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ORIGINAL ARTICLE

Life cycle assessment and mechanical strength of cement composites with conventional, and recycled fine aggregate

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Abstract: Generally, sand as a filler material in the concrete composite is mined from the riverbed, which is the primary source of the entailed fine aggregate to keep pace with the emergent demand for concrete production. Unbridled sand extraction from the riverbed and the river bank has detrimental impacts on the environment and river geomorphology. On the other hand, construction and demolition sites generate a significant amount of solid waste, which contains fine aggregate. This study aims to explore the applicability of recycled fine aggregate (RFA) in comparison to coarse sand and fine sand in cement composites, considering their compressive strength, financial aspect, and environmental sustainability by means of Life Cycle Assessment (LCA). Hence, 12 (twelve) different combinations of the aforementioned fine aggregates were taken into consideration to determine the extent of using RFA as a replacement for conventional fine aggregates, signifying the motivation of the study. In this study, the crushing strength of cement mortars at different curing ages was compared. At 28 days, mortar with 100% coarse sand showed 25% higher, and mortar with 100% fine sand showed 67% lower compressive strength than the mortar with 100% RFA. The mix combination of 25% RFA and 75% coarse sand produced the cement mortar with a maximum compressive strength of 48.25 MPa. From LCA, subsuming the waste product (RFA) into cement composite exhibited the lowest environmental impact, in contrast to those made with natural sand. Considering the physical properties of fine aggregates, and the crushing strength of mortar along with environmental and economic aspects, cement mortar with RFA can be an environmentally sustainable option and an approach to reduce construction waste and expenses.

Keywords: Recycled fine aggregate; sustainability; construction and demolition waste; cement composite; life Cycle Assessment; compressive strength; scanning Electron Microscope (SEM)

1 Introduction

Urbanization is responsible for the increased global demand for concrete which is a widely used construction material with a yearly worldwide consumption rate of about 25 gigatons [1]. The demand associated with concrete production brings about a high consumption of aggregates. In 2015 construction-related aggregate consumption was approximately 48.3 billion tons worldwide, and the estimated amount of consumption of fine aggregate was roughly 10 billion tons [2,3]. Being widely available fine aggregate, sand has become one of the crucial constituents of mortar and concrete [4].

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Hence, global extraction of sand and gravel was estimated to be between 32 and 50 billion tons resulting in potential threats to river morphology and interdependent riparian zones [5–7]. Sand mining can alter physicochemical parameters through erosion and siltation, which impact the active channel flow and floodplain. The progressive increase in salinity and turbidity of downstream water due to sand mining results in detrimental effects on aquatic animals [8–10]. However, the abrupt extraction of natural aggregates, mainly sand from the riverbeds, for the construction industry and consequential environmental impacts aroused interest in alternative aggregates. On the other hand, demolition is required along with the construction process, which generates excessive waste, commonly named construction and demolition waste (CDW) comprising around 36% of the worldwide solid waste [11]. The countries with most of the CDW generation around the world in 2018 are shown in **Fig. 1**. China produced the highest amount of CDW at approximately 2360 million tons, followed by the United States with around 600 million tons, and India with about 530 million tons in 2016. The European Union also generated a substantial amount of CDW, with France and Germany being the leading contributors, producing 240 million tons and 225 million tons, respectively [12].

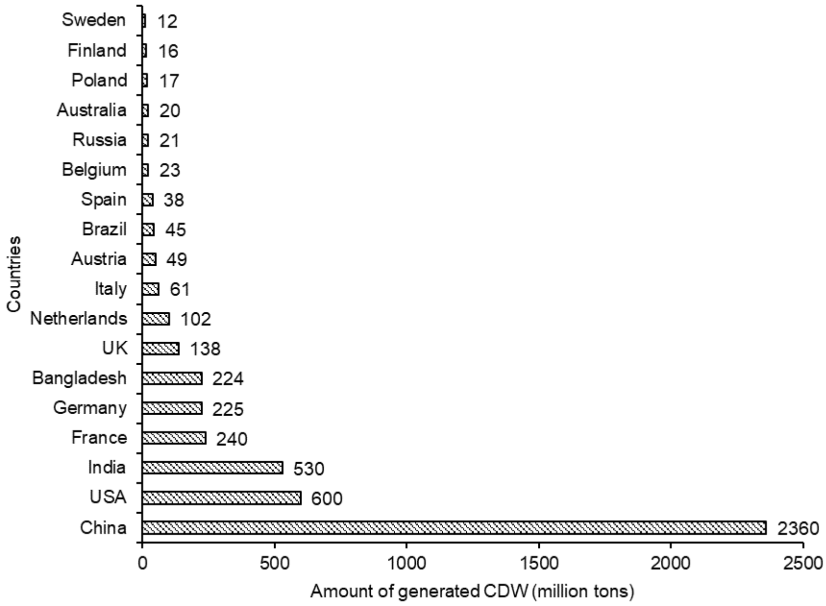


Fig. 1. Amount of CDW generation in different countries [12].

Disposal of CDW requires large areas for landfill amid a scarcity of lands due to rapid urbanization. Around 35% of the global CDW is landfilled [13]. Furthermore, while CDW is typically inert, certain building materials may contain hazardous elements that can lead to soil and water contamination, landscape degradation, and the spread of diseases [11,14]. To achieve sustainable development, it is crucial to prioritize the reuse and recycling of this type of solid waste [15]. Recycled concrete aggregate could be a probable solution to address this issue as sustainability is a burning topic focusing on the preservation of natural resources, declination of carbon emissions, and maintenance of the environmental aspects [16–18]. According to previous studies, 80% of the CDW could be used further due to its significant recycling potential and considerable economic value [14]. Moreover, considering only the fine aggregates, recycling construction waste can be a beneficial choice for the construction industry, especially in European countries where the raw materials are already scarce [11,19,20]. The potential consequences and drawbacks of using coarse recycled aggregates in concrete are widely recognized and documented. Furthermore, researchers have been exploring the possibility of substituting sand in cement mortar to minimize natural aggregates' consumption by replacing them with alternative resources [21–23]. Types of alternative sand and their application in cement composites from previous studies are shown in **Table 1**.

Apart from natural resource conservation, the benefits related to the reduction of the CDW also include cost minimization for construction, dealing with waste disposal, and scaling down health-related problems in communities around construction sites [24]. However, increasing the replacement percentage enhances the porosity and demands more water. Depending on the stone's quality, including porosity, the derived dust as a filler in mortar can be favorable or unfavorable to mortar strength. Compared to natural sand, recycled fine aggregate (RFA) processed from CDW has inferior mechanical properties, primarily because of the residual old cement paste adhering to their surfaces [25]. When it comes to the mechanical properties of mortar and concrete, the substitution of sand with stone dust is permissible up to a limit of 10% [18,26,27].

