Comparison of the energy consumption in the production of natural and recycled concrete aggregate: A case study in Kerala, India

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Abstract. The growth of construction sector in India is gaining pace to cater to the overwhelming demands of the rising urban population and this has in turn resulted in overexploitation of natural resources for production of natural aggregates (NA). The prospects of recycling demolition debris to produce recycled concrete aggregate (RCA) is little explored, due to the underestimation of actual data on the construction and demolition (C&D) waste generated in India. The different stages involved in the production of NA and RCA were investigated by field study in an aggregate quarry and a demolition site in Kerala, India. The energy consumption involved in the recycling of the demolition debris from a reinforced concrete (RC) structure and the production of NA was determined. The energy consumed to produce 1 tonne of NA and RCA was determined as 21112 KJ/tonne and 16178 KJ/tonne respectively. The production of RCA showed a 30.5% savings in the energy consumption compared to that of NA. A specific sensitivity analysis suggested that the energy consumed to produce RCA was less than that to produce NA for a maximum distance of 13.5 km. As the energy consumption was evaluated based on the diesel consumption of the machinery involved, the reduced diesel consumption and its subsequent cost savings could also add to the prospects of using RCA. Although the results are site specific, such local case studies could contribute to the development of C&D waste recycling infrastructure in the country.

1. Introduction
The rising population and rapid urbanisation has significantly contributed to the growth of construction market in India. The urban population in India as per the Census 2011 is estimated to be 31.16% [1] and is likely to become 50% of the total population by 2050 [2]. In order to accommodate the increasing urban population, government initiatives such as Pradhan Mantri Awas Yojana (Urban) have been introduced to ensure housing for everyone by 2022. However, 7.07 million houses are yet to be constructed under this project [3]. Thus, India is set to become one among the flag-bearers of the global growth of construction market by 2030, thereby meeting the demands of its overwhelming urban population [4].

The expansion of construction sector has been witnessed by huge increase in the number of reinforced concrete (RC) structures and a steep increase in the demolition of existing buildings to pave way for newer construction. This had further strained the natural resources for the extraction of raw materials such as aggregates, as well as, stressed the importance of construction and demolition (C&D) waste management. The coarse and fine aggregates are indispensable in the construction of RC
structures as it accounts for 60-75% of the total volume of concrete. The present annual consumption of sand and crushed stone in India is estimated to be about 1.4 billion tonnes and 2 billion tonnes respectively [5]. Also, river sand is now being replaced by manufactured sand (M sand), further aggravating the pressure on quarries. The indiscriminate mining to meet the overwhelming demands has led to exhaustion of natural aggregates and stress the need for secondary materials to replace it. Demolition of buildings holds the major contribution in the generation of C&D waste. As per the government figures, the annual C&D waste generation in India is about 12-15 million tonnes [6]. However, many researchers have reported that there is gross underestimation of the actual C&D waste generated in India. Ram and Kalidindi [7] estimated that the C&D waste generated was about 36% of the municipal solid waste in the Chennai city for the year 2013 and found that it was comparable to the C&D waste generation in other developed countries/regions. Jain et al. [8] estimated that the C&D waste generation in India was between 112 and 431 million tonnes for the year 2016. Figure 1 shows the composition of C&D waste in India, reported in different studies [6] [9] [10]. Ram et al. [10] reported the composition of C&D debris that gets dumped in two landfills in Chennai where materials such as metal and wood are excluded due to their recyclability. It can be observed that the concrete and masonry waste constitute 53% to 60% of the total C&D waste composition in India and are often directly landfilled. Thus, there exists a huge potential in the recycling of C&D waste in India, which is little explored. Recycling of C&D waste by introducing them in new concrete as recycled aggregates has become an effective solution to compensate for the depletion and exploitation of natural resources, as well as efficient waste management system for C&D waste. Provisions are introduced in IS 383: 2016 for the replacement of 20% natural coarse and fine aggregates with recycled concrete aggregates (RCA) in the reinforced concrete [11]. Thus, the introduction of RCA into the supply system can result in a sustainable construction practice.

