

ENHANCING SUSTAINABLE CONCRETE PRODUCTION IN THE CONSTRUCTION INDUSTRY USING VARIOUS RECYCLED WASTE MATERIALS AS COARSE AGGREGATE EMPHASIZING COMPRESSIVE STRENGTH AND COST EFFICIENCY

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ABSTRACT

Global waste generation increases day by day but ineffective recycling results in rising energy consumption and environmental damage. Dealing with this serious issue has now become a global challenge. This paper analyses the possibilities of replacing natural coarse aggregates with Iron slag, plastics, ceramic waste, rubber tires, demolished concrete, and glass, especially focusing on sustainability evaluation and compressive strength analysis. Using data from previous research studies, a literature review was conducted to analyze different recycled waste materials and identify their parameters (cost, carbon emission, and compressive strength). The result shows that replacing coarse aggregate with various recycled waste materials mentioned above enhances mechanical properties, reduces carbon emissions, and lowers production costs. From the result, it is clearly visualized that rubber tires are the best alternative for natural coarse aggregate with a compressive strength of 45 MPa and also have the minimum production cost and embodied energy. This paper introduces a new aspect of sustainable concrete production by utilizing recycled waste materials which is sustainability and waste reduction.

Keywords: recycled waste materials, coarse aggregate, sustainability, waste reduction, compressive strength.

INTRODUCTION

The construction industry is growing rapidly all over the world. Construction materials are in high demand due to increased construction activity. Concrete is used as the main component of construction among all the materials included in the construction industry. More than 10 billion tons of concrete are produced every year [1]. Concrete has several benefits, including strength, ease of production, water tightness, durability and versatility [2, 3].

About 70–80% of the volume of structural concrete is occupied by aggregates, in which 25–30% is occupied by fine aggregate and 40–50% is occupied by coarse aggregate [1, 4]. The quantity and properties of coarse aggregate has considerable impact on fresh and hardened properties of concrete. Excessive extraction of natural aggregates from rivers could hamper the construction industry's growth due to limited resources available and environmental damage. The depletion and high demand for natural coarse aggregate come together with the global community's growing concern about sustainable development and climate change [5]. To mitigate the environmental impact of natural aggregate

depletion, study has been focused on utilizing various waste materials instead of traditional aggregates [6]. In a research study, construction and demolition waste generation in 40 global countries reached over 3.0 billion tons per year until 2012, a trend that continues to rise [7]. Additionally, ceramic waste production is 100 million tons per year in India only, and also in 2002, the total amount of glass waste produced in the EU was 3 million tons while in 2008, it was 4.1 million tons [8]. It has been estimated that the United States of America alone generated almost 12,250,000 tons of municipal solid waste (MSW) glass in 2018. Of this, 7,550,000 tons were landfilled. In comparison, Australia produced 1,200,000 tons of waste glass in 2018–19 [9]. This huge amount of waste materials creates disposal problems as well as negative environmental impacts. For this reason, recycled waste alternatives have gained acceptance due to the ease of disposal and preservation for the foreseeable of natural resources as well as low cost [10]. In this paper, different waste materials have been assessed and categorized for potential use as coarse aggregates in concrete. In this context, the present study reviews the previous research studies that explored the applicability of different recycled wastes, such as iron slag, ceramic waste, rubber tires, demolished concrete, and glass based on compressive strength analysis and sustainability evaluation. Using these potential recycled wastes as replacements for coarse aggregate in concrete production can encourage green innovation and minimize the environmental impact.

This paper offers an overview of the emergence of various recycled waste materials as potential replacements of coarse aggregate especially focused on compressive strength analysis and sustainability evaluation. This systematic review provides practitioners with a better understanding of present practices, limitations, and future prospects for benchmarking the sustainability of green concrete using various waste materials. In the context, this paper explores the effects of these recycled waste materials on workability, compressive strength, flexural strength, split tensile strength, and their environmental effects. The paper also introduces a strategy for determining each waste material's suitability, placing a spotlight on a thorough assessment of sustainability. This evaluation takes into account social engagement, economic factors regarding overall cost efficiency, and ecological considerations with a focus on low carbon emissions.