Table 1. Application of alternative sand in cement composites

Type of recycled fine aggregate	Type of Replaced fine aggregate	Replacement level	Mechanical Properties	Observation	Ref.
Marble powder	Natural sand	0% to 100% with 20% interval	Compressive strength	mortar with 20% substitution of river sand provides optimum results	[28]
Crushed limestone sand	River sand	0% to 100% with 25% interval	Crushing strength	Mortar with limestone crushed sand provides more compressive strength	[29]
Ceramic waste	Sand	20% to 100%	Crushing and flexural strength	70% addition instead of ceramic waste shows better compressive strength, but 100% replacement level performs well in the flexural test.	[30]
Crumb Rubber	Sand	10 and 20% of the sand	Compressive strength	Significantly reduces the mortar strength	[31]
Desert Sand	Sand	25, 50, and 75% of the sand	Compressive strength	Reduces the concrete strength with the increasing replacement of sand	[32]

According to **Fig. 2**, despite being good alternatives, reusing and recycling of aggregates are limited in China and Bangladesh. Due to rapid urbanization, it is required to demolish the old structures to construct multistoried buildings, especially in Dhaka, the capital of Bangladesh. Unfortunately, around 98% of the total CDW is landfilled in Dhaka [11,21].

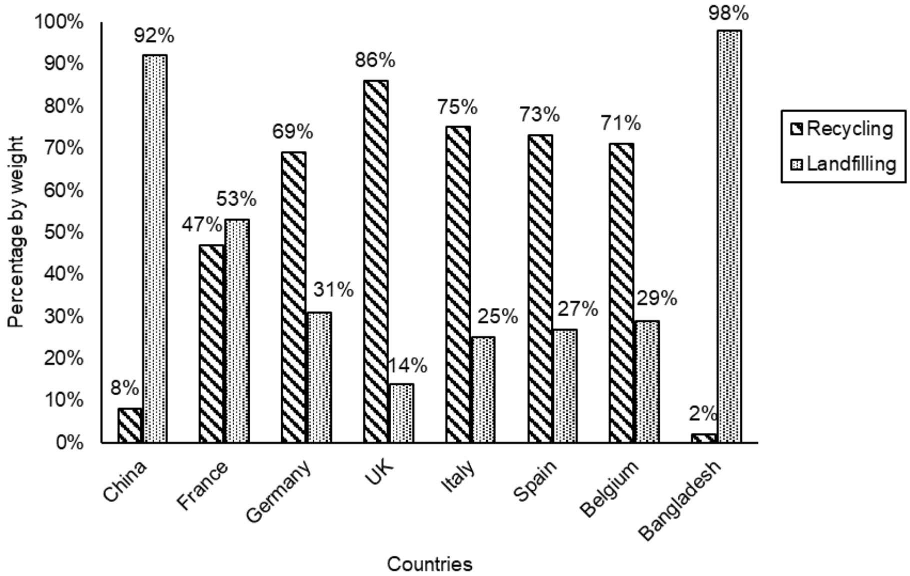


Fig. 2. Landfilling and recycling status of CDW in different countries [21].

Previous research indicates that the challenges stemming from the rising demand for aggregates and unregulated sand mining are driving efforts to recycle substantial quantities of CDW. Mortar occupies a notable sector in concrete technology. Hence, the applicability of recycled fine aggregate is a burning research interest. The expected properties of fine aggregates and crushing strength of mortar are well established. However, recycling is not up to the mark in most of South-Asian countries, and

Bangladesh is one of the leading countries in this trend. Additionally, for a precise comprehension of the environmental advantages of using recycled dust in mortar, specific tools are essential for proper evaluation. Life cycle assessment (LCA), an optimal tool for examining the environmental impact of construction materials, quantifies and contrasts the environmental effects of human activities [33,34]. This comprehensive approach encompasses every stage of a product's life, providing a holistic view of its environmental footprint [35]. LCA is used to evaluate the environmental impacts of construction materials, pipe materials, buildings, and bridges to ensure sustainability and informed decision-making throughout the lifecycle of the projects [36–38]. Multiple research works focused on the LCA of mortars that include recycled aggregates and industrial wastes [35,39–43]. Researchers also utilized LCA to assess the environmental impact of using CDW in the production of RA (Recycled Aggregate) and found that incorporating CDW in RA production could result in a substantial decrease in greenhouse gas emissions, possibly up to seven times more than traditional methods [43]. Employing CDW presents considerable benefits, including reduced greenhouse gas emissions, decreased energy consumption, lesser land use, and diminished water usage [42]. According to Cuenca-Moyano [39], the most significant reduction achieved through CDW was in the Land Use category. This reduction is attributed to avoiding landfill disposal of CDW, which in turn lessens the need for land occupation and transformation for constructing inert landfills, as well as conserving natural resources [39]. Nevertheless, the LCA of mortar using locally available natural sand and recycled fine aggregate has not been extensively explored in South-Asian countries, especially in Bangladesh, where fine sand is widely used for masonry as well as plastering, and coarse sand is used for concrete production.

As most of the developed countries reuse CDW, keeping pace with the demand for aggregates, Bangladesh needs to focus on the recycling of CDW in concrete technology, which requires intensive study on recycled fine aggregate compared with the available aggregates in terms of environmental impacts, financial aspects, and strength criteria. This study explored the effects of different types of fine aggregates in mortar. Application of such type of CDW in cement composites is not a new concept. Hence, in this research, a comprehensive range of mix combinations with recycled fine aggregate, fine sand, and coarse sand were considered to provide detailed insights into their effects on mortar strength. Most of the research conducted on this topic focused on the compressive strength of mortar or life cycle assessment individually. Along with crushing strength, the combined approach consists of assessing environmental sustainability, and the economic aspects are the prime motivations of this investigation. This research examined the range of percentage replacement of natural sands with RFA in cement composites, focusing on the physical properties of the sands, compressive strength of mortar, cost perspective as well as environmental sustainability. To achieve the objectives of the study, specific tasks were undertaken:

Observation and comparison of the physical properties of different types of fine aggregates;

Determination of crushing strength of mortar with natural sands and recycled fine aggregate at different combinations;

Cost analysis and Life Cycle Analysis of the cement composites.

2 Materials and Methodology

2.1 Materials

Ordinary Portland Cement (OPC), i.e., Type I cement, was considered as the main binder in the mortar mixes. Two types of natural sands with stark differences in properties were considered to conduct the study. Sand with a larger grain size was mined from upstream of the Surma River at Jaflong, Sylhet, whereas the other type was collected from downstream of the Rupsha River at Khulna. Concrete waste, free of impurities, was collected from a demolished residential building in Dhaka. All the materials are shown in **Fig. 3**. The substantial waste was then crushed into aggregate using a stone crusher machine, and the finer portion was separated by sieving through a No. 4 (4.75mm) sieve. Thus, the separated fine aggregate is considered as RFA, consisting of stone dust and both hydrated and un-hydrated cement paste. The fineness modulus, an index number representing the mean size of the particles, was determined by sieve analysis in line with the standards of ASTM C136 [44].

Determination of specific gravity and water absorption was conducted according to ASTM C128 [45]. Furthermore, ASTM C29 [46] was followed to determine the fine aggregates' unit weight.

(a) Cement (b) Coarse Sand (c) Fine Sand (d) RFA

Fig. 3. Materials used to prepare mortar mixes.