![Figure 1. Composition of C&D waste.](image)

However, the prospects of C&D waste recycling need to be assessed and quantified. Several studies have reported the environmental benefits of recycling C&D waste in comparison to landfilling by carrying out Life Cycle Assessment (LCA) [12] [13]. Blengini [14] reported that the recycling of steel could significantly contribute to the environmental benefits obtained in recycling demolition waste. In most of the studies, the environmental benefits obtained were mainly dominated by the recycling of materials such as steel and wood. Hence the environmental benefits of C&D debris alone, which forms the quantum of C&D waste in India, needs to be evaluated. Ram et al. [10] reported that recycling of C&D debris showed environmental benefits in all 15 impact categories compared to landfilling. Comparative LCA studies on the production of recycled aggregates (RA) and natural aggregates (NA) have also been carried out by the authors. Estanqueiro et al. [15] performed a comparative LCA of NA and coarse recycled aggregate (RA) used in concrete production either using a fixed or mobile plant. The environmental benefits of coarse RA when compared to NA were observed only in the land use and respiratory inorganics impact categories and it was suggested that
the benefits can be improved by using fine RA also in the concrete production, instead of landfilng. Rosado et al. [16] performed a life cycle assessment of NA and mixed RA production in Brazil. The mixed recycled aggregate was a better option for all the environmental impact categories if the transportation distance of RA was 20 km longer than that of NA. Significant number of LCA studies on C&D waste, were from European countries whereas LCA studies based on Indian scenario is very limited. A cost reduction of 19-22% was estimated for the paving blocks made with C&D waste from Ahmedabad and Bangalore, than NA [17]. Thus, the environmental and economic aspects involved in the production of both natural and recycled concrete aggregate needs to be quantified and compared with the primary material savings and C&D waste management.

2. Research significance
Kerala is one of the densely populated states in India with a population density of 859 per sq. km [18]. Ernakulam district has the highest urban population in the state [19]. It has been reported that Ernakulam has the highest number of dwelling houses constructed in the urban sector of the state, for the year 2016-17 [20]. Ernakulam also top in the number of active quarries in the state [21]. This gives a clear evidence on the dependence of the increasing construction activities on the natural aggregate quarries, to cater to the demands of the urban population. Ernakulam has witnessed the demolition of the 4 multistoried framed RC structures in the Maradu municipality in January,2020. The RC structures were demolished before the end of their service life, under the court order for violation of Coastal Regulation Zone. The debris generated from the demolition was to be recycled and reused, emphasizing the importance of C&D waste management. The Ministry of Urban Development had instructed all states to set up environment friendly C&D waste recycling facilities in all cities/towns with population of over 1 million. But, India with a population over a billion has only 5-6 operational recycling plants. Although, the Construction and Demolition Waste Management Rules was introduced in 2016 to address the roles and responsibilities of waste generators and various stakeholders in C&D waste management, its implementation remains in infancy [22]. Thus, local case studies on the strategy adopted in recycling of demolition debris could further accelerate the development of C&D waste recycling infrastructure in India. Thus, a study on the production of RCA is carried out with respect to the recycling strategy adopted on the demolition waste generated in Maradu. The present case study investigates the various stages and compares the energy consumption involved in the production of 1 tonne natural and recycled concrete aggregates.

3. Methodology
The nearest aggregate quarries to the Maradu demolition site were identified and were approached to conduct a field study. However, only one active aggregate quarry, located in the Mazhuvannur village, had granted permission to carry out the field study. The quarry engaged in the production of aggregates by extraction and crushing of granite rocks was visited. Among the 4 multistoried structures (Alfa Serene (A), Holy Faith H2O (H), Jain Coral Cove (J) and Golden Kayaloram (G)) demolished in Maradu municipality, the demolition sites of (A) and (H) were visited. Upon visual inspection, it was observed the debris in (A) was mostly of concrete chunks and bricks, whereas the debris in (H) was mostly of concrete chunks and solid blocks.