METHODOLOGY

For this comprehensive assessment, Searches across multiple databases, including Web of Science, Scopus, and Google Scholar, were conducted to gather research on sustainable concrete incorporating various recycled waste materials (Fig. 1). Due to its extensive usage and accessibility of research papers, Google Scholar was the main database searched. To conduct the research, a list of relevant search terms was compiled, such as low carbon emissions, sustainability, recycled wastes, compressive strength, sustainable concrete, and coarse aggregate replacement. Only articles published in English were included in the search. Further refining, only research relevant to recycled waste materials as coarse aggregate replacement in sustainable concrete production was chosen, resulting in a selection of more than 150 papers. Then, the abstract was selected and screened to ascertain its applicability to the study. A study regarding different recycled waste materials used as replacements for coarse aggregate to produce sustainable concrete in terms of environmental impact, cost analysis, and social acceptability without compromising its compressive strength. After screening and choosing 15 articles, analysis, and review were conducted by taking into account the different kinds of recycled waste materials that were utilized in sustainable concrete production. Furthermore, all the chosen articles that were examined were part of the peer-reviewed literature and were discussed in the final set.

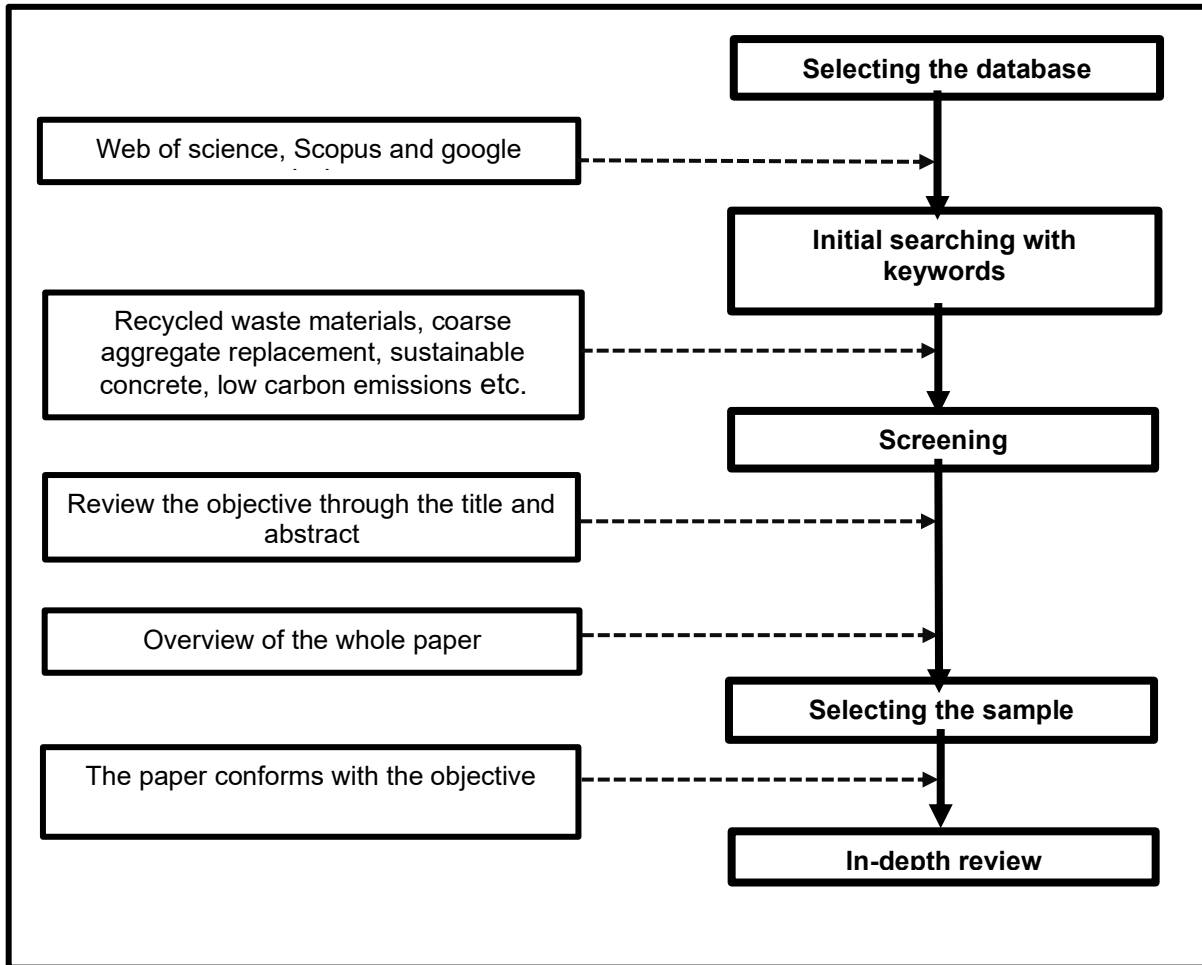


Figure 1. The five-step work-flow for reviewing the literature

DATA ANALYSIS

Tables 1 and 2 represent the physical and chemical properties from various research papers on the production of sustainable concrete using various waste materials instead of fine aggregate including sand. A thorough review of these tables reveals significant similarities between the physical and chemical compositions of different wastes and traditional fine aggregates.