2.2 Methodology

Cement mortar cubes having the dimension of 2 inches × 2 inches × 2 inches were prepared using coarse sand, RFA, and fine sand at 12 (twelve) different combinations (Fig. 4). One part of OPC was mixed with 2.75 parts of fine aggregate by mass, maintaining a water-cement ratio of 0.485. The mechanical mixing was carried out as per the prescribed procedure of ASTM C305 [47]. The mortar cubes were prepared and cured according to the procedure prescribed in ASTM C109 [48] (**Fig. 4**). The mix compositions shown in **Table 2** encompass twelve different mix proportions to identify the optimum aggregate variation for maximum compressive strength and overall performance.

Table 2. Mix Composition of the Cement Mortars

Mix Composition	Mix ID	Recycled Fine Aggregate (%)	Fine Sand (%)	Coarse Sand (%)
1	C100	0	0	100
2	F100	0	100	0
3	R100	100	0	0
4	R25F75	25	75	0
5	R50F50	50	50	0
6	R75F25	75	25	0
7	F25C75	0	25	75
8	F50C50	0	50	50
9	F75C25	0	75	25
10	R25C75	25	0	75
11	R50C50	50	0	50
12	R75C25	75	0	25

2.3 Life Cycle Assessment (LCA)

In this research, the LCA was conducted adhering to the standards of ISO 14040 [49] and ISO 14044 [50], with the LCA process encompassing four stages: establishing the goal and scope, conducting inventory analysis, assessing impacts, and interpreting the results.

2.3.1 Goals and Scopes

This research focuses on assessing the suitability of RFA in cement composites with a focus on environmental aspects. One of the major objectives is to identify the optimum combinations of fine aggregates with minimal negative environmental impacts. Several key assumptions underpin this analysis:

Owing to the absence of specific data, the dataset from ecoinvent v3.7.1—a comprehensive and widely used database for life cycle assessment (LCA) and environmental impact analysis—was utilized for various processes involved in manufacturing cement mortar.

The ecoinvent database does not contain datasets specific to Bangladesh, so datasets adapted for the rest of the world (RoW) were employed. However, the built-in dataset specific to Bangladesh was used for energy consumption through electricity.

The materials were handled manually, and therefore, the environmental impacts of this process were not included in the assessment.

The study did not consider the environmental impacts of storing materials like cement, sand, and recycled fine aggregate.

Direct data on transportation distances was unavailable. Therefore, approximate distances were derived from Google Maps.

A generalized approach was used for the transportation mediums for all materials, with information extracted from the ecoinvent database.

(a) Mortar mixing machine

(b) Mortar mix after mixing

(c) Mortar mix in the molds

(d) Specimens in curing tray

(e) Compression Testing Machine

Fig. 4. Cement Mortar Mixing Process and Compressive Strength Test Setup.

This study operates within a "Cradle to Gate" system boundary and focuses on producing 1m^3 of cement mortar in Bangladesh as its Functional Unit (FU). Data sources include information gathered from visits to demolition sites, Google Maps, various literature reviews, and the ecoinvent database. An essential part of the study is a comparative analysis that evaluates the environmental performance of using recycled fine aggregate to produce one cubic meter of cement mortar, in contrast to the use of Sylhet sand and river sand for the same amount. This comparison highlights the environmental impacts and efficiencies of different materials in cement mortar production. The system boundary for cement mortar and the production systems for the components of cement mortars are depicted in **Fig. 5**, **Fig. 6**, and **Fig. 7**.

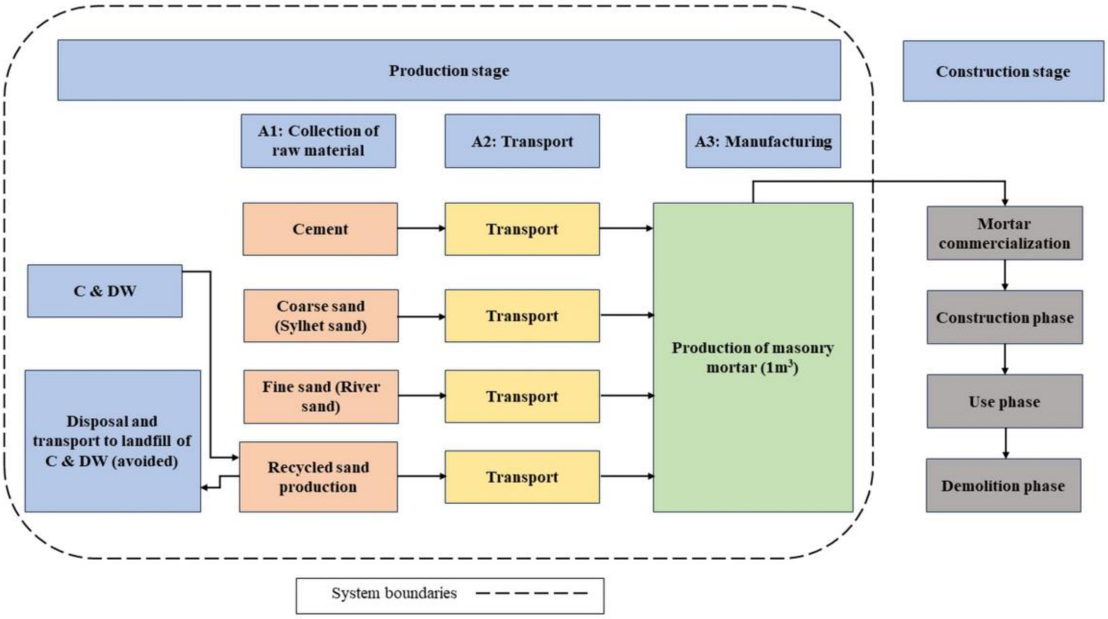


Fig. 5. System boundary of cement mortar.

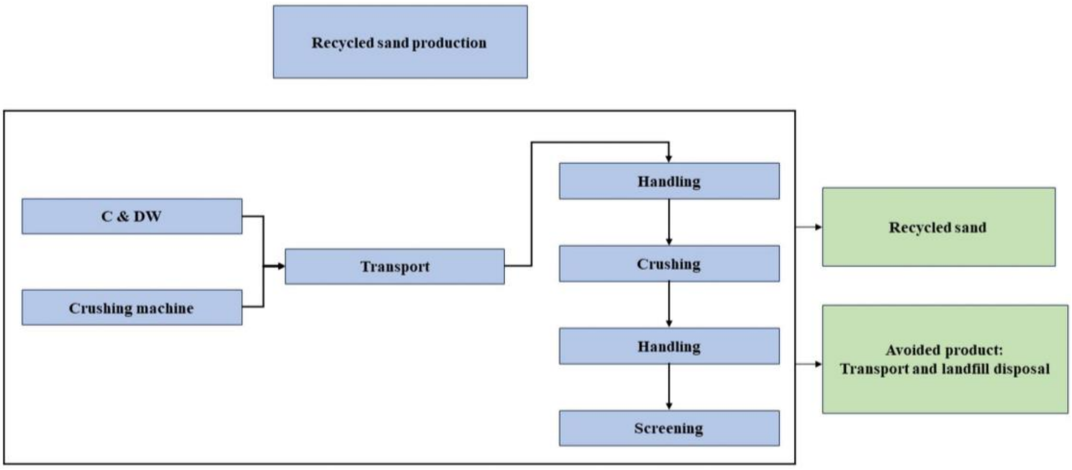


Fig. 6. Production process of recycled fine aggregate.