Discussions were carried out with the officials of the contracting firm which had been awarded the tender for the removal of debris and was informed that the interior walls of (A) and (G) were built using bricks, which makes segregation and downsizing of the mixed brick and concrete debris difficult. Whereas, the interior walls of (H) and (J) were built using solid blocks, which makes the debris more of concrete waste. Thus, the segregation of steel and concrete debris and subsequent downsizing becomes easy. Hence, the recycling of debris from demolition site of (H) was considered for the study. Figure 2 shows the location and photograph of the NA quarry and demolition site (H).
3.1. Natural aggregate production

The quarry has its own crushing facility within its area. The average production of NA from the quarry is estimated to be 1500 tonnes per day. Figure 3 shows the process flow in the production of NA.

The overburden on the top of the quarry was stripped to expose the underlying ore body. Drilling involves the creation of holes in the ore body by using jack hammers, with the help of a compressor connected to the tractor providing sufficient pressure for its operation. Figure 4 shows the drilling process carried out using jack hammer. Drilling is done prior to blasting for the placement of the explosives. Figure 5 shows the various blasting equipment used. As per the drilling-blasting design adopted, gelatine sticks (see figure 5 (a)) were placed in each hole and were connected to a non electric detonator (see figure 5(c)). The holes were then filled with rock powder for one- third of its depth, known as stemming. The non electric detonators from each hole were connected in series and then connected to an electric detonator (see figure 5(b)). The electric detonator was connected to the initiation system (see figure 5 (d)) which initiates the blast. Breaking involves the size reduction of the rock boulders produced from blasting by using hydraulic breakers. Also, rock surface after blasting, was again fragmented using a hydraulic breaker so as to remove remaining loose rocks and create a hard surface for next drilling and blasting to be carried out. This process involves additional production of rock fragments. The fragmented rock was loaded into the trucks by an excavator. The truck carries the fragmented rock from the extraction site to the crusher unit located within the quarry. Figure 6 shows the process of breaking, loading, haulage and unloading at the crusher unit respectively. The size of the rocks obtained from the quarry may vary from 350 mm boulders to fine...
particles. Once the rocks are brought to the crusher unit, they are fed into the dump hopper. Aggregates of the required sizes of 40 mm, 20 mm, 12 mm, 6 mm, 4.75 mm and less than 3 mm are obtained using vibrator screens of required size. Fine particles of both 4.75 mm and less than 3 mm are subsequently carried by the belt conveyors for washing and classifying. Fine aggregates of 4.75 mm are used as M sand and those less than 4.75 mm are used as P sand.

3.2. Recycled concrete aggregate production
The demolition waste from the site (H) includes large sized concrete chunks, solid block and steel. Figure 7 shows the process flow in the production of RCA. The separation of the steel and concrete from the structural elements of the demolished RC building (H) was done using hydraulic breakers. It was used to break the concrete adhering to the steel reinforcements into smaller fractions, thereby separating out the steel. Thus, on site segregation was carried out. Oxy-fuel cutting process was used then to cut the steel, thereby removing the smaller concrete blocks adhering to the steel surface. Depending on the diameter of the steel obtained, it is separated out for further processing, either rolling or melting, which is beyond the scope of study. Figure 8 shows the segregation process carried out by (a) hydraulic breaker and (b) oxy-fuel cutting. The segregation process was carried out for 51 days. The segregated concrete debris was then loaded into trucks using excavator. The loaded trucks were then transported to crusher unit. Figure 9 shows the recycled concrete aggregate produced after crushing. The concrete debris was also transported to various godowns and industrial sites for road formation and basement filling activities. The consolidated data on the weekly transport of concrete debris was obtained from the contracting firm involved in the debris removal. The actual tonnage of debris removed from the demolition site (H) was approximately 20450 tonnes. The properties of the recycled concrete debris also need to be studied. The contracting firm had manufactured concrete blocks using the recycled fine and concrete aggregate after crushing.