Table 3 shows the mix proportions of various concrete mixes. The mixes are derived from the mix proportion table of various papers in which natural fine aggregate is replaced with waste materials to achieve the best mechanical properties and sustainability criteria. In those tables, fine aggregate has been replaced at various percentages, but we have chosen the optimum replacements with the highest compressive strength. A concise overview of the optimal mixes is represented in Table 4, establishing the relationship between the optimum replacement percentages and the superior attributes defining these concrete blends with waste products. This paper compares five different waste materials, which will undoubtedly lower concrete's overall embodied CO₂ emissions. For this, it used the eco-strength efficiency of concrete, a metric applied to the environmental impact assessment for evaluation. It is called the CO₂ intensity [10], and it is the amount of CO₂ emissions produced per unit of performance. It was determined using formula (i) & (ii): -

$$C_i = EC/f_c \quad (1)$$

$$E_f = (E-Energy)/f_c \quad (2)$$

Where f_c is the compressive strength for 28 days, C_i represents the eco-strength efficiency or the intensity of CO₂, E_f is the embodied energy parameter, EC represents the embodied carbon dioxide emissions released by the concrete mixes as determined using Table 7, and E -energy is embodied energy of concrete by the concrete mixes, as calculated using Table 3 and Table 4. The lower E_f and C_i the amount indicates greater sustainability.

EMBODIED CARBON (EC)

Using the inventory data in Table 7, Eq. (3) may be used to compute the EC of each ternary and binary mix:[11].

$$EC = \sum_{i=1}^n f_i r_i \quad (3)$$

Where EC is a combination of Embodied CO₂ (kg-CO₂/m³); f_i is the E-CO₂ unit of materials (i), n = (1– 9), as mentioned in Table 6; and r_i was the weight of the used material (i), as described in Table 3. The unit CF of each combination was computed using Eq. (3). The Eco-strength efficiency of CO₂, C_i (kg- CO₂./m³/MPa) of each matrix was estimated using its compressive strength (MPa) at 28 days and Eco-strength efficiency in Fig 5.