2.3.2 Selection of Impact Categories

The impact assessment was carried out in accordance with the impact categories recommended by EN 15804+A1 [51], which relates to the sustainability of construction works, particularly focusing on construction products and services such as masonry mortars [39]. CML-IA baseline and Cumulative Energy Demand (CED) were selected as the impact assessment methods. The CML-IA baseline method encompasses a wide array of environmental impact categories, including global warming, acidification, eutrophication, human toxicity, eco-toxicity, and resource depletion [39], and the CED method centers on the complete energy demand connected to a product or process throughout its entire lifecycle. This encompasses the energy used in the extraction of raw materials, production, transportation, utilization, and disposal [52]. The information gathered in the inventory stage was inputted into the openLCA 2.1.1 program [53], and the evaluation was carried out using the CML-IA baseline and the CED approach.

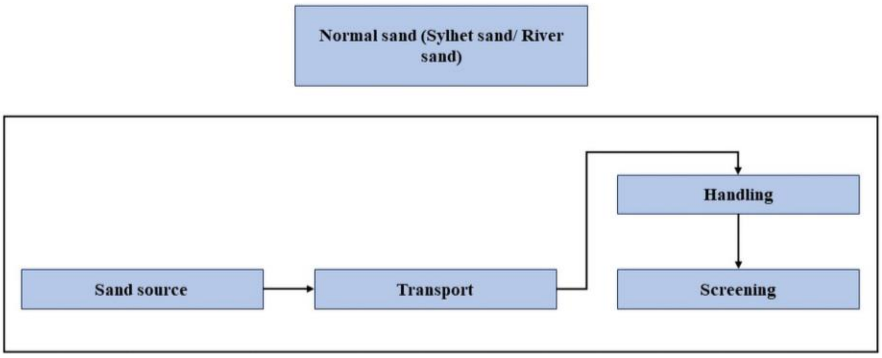


Fig. 7. Production process of normal fine aggregate.

2.3.3 General Calculation Method of LCA

OpenLCA works as a linear model. Both CML-IA baseline and CED methods are linear. The equations for each impact category in the CML-IA baseline method are based on characterization factors that relate emissions or resource use to their respective impact categories. The formula for each impact category is:

$$Impact\ category\ value = \sum_i EF_i \times CF_{i,category} \tag{1}$$

Here, EF_i = the emission factor for a substance i;

CF_i = the characterization factor for the impact category

In openLCA, emission factors (EFs) are typically part of the inventory data within the Life Cycle Inventory (LCI) databases (in this case ecoinvent). These factors are associated with specific processes and quantify the amount of emissions or resource use per unit of activity. The characterization factors (CF) for different impact categories are integrated into the LCIA methods available within the software.

For a mixed composition, the equation can be generalized like this:

$$I_{mix} = \sum_{i=1}^{n} I_{components,i} \times A_i \tag{2}$$

Here, I_{mix} = total impact value of each mortar mix;

$I_{components,i}$ = the impact per unit of component I;

A_i = the quantity of component i used in the product;

n= the total number of different components in the product

3 Results and Discussion

A total of one hundred and eight cube samples were examined in the study. The following section presents the results of the material property tests, compressive strength tests, Scanning Electron Microscope (SEM) analysis with Energy dispersive X-ray analysis (EDX), LCA, and cost analysis.

3.1 Material Properties

The characteristics of cement composites are greatly influenced by the physical and mechanical attributes of their components. **Table 3** presents the physical characteristics of the fine aggregates utilized in this research, including their percent water absorption, fineness modulus (FM), specific gravity, and unit weight.

The unit weight of coarse sand was 1608 kg/m^3, while recycled sand had the maximum unit weight among the considered aggregates. However, the unit weight of the recycled fine aggregate entirely depends on the source or the mother concrete. Due to the presence of both hydrated and un-hydrated cement paste on the surface of the finer portion of RFA, it exhibited higher water absorption than both fine and coarse sand. However, the absorption capacity was observed within the allowable limit as per

BS 6349-1:2000 [54], i.e., the maximum water absorption capacity of sand was 3%. A higher percentage of water absorption of fine sand requires a higher w/c for proper hydration of mortar or concrete. Remarkably, the water absorption capacity of RFA was within the expected limit, which makes such type of sand applicable to concrete or mortar. The gradation chart (**Fig. 8**) showed the grain size distribution, including the prescribed upper and lower limits of fine aggregate suitable for concrete mix use.

Table 3. Physical properties of fine sand, coarse sand, and recycled sand

Type of Sand / Parameters	Fine Sand	Coarse Sand	Recycled Sand
Percent Water Absorption, %	1.15	1.01	2.92
Fineness Modulus	1.45	2.97	2.50
Bulk Specific Gravity SSD	1.98	2.60	2.61
Bulk Specific Gravity OD	1.84	2.58	2.53
Apparent Specific Gravity	2.15	2.65	2.74
Unit Weight (kg/m^3)	1348	1608	1649

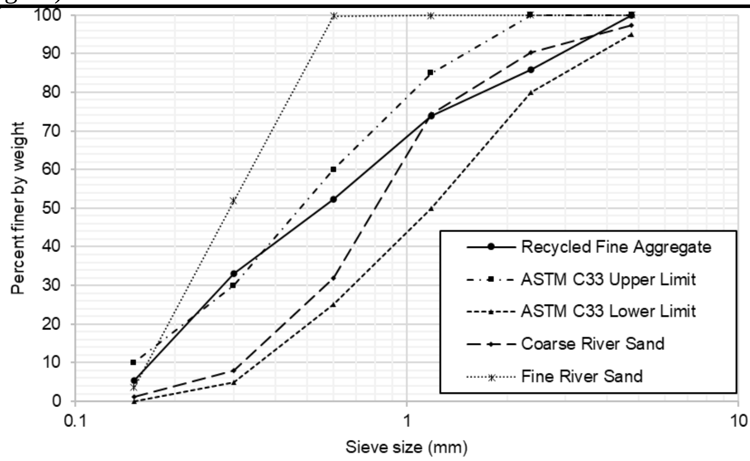


Fig. 8. Gradation curve of the fine aggregates.

The formation of fine sand requires so much abrasion, which is lacking in construction and demolition sites for the random generation of waste. Hence, the recycled sand showed a similar gradation curve and fineness modulus to medium sand. According to ASTM C33 [55], the fine aggregate suitable for concrete production should have a fineness modulus of more than 2.3 and less than 3.1, which proves the applicability of coarse sand and recycled fine aggregate in concrete technology regarding fineness modulus. However, fine sand did not meet the criterion mentioned above.