![Figure 4. Drilling.](image1)

![Figure 5. Blasting equipment.](image2)

![Figure 6. (a) Breaking (b) Loading (c) Hauling and unloading.](image3)

![Figure 7. Process flow of recycled concrete aggregate production.](image4)

![Figure 8. Segregation process carried out by (a) hydraulic breaker and (b) oxy-fuel cutting.](image5)
3.3. Computation of energy consumption

The process involved in the production of NA was thoroughly studied. The machinery involved in the different stages of production were identified and its average diesel consumption was obtained by verifying the diesel statement from the store. As the crusher unit was within the quarry, the transportation distance between the extraction site to crusher unit was assumed to be 1 km. Thus, the energy consumption involved in the different stages of production of 1 tonne of NA was formulated based on the diesel consumption of machinery. A questionnaire was formulated to obtain similar data on aggregate production from different quarries so as to compare and check for variability, if any, in the production process. Similarly, the different stages of production and the machinery involved in the production of RCA was studied with respect to the recycling strategy adopted on the demolition debris from (H). The diesel consumption of the machinery was collected from field. The total quantity of concrete debris generated from the site (H) was assumed to be converted to RCA in the crusher unit. The nearest crusher unit to the demolition site (H) was identified from KOMPAS [21] and the distance was measured to be approximately 7km. Hence, the transportation distance from the demolition site to crusher was assumed to be 7km. The energy consumption involved in the different stages of production of 1 tonne of RCA was formulated based on the diesel consumption of machinery. Since the crushing process was common to both the production, the energy consumption involved was assumed to be same and hence neglected in the calculation. The comparison between the energy consumption involved in the production of 1 tonne of NA and RCA was carried out based on the assumption that 1 tonne of RCA could significantly replace 1 tonne of NA in its usage.

4. Results and discussion

The energy consumption involved in the different stages of production of 1 tonne of NA and RCA were calculated and are summarized in Table 1. The energy consumed to produce 1 tonne of NA and RCA was determined as 21112 KJ/tonne and 16178 KJ/tonne respectively. It was found that there would be 30.5% savings in the energy consumption, if the production of RCA could replace that of the NA in the current scenario.

| Stages of production | NA | Total energy consumption (KJ/tonne) | Stages of production | RCA | Total energy consumption (KJ/tonne) |
|----------------------|----|-----------------------------------|----------------------|-----|-----------------------------------|
| Drilling             | 3397 | 21112                             | Segregation          | 8715 | 16178                             |
| Breaking             | 8251 |                                    | Loading              | 2367 |                                    |
| Loading              | 8736 |                                    | Transport            | 5096 |                                    |
| Transport            | 728  |                                    |                      |      |                                    |
Figure 10 compares the energy consumption involved in the different stages of production of 1 tonne of NA and RCA. The energy consumption of the hydraulic breaker employed in breaking the rocks into fragments and segregating the concrete debris from steel was found comparable. The variation in the loading stage of both rock fragments and concrete debris may be due to the difference in the specifications of excavator employed in both job conditions. The excavator used in the quarry was of larger bucket capacity and power, to load the heavy boulders of rock, which involves higher fuel consumption and hence increasing the energy consumption. When comparing the effect of transportation in the savings for energy consumption, based on the assumptions it is found that the energy consumption was highly sensitive to the distance between the quarry/ demolition site and the crusher unit. In order to find the distance to which the energy consumption involved in the production of RCA is favourable than the production of NA, a sensitivity analysis is performed. The analysis has been performed by keeping the distance from the quarry to the crusher unit constant at 1 km, i.e., the crusher unit is within the quarry area. The distance from the demolition site to the crusher unit was gradually increased in steps of 1 km. Figure 11 shows the sensitivity analysis for the energy consumption, affected by the transportation distance. It was observed that the energy consumed to produce RCA was less than that to produce NA for a maximum distance of 13.5 km.