EMBODIED ENERGY (EE)

The EE of each binary and ternary combination may be computed using Eq. (4) using the inventory data in Table 7:[11].

$$EE = \sum_{i=1}^n e_i r_i \quad (4)$$

where EE is the energy of a combination; e_i denotes the EE unit of the materials (i) and n = (1– 9), as mentioned in Table 7; and r denotes the weight of the material (i), as mentioned in Table 3. The unit EE of each combination mixture was estimated using Eq. (4). The Energy efficiency per unit of strength EE (MJ/m³/MPa) of each matrix was estimated using the compressive strength (MPa) at 28 days and Energy efficiency in Fig 6.

COST ANALYSIS

Using the inventory data in Table 7, Eq. (5) may be used to determine the unit cost of each mixture:[11].

$$C = \sum_{i=1}^n X_i Y_i \quad (5)$$

where C is the unit cost of a matrix/m³ (unit: tk/m³); X_i is the unit cost (unit: \$/kg) of the materials (i), where n = (1– 9), as shown in **Table 6**; and Y_i is the weight of the material (i), as mentioned in Table 3. The unit cost of each combination was determined using **Eq. (5)**. The Cost per strength unit (tk/m³/MPa) was estimated using the compressive strength of each combination at 28 days and Cost index Enhancement in Fig 7.

Table 1 Physical properties

| Waste Materials | Size(m m) | Unit Weight(kg/m ³) | Specific Gravity | Absorption (%) | Reference |
|-----------------|------------|---------------------------------|------------------|----------------|-----------|
| Sand | 0.425-2 | 1762 | 2.51 | 1.55 | [12] |
| Iron Slag | 0.15 - 0.6 | 1600-1920 | Maximum 3.6 | Maximum 3 | [13, 14] |
| Ceramic | 0.074 | 1323 | 2.52 | 21 | [15] |
| Rubber Tire | < 2 | 900-1160 | 1.15 | Negligible | [16] |
| C&D Waste* | 0.5-2 | 1200-1400 | 2.19-2.48 | 2.15-7.15 | [17] |
| Glass | < 0.149 | 1120 | 1.96-2.41 | 0.55-1.07 | [18] |

C&D Waste* : Construction & Demolition Waste

Table 2 Chemical properties

| Waste Materials | SiO ₂ | Al ₂ O ₃ | CaO | MgO | MnO | FeO, Fe ₂ O ₃ | S | P ₂ O ₅ | TiO ₂ | K ₂ O | Na ₂ O | Rubber | C(black) | (CH ₃) ₂ CO | C ₅ H ₈ | H ₂ O | Ash | Fiber | Metal Content | Reference |
|-----------------|------------------|--------------------------------|------------|-----------|-------|-------------------------------------|-------|-------------------------------|------------------|------------------|-------------------|--------|----------|------------------------------------|-------------------------------|------------------|-----|-------|---------------|-----------|
| Sand | 87.9 | 4.70 | > 0.14 | 0.3 | - | 0.94 | 0.09 | - | - | - | - | - | - | - | - | - | - | - | - | [19] |
| Slag | 8-40 | 1-22 | 30-42 | 5-15 | 0.1-8 | 0.1-35 | 0.2-2 | 0.1-1.7 | 0.4-2 | - | - | - | - | - | - | - | - | - | - | [14, 20] |
| Ceramic | 61.2-68.41 | 3.6-18.6 | - | 0.67-25.3 | - | 0.91-5 | - | - | - | 0.14-3.3 | 0.32-2.38 | - | - | - | - | - | - | - | - | [21] |
| C&D Waste | 39.97-68.43 | 5.49-15.85 | 3.48-24.09 | 1.10-2.84 | - | 2.40-3.05 | - | - | - | 0.4-0.74 | 0.94-4.71 | - | - | - | - | - | - | - | - | [3, 17] |
| Glass | 64.3-70.4 | 1.9-3.4 | - | 0.63-10.3 | - | 1.2-6.25 | - | - | - | 0.4-0.74 | 12.52-14 | - | - | - | - | - | - | - | - | [22, 23] |
| Rubber | - | - | - | - | - | - | - | - | - | - | - | 45.2 | 25.8 | 14.2 | 12.1 | 0.8 | 0.9 | 0.5 | 0.08 | [24] |

Where f_c is the compressive strength for 28 days, C_i is the eco-strength efficiency, or the intensity of CO₂, E_f is the embodied energy parameter, E-CO₂ is the embodied carbon dioxide emissions, and E-energy is embodied energy of concrete by the concrete mixes, as calculated using **Table 5** and **Table 6**. The lower values of E_f and C_i mean better sustainability.