3.2 Compressive Strength

The compressive strength of cement mortar is one of the most important mechanical properties, as mortar is a brittle material with insufficient tensile strength. Cement mortar strength is not directly related to concrete strength but can be used as a quality control measure. All the specimens imparted similar failure patterns under compression. The texture of the fragments collected from the specimens after compressive failure was studied for comparison (**Fig. 9**).

(a) C100 (b) F100 (c) R100 (d) R25C75

Fig. 9. Texture of the specimens.

C100 had a more solid texture, whereas R100 and F100 exhibited a porous medium. R25C75 mix showed an inner surface similar to that of C100. Among the mixes, maximum compressive strength was observed in the mortar specimen incorporated with 100% coarse sand (**Fig. 10**). The variation in compressive strength of mortar mixes with respect to recycled fine aggregate mortar (R100) is shown in **Fig. 11.**

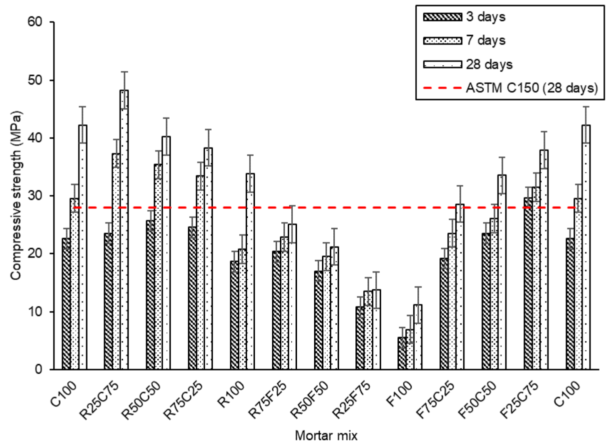


Fig. 10. Compressive Strength Test Results of Mortar Mixes.

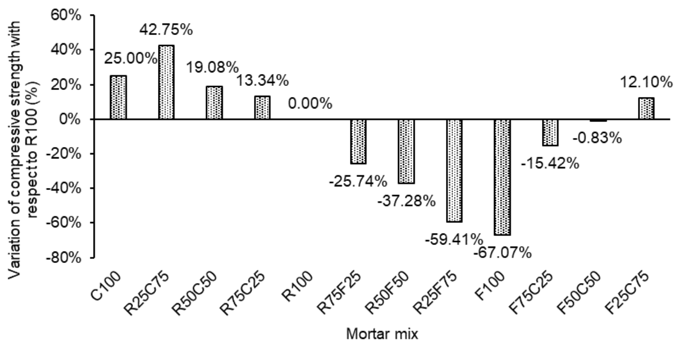
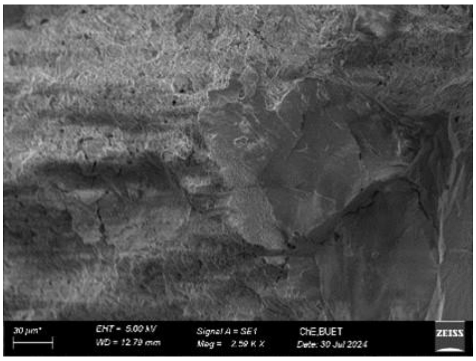


Fig. 11. Variation in Compressive Strength in percentage with respect to 100% recycled fine aggregate mortar.

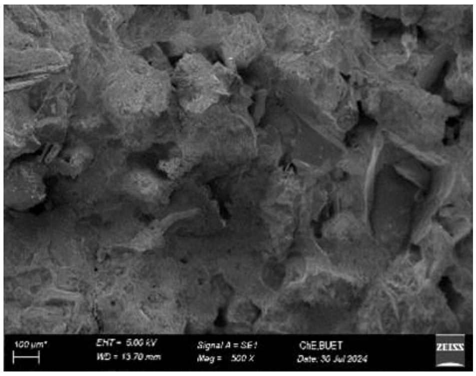
Being uniformly graded, fine sand provided less compact mass, resulting in lower compressive strength. On the other hand, well-graded coarse sand imparted higher strength. Mortar with recycled sand was more porous than coarse sand. For the same w/c ratio, it absorbs more water, leaving less water to form calcium silicate hydrate (C-S-H) gel, which leads to less strength compared to coarse sand mortar. The compressive strength results of various mortar mixes showed significant variations based on the proportions of coarse sand, fine sand, and recycled sand. The mix C100 achieved a high compressive strength of 42.25 MPa at 28 days, showing a 25% increase compared to the reference mix R100 with 33.80 MPa. Coarse sand (Sylhet Sand), for its angular shape and rough texture, provides excellent mechanical interlocking and reduces voids in the mix, leading to high compressive strength. Coarse nature allows for better load distribution and lower water demand, contributing to strong cement hydration and strength development [56]. Conversely, F100 exhibited the lowest strength of 11.13 MPa, reflecting a 67.07% decrease with respect to the reference sample. Mixes with higher proportions of fine sand generally showed reduced strength. It can be attributed to its poorer packing density and particle interlocking due to its larger surface area and round and smooth surface as opposed to coarse sand [57]. Mixes combining recycled sand with coarse sand, particularly R25C75, demonstrated the highest improvement, achieving 48.25 MPa, a 42.75% increase. All mixes, except F100 and the combinations of fine sand and RFA in mortar, meet the requirement of compressive strength of 28 MPa at a 28-day curing period, as per ASTM C150 [58]. Due to the higher interlocking and lower void content, the mix of 25% RFA and 75% coarse sand was optimized and contributed to higher strength. From the perspective of compressive strength, RFA can be a cost-effective alternative to naturally mined sand. However, cement mortar strength is not directly related to concrete strength but can be used as a quality control measure.

3.3 SEM Analysis

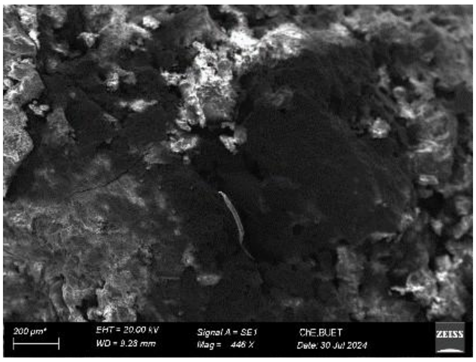
An SEM analysis was conducted to explore the micro-level characteristics. The texture-based observations were consistent with the SEM images (**Fig. 12**).