Figure 10. Energy consumption involved in the different stages of production of 1 tonne of natural and recycled concrete aggregate.

Figure 11. Sensitivity analysis on the energy consumption and transport distance of natural and recycled concrete aggregate.
The top five regions where maximum number of construction activities occurred in the district of Ernakulam were identified from the Building Statistics 2016-2017 conducted by the Government of Kerala [20]. The top five regions in the urban sector and the number of buildings constructed in the year 2016-2017 are as follows: Cochin corporation (7104), municipalities such as Kalamassey (2241), Thrikkakkara (1942), Trippunithura (1788) and Maradu (928).

Figure 12 shows the location of top five regions where the highest number of construction activities were reported in the district for the year 2016-2017. Based on the sensitivity analysis for the energy consumption, it was known that the RCA production was favourable than NA only up to a distance of 13.5 km. Keeping the demolition site as the centre, a red coloured circle has been drawn with a radius of 13.5 km which indicates the regions where RCA production can be favourable than the NA production. From the figure it can be observed that the top five regions with the highest number of construction activities were much closer to the demolition site and falls within the red circle. Thus, recycling of the concrete debris from the demolition site to produce RCA could cater the demands of the construction activities in the district, as a replacement to NA with the prospects of reduced energy consumption. As the energy consumption was evaluated based on the diesel consumption of the machinery involved, the reduced diesel consumption and its subsequent cost savings could also add to the prospects of using RCA.

Figure 13 shows the location and number of active quarries in the district engaged in the mining of granite and production of building stone as per the KOMPAS [21]. It can be observed that the quarries are in the eastern side of the district, whereas, majority of the construction activities are happening in the western side of the district. Hence the aggregates need to be transported to longer distances from the quarries located far away from the construction sites, which involves higher transportation cost. This gives an advantage to recycled aggregates in terms of lower transport distances and points to the prospects of setting up recycling units. However proper supply, quantity and quality of recycling C&D waste into RCA needs to be ensured. Experts state that the indiscriminate and rampant quarrying has significantly contributed to the heavy landslips in the northern districts of Kerala during the floods in 2019. Considering the number of active quarries in the central part of the state, which includes Ernakulam, there exists a possible risk of danger. Also, the illegal disposal of C&D debris was found to be a major reason for choking the sewers further leading to the floods in Chennai in 2015. Thus, proper C&D waste management with production of recycled
aggregates can be the best solution to the environmental implications stated above. The study can be further extended to address the environmental benefits/impacts of recycling by carrying out LCA.

![Figure 13. Location of active quarries in Ernakulam.](image)

5. Conclusion
The actual potential of C&D waste recycling in India is least explored. The perception of takers for RCA in congruence with the NA can be ensured only if the quality and benefits of recycling can be quantified. Local case studies on recycling demolition waste can be used to quantify the impacts and further facilitate to the development of C&D waste recycling infrastructure. The study investigated the different stages of production of RCA and NA with respect to the recycling strategy adopted for the demolition debris generated from RC structure in Ernakulam, Kerala. About 30.5% savings was observed in the energy consumption to produce 1 tonne of RCA over NA. The sensitivity analysis on the energy consumption indicated the production of RCA was favourable compared to that of NA for a maximum distance of 13.5 km. It was observed that majority of the construction activities in the urban sector of the district was within the 13.5 km. Hence the recycled concrete debris from the demolition site could cater the requirements of NA with reduced energy consumption. The energy consumption was calculated based on the diesel consumption of the machinery involved. Thus, the reduction in energy consumption could attribute to savings in diesel consumption. The study could be further extended to compare the environmental impacts of the production of NA and RCA and also compare the environmental prospects of recycling over landfilling, by performing LCA.

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