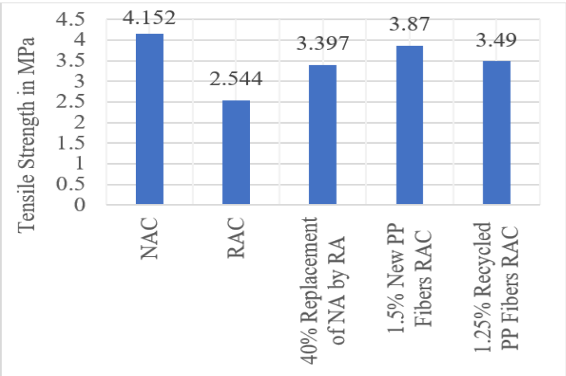

Fig. 13. Tensile strength for different types of concrete

3.4. Life Cycled Costing Analysis (LCCA)

IS 13174 (Part 2) recommend to work on life cycle cost (LCC) analysis of various alternatives of individual elements rather than working for whole building because it helps in selecting different combination alternatives from various elements. After having the LCC of different alternatives of all the elements, a combination consisting of one alternative from each element may be selected to give the minimum LCC for complete building. Therefore, throughout analysis, only the cost of coarse aggregates was considered, keeping the cost of water, cement, and sand remains the same for all the alternatives from the design mix. Considering a residential building that requires 100 m3 of concrete for all alternatives, three alternatives were considered:

Alternative 1: Natural Coarse Aggregate Concrete.

Alternative 2: Recycled Coarse Aggregate Concrete.

Alternative 3: Hybrid scenario (optimum) with recycled aggregates 40 percent and remaining natural aggregates.

The general LCC consists of initial cost, operation and maintenance cost, and salvage values. For the production of 100 m^3 of concrete, it required 52.1 m^3 of natural aggregates (Alternative 1). As per BSR-2021, the rate of crushed stone of 20 mm size is Nu. 967.20 Per m3 for Phuentsholing and it makes an initial cost of Nu.50,391.12. Similarly, the recycled aggregates (alternative 2) requirement for 100 m^3 of concrete production is 49.48 m^3. Since there is no rate for recycled aggregates in Bhutan it interpolates from the cost of natural and recycled aggregates in India considering cost variations between the two is the same. After interpolating, the rate for 1 m3 of recycled aggregates in Phuentsholing (Bhutan) comes around Nu.800.95 and the initial cost of recycled coarse aggregate required for 100 m^3 is Nu.39,631.1. For the hybrid scenario (optimum) with recycled aggregates at 40 percent and remaining natural aggregates, the initial cost comes to around Nu.46,087.11 taking the initial cost of the first and second alternatives in percentages. The operation and maintenance cost are the same for all the alternatives [15]. Residual value is calculated by using

$$s=p(1-i)^r$$

where, s=salvage value
p=initial cost/original price
i=nominal depreciation rates
r=age in years

The salvage value was calculated considering 3.5 percent nominal depreciation rates for permanent building as per Property Management Manual of Bhutan (2016) and the age of the building after 20 years is shown in Table 4.

Most commonly used conceptual method for life cycle cost analysis is given by **Present worth methods/present value methods**. All future costs are recalculated to present values by adjusting discount rates for inflation and interest.

$$present\ worth\ factor\ (pwf)=1/(1+i)^t$$

Where *i*= discount rate, *t*=numbers of years or study period, The discount rate can be calculated using following equations:

$$i=(1+interest\ rates)\times(1+inflation\ rates)-1$$

The average inflation rate of Bhutan for the past decade was recorded at 5.99 percent at the end of the year 2020 as per the World Bank report and an interest rate of 6.86 percent at end of June 2021. Substituting the inflation and interest rate in the discount rate equation, we get a discount rate of 0.1326. From the present worth factor equation, we get pwf 0.083 upon substituting the discount rate and study period of 20 years.

From the above analysis, the Life cycle cost for alternative 2 i.e. using recycled aggregates as concrete ingredients was found to be the minimum compared to other alternatives by both methods. Therefore, using recycled aggregates in concrete production reduces the life cycle cost compared to natural aggregates.

TABLE 4. Life cycle cost analysis by Present worth method

Items	Alternative 1		Alternative 2		Alternative 3	
	Estimated Cost (Nu)	Present Worth (Nu)	Estimated Cost (Nu)	Present Worth (Nu)	Estimated Cost (Nu)	Present Worth (Nu)
Total initial Cost	50,391.12	50,391.12	39,631.10	39,631.10	46,087.11	46,087.11
Repairing &Maintenance Cost	same for all alternatives	same for alternatives	same for all alternatives	same for all alternatives	same for all alternatives	same for all alternatives
Salvage Value Cost	24,711.57	2,051.06	19,434.90	1,613.10	22,600.90	1,875.87
Life Cycle Cost		48,340.06		38018.00		44,211.24

Notes:

1. Present worth for the initial cost is kept the same as the estimated cost because the initial cost is usually incurred within a time span of a few months or years.
2. Estimated Salvage value cost should be multiplied pwf to convert the salvage value at end of 20 years to present worth.
3. Present-worth Life cycle cost is obtained by taking the difference between the present-worth initial and salvage cost.

CONCLUSION

Based on the results, observations, and discussion, the following conclusions were drawn:

- Natural aggregate can be replaced by RCA in concrete production by up to about 40% without significantly compromising its strength with variations of 5.11% and 11.37% for compressive and tensile strength respectively w.r.t 0% replacement.
- Maximum compressive strength (28.37 MPa) and tensile strength (3.87 MPa) for new PP fibers reinforced concrete was obtained when 1.5% of PP fibers were added by the weight of cement.
- Similarly, Maximum compressive strength (28.56 MPa) and tensile strength (3.49 MPa) for recycled PP fibers reinforced concrete was obtained when 1.25% of PP fibers were added by the weight of cement.
- There was no significant variation of strength between NAC, 40% replacement NAC, 1.5% new PP fibers reinforced RAC, and 1.25% recycled PP fibers reinforced RAC.
- The LCC of concrete produced using recycled aggregate as concrete ingredients were found to be the minimum.

Additional research is necessary to investigate the physical properties of concrete when NA is replaced with RCA and the inclusion of PP fibers. This study should focus on examining parameters such as shrinkage deformations, change in surface adhesion, porosity, water permeability, and other relevant factors.

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