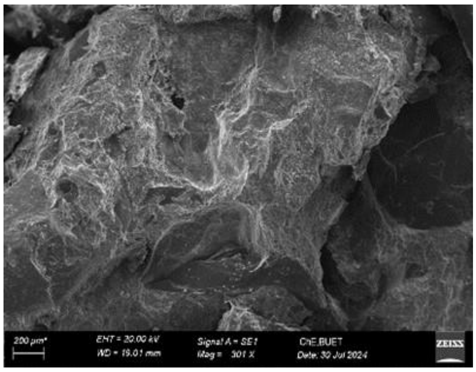
(a) C100



(b) F100



(c) R100



(d) R25C75

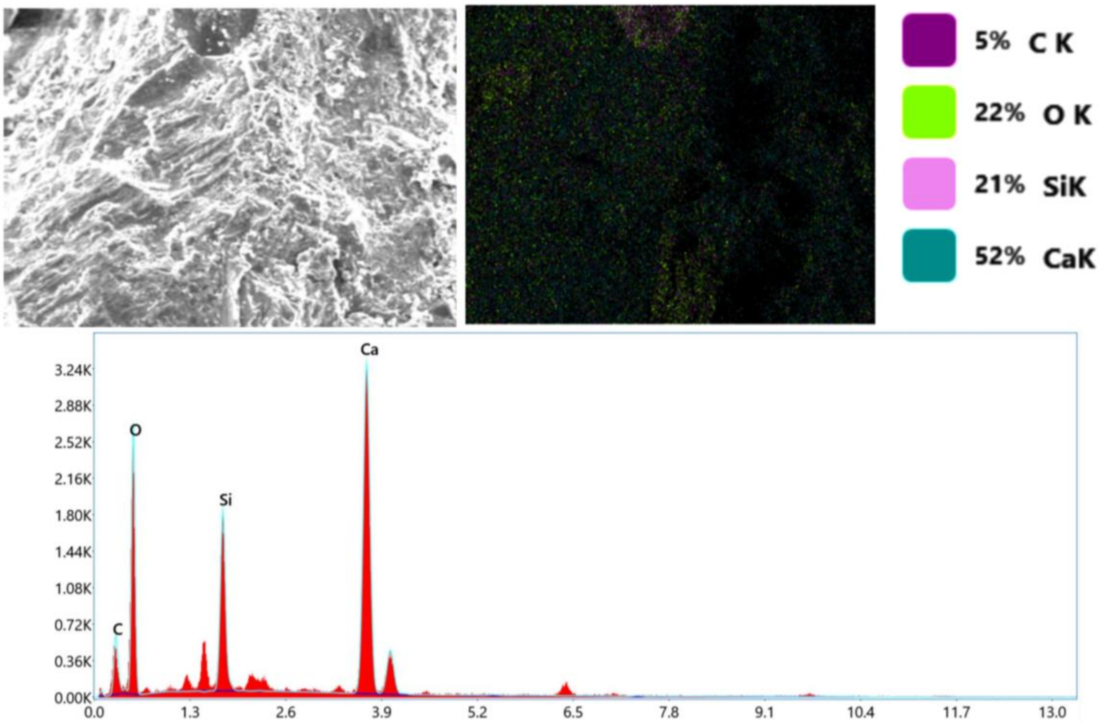
Fig. 12. SEM Analysis of mortar mix.

Table 4. Impact Categories based on CML-IA baseline

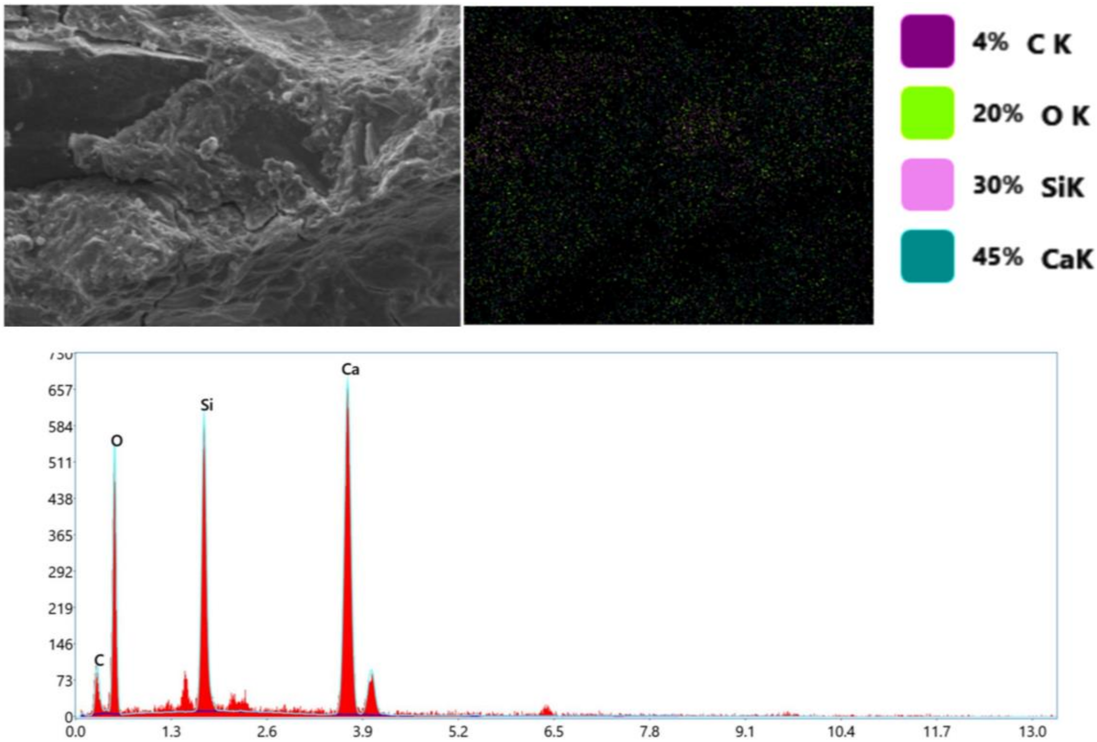
Impact Categories	Unit	R100	F100	C100	R25C75
Abiotic depletion	kg Sb eq ($\times10^{-3}$)	2.53	6.11	5.20	4.53
Abiotic depletion (fossil fuels)	MJ ($\times10^{3}$)	1.80	3.07	2.81	2.56
Acidification	kg SO_2 eq ($\times10^{0}$)	0.74	1.08	1.03	0.96
Eutrophication	kg PO_4--- eq ($\times10^{-1}$)	3.12	4.18	3.99	3.77
Freshwater aquatic ecotox.	kg 1,4-DB eq ($\times10^{1}$)	5.49	9.30	8.42	7.69
Global warming (GWP100a)	kg CO_2 eq ($\times10^{2}$)	3.66	4.55	4.37	4.19
Human toxicity	kg 1,4-DB eq ($\times10^{1}$)	7.64	11.90	10.90	10.10
Marine aquatic ecotoxicity	kg 1,4-DB eq ($\times10^{5}$)	1.13	1.72	1.59	1.47
Ozone layer depletion (ODP)	kg CFC-11 eq ($\times10^{-5}$)	1.11	2.54	2.26	1.97
Photochemical oxidation	kg C_2H_4 eq ($\times10^{-2}$)	4.53	7.58	6.89	6.30
Terrestrial ecotoxicity	kg 1,4-DB eq ($\times10^{-1}$)	3.11	4.22	3.96	3.75

The coarser grading of sand with higher bulk density requires less water than an equivalent weight of finer sand, which enhances the compressive strength of mortars [59]. SEM analysis (**Fig. 12**) revealed that the porous surface of F100 corresponded to the porous matrix due to its higher water content. Similarly, the old mortar adjacent to the surface of RFA demanded more water because of the weak, porous interfacial transition zone. Consequently, R100 exhibited a porous surface in SEM analysis. In the case of the R25C75 mix, specimen fragments displayed smooth stone-faced surfaces similar to C100.

Energy-dispersive X-ray analysis was also conducted to examine the elemental composition within the matrix. EDX showed that R25C75 contained a comparatively higher percentage of C-S-H in the matrix (**Fig. 13** (b)) reflecting the presence of an old cement matrix adjacent to the R100 (**Fig. 13** (a)). C100 displayed a higher percentage of siliceous stone volume.



(a) R100



(b) R25C75

Fig. 13. EDXS-mapping.

3.4 Life Cycle Assessment

The outcomes from the simulation conducted using openLCA software are presented in **Table 4** and **Table 5**. The environmental impact of cement mortars was evaluated across eleven categories using the CML-IA baseline method and in six different categories based on the CED method. The results were normalized to the cement mortar made with fine sand, which is shown in **Fig. 14** and **Fig. 15**.

Table 5. Impact Categories based on CED

Impact Categories	Unit	R100	F100	C100	R25C75
Non-renewable, fossil	MJ ($\times 10^3$)	1.92	3.27	3.00	2.73
Non-renewable, biomass	MJ ($\times 10^0$)	8.92	8.97	8.96	8.95
Non-renewable, nuclear	MJ ($\times 10^1$)	3.07	5.14	4.62	4.23
Renewable, biomass	MJ ($\times 10^2$)	1.00	1.14	1.10	1.08
Renewable, water	MJ ($\times 10^1$)	3.79	4.90	4.66	4.44
Renewable, wind, solar, geothe	MJ ($\times 10^0$)	6.73	16.07	13.63	11.90

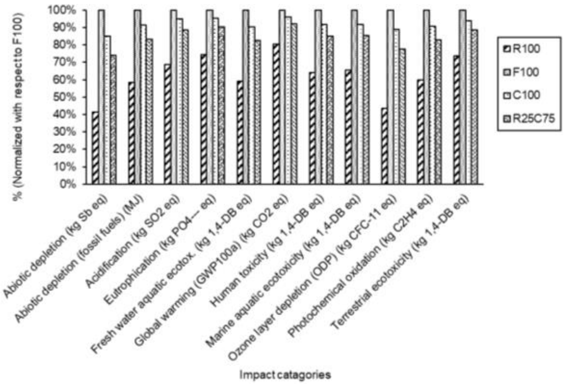


Fig. 14. Environmental impact of cement mortars (CML-IA baseline method)

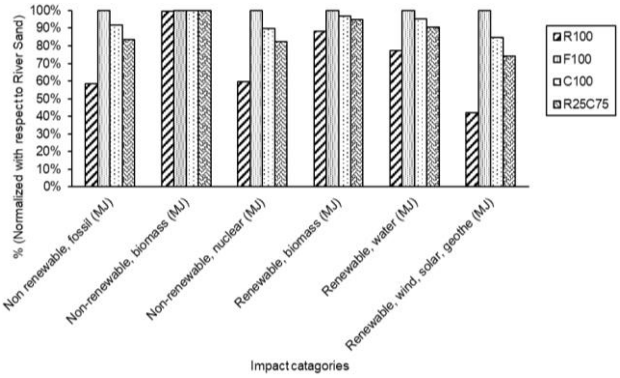


Fig. 15. Environmental impact of cement mortars (CED method)

According to the assessment, R100 demonstrated a reduced environmental impact across all indicators in both methods, positioning it as a more sustainable option in mortar compared to other fine aggregates like Sylhet sand and river sand. The main factors influencing the impact categories were "cement production" and "transport distance". Since the cement quantity in the mortars was consistent, the distance traveled from the material source to the mortar production site became the critical factor affecting environmental impact. For recycled fine aggregate, the transportation distance from the demolition site to the landfill was avoided, leading to a considerably reduced total travel distance from the demolition site to the production facility in comparison to the routes for coarse sand and fine sand (**Fig.16**).

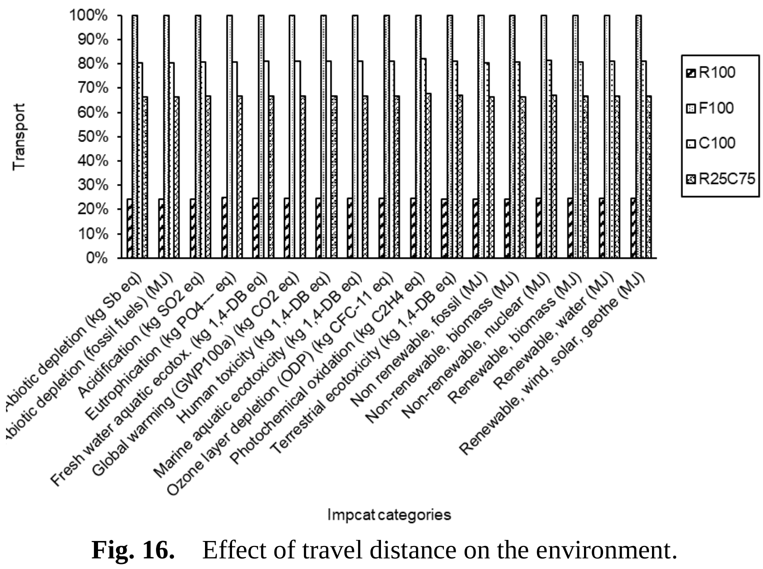


Fig. 16. Effect of travel distance on the environment.

Transportation is the primary component associated with fossil fuels [41]. Hence, the environmental impact was the least in this category for cement mortar with recycled fine aggregate. Where cement was the primary influencing factor, such as non-renewable and renewable biomass, there was virtually no difference in environmental impact among the different cement mortars.

Fig. 17 presents the relationship between the compressive strength of various mortar mixes at 28 days and their environmental impacts, focusing on global warming potential (**Fig. 17** (a)) and abiotic depletion (fossil fuels) (**Fig. 17** (b)). The construction industry is a significant contributor to greenhouse gas emissions. Hence, understanding the impact of different materials on global warming is crucial. On the other hand, abiotic depletion (fossil fuels) measures the depletion of non-renewable energy resources, which is an important indicator of resource sustainability.

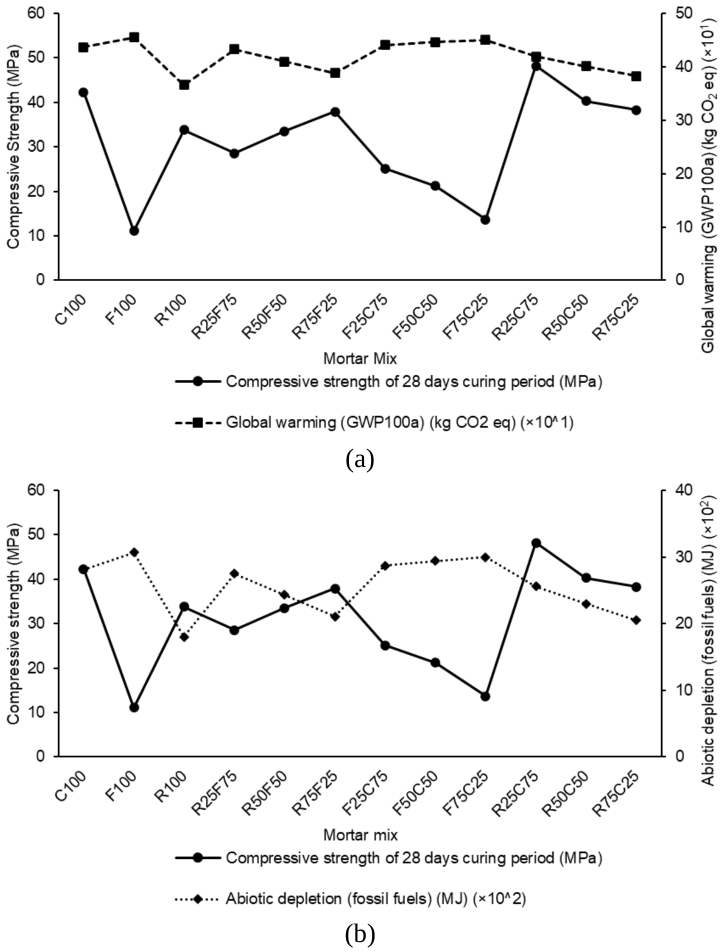


Fig. 17. Comparison of Compressive strength and Impact Categories for the mortar mixes.

This analysis highlighted the least environmental effect of R100. From the environmental perspective, each combination of RFA with coarse sand is a viable option without compromising strength.

3.5 Cost Analysis

As the quantities of all materials except the sands are the same in the mortar mixes, a cost comparison among the sands was conducted to determine which is the most cost-effective. The fineness value is provided according to the Government of the People's Republic of Bangladesh, Public Works Department Schedule of Rates (SoR) 2022 for Civil Works [60]. As brick chips were used in most of the old structures in Bangladesh [61], the cost of recycled aggregate was based on the price of breaking down 12 mm brick chips, as stated in the Public Works Department's 'Schedule of Rates' (**Table 6**). The inclusion of a higher percentage of RFA improved economic benefits, but it reduced the compressive strength. Without compromising the compressive strength as required by ASTM C150 [58], all mix combinations of RFA and coarse sand, as well as mixes F50C50 and F25C75, demonstrated higher strength with lower cost (**Fig. 18**).

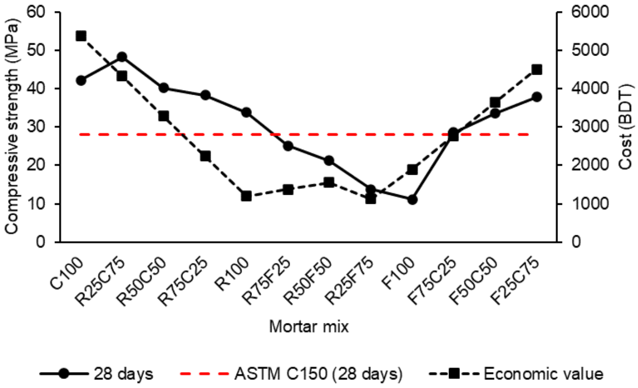


Fig. 18. Comparison of compressive strength and economic values for the mortar mixes**.**

Table 6. Rate of different types of fine aggregates discussed in this research

Materials	Quantity	Rate (Bangladeshi TK, BDT)
Fine Sand (FM 1.2)	100 cft	1900
Coarse Sand (FM 2.2)	100 cft	5380
RFA	100 cft	1200

4 Conclusions

The applicability of recycled fine aggregate as a filler material in cement mortar instead of using natural sand was justified in terms of the compressive strength of mortar, physical properties of the incorporated fine aggregates, and overall environmental and economic impacts. A combination of coarse sand and RFA can be considered an alternative source of fine aggregate that can reduce the amount of CDW in the environment and ensure a cost-effective solution. To conclude, the following observations can be considered comparing the basic properties of fine aggregates and their effectiveness on cement composite.

The compressive strength of the mortars with RFA and coarse sand conformed to ASTM C150, whereas no mix combination of RFA and fine sand met the ASTM standards. After a 28-day curing period, 100% RFA-incorporated mortar (33.8 MPa) provided about 25% lower compressive strength compared to mortar with 100% coarse sand (42.25 MPa). However, replacing 25% of coarse sand with RFA resulted in the highest compressive strength (48.25 MPa). Conversely, F100 (11.13 MPa) and any combination of RFA and fine sand yielded the lowest strength.

SEM images revealed that fine sand resulted in a porous matrix due to its higher water content, whereas RFA demanded more water because of its weak, porous interfacial transition zone. The R25C75 mix showed a smooth surface with a higher percentage of C-S-H, contributing to better strength.

The environmental impact assessment indicated that using R100 resulted in a reduced environmental footprint compared to natural sands, especially fine sand, primarily due to the shorter transportation distance from the source and the elimination of transporting demolition debris to landfills. Replacement percentages of RFA with coarse sand (R25C75, R50C50, R75C25) demonstrated a balance between maintaining high compressive strength and reducing environmental impact. These mixes showed that incorporating RFA can significantly reduce environmental impacts without compromising the structural integrity of the mortar.

The combination of RFA and fine sand offers the most economical benefits but does not conform to the required minimum strength of the ASTM standard. On the other hand, any mix containing RFA and coarse sand leverages the low cost of RFA while maintaining substantial compressive strength, making it a cost-effective and efficient solution for construction applications without significantly impairing performance.

Considering the combined aspects of compressive strength, environmental sustainability, and economic benefits, various percentages of RFA can be recommended as a replacement for available local sand in concreting and plastering works to replace natural fine and coarse sand.

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Credit authorship contribution statement

Sk. Rakibul Islam: Conceptualization, Investigation, Methodology, Formal analysis, Writing – original draft. **Sanjima Nabila Majumder**: Investigation, Methodology, Formal analysis, Life Cycle Analysis, Writing – original draft. **Rupak Mutsuddy**: Conceptualization, Supervision, Writing – review & editing.

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

Availability of Data and Material

This manuscript, titled "Life cycle assessment and mechanical strength of cement composites with conventional, and recycled fine aggregate" is a research paper that provides an examination of the physical properties of fine aggregates and the compressive strength of mortar prepared with 12 (twelve) combinations of fine sand, coarse sand, and recycled fine aggregate. Moreover, environmental aspects are also considered and quantified in terms of life cycle assessment. All the mechanical and physical properties used in this study are obtained from lab experiments. Moreover, other required material and datasets utilized in the LCA are sourced from open-access repositories and publications, assuring their availability to the entire scientific community and interested readers. Additionally, the data utilized in this study may be publicly accessed online, further encouraging transparency, reproducibility, and research on the subject.

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