Table 3 Mix proportion of concrete mix

| Waste Materials | Replacement quantity(kg) | Cement (kg) | Sand (kg) | Water (Lit) | Coarse aggregate(kg) | Reference |
|-----------------|--------------------------|-------------|-----------|-------------|----------------------|-----------|
| Sand | - | 470 | 467 | 188 | 1140 | [25] |
| Iron Slag | 900 | 340 | 733.33 | 125.8 | 402.6 | [14, 26] |
| Ceramic | 442 | 382 | 637 | 184 | 661 | [21, 27] |
| C&D Waste | 208 | 274 | 1050 | 185 | 546 | [28] |
| Glass | 390 | 440 | 760 | 167.2 | 690 | [23, 29] |
| Rubber | 6.51 | 14.80 | 10.45 | 6.3 | 26.0 | [30, 31] |

Table 4 Literature on the use of different waste materials as coarse aggregate replacement in concrete

| Waste Materials | Replacement | Optimum replacement | w/c ratio | Cement type | Other ingredients | Superplasticizer (SP) | Reference |
|-----------------|-------------|---------------------|-----------|----------------|---------------------------|-----------------------|-------------|
| Iron Slag | 0-100% | 75% | 0.45 | OPC (53 grade) | - | 1.2% | [14, 32] |
| Ceramic | 20-80% | 40% | 0.49 | OPC | - | - | [21, 33] |
| C&D Waste | 21-30% | 30% | 0.5 | OPC (43 grade) | Argillaceous, calcareous. | 0.5% | [3, 34, 35] |
| Glass | 0-40% | 20% | 0.38 | CEM1 | - | - | [23, 36] |
| Rubber | 1-20% | 10% | 0.67 | OPC | - | 2.35% | [3, 31, 37] |

RESULT AND DISCUSSION

EVALUATION OF MECHANICAL STRENGTH OF OPTIMUM MIX

Figure-2 represents the Mechanical Strength of different waste materials as coarse aggregate replacement in concrete production using iron slag, C&D waste, glass, rubber, sand, and ceramic at their optimum replacement proportions; the best mixture contained 75% iron slag [14]. The compressive strength of using glass was shown to be optimal at 20% [23], with rubber at 10% [3], ceramic at 40% [21], and with C&D waste at 40% [3] according to another study. Without various waste materials, other components of the mixtures were not at a constant rate. To some of the mixtures, admixtures, fly ash, and silica fume were added.

Table 5 Mechanical Strength of Optimum different waste materials as coarse aggregate

| Geopolymer | Optimum Replacement | Compressive Strength (MPa) | Splitting tensile strength (MPa) | Flexural Strength (MPa) | Reference |
|------------|---------------------|----------------------------|----------------------------------|-------------------------|-----------|
| Iron slag | 75% | 18 | 2.70 | 4 | [14] |
| Glass | 20% | 37 | 2.78 | 4.27 | [23] |
| C&D waste | 30% | 75 | 3.42 | 5.63 | [3, 38] |
| Rubber | 10% | 45 | 3.18 | 3.3 | [3, 31] |
| Ceramic | 40% | 38.5 | 3.75 | 5.67 | [21] |

EVALUATION COMPRESSIVE OF STRENGTH

Figure-2 represents the compressive strength of different waste materials as fine aggregate replacement in concrete production. In 30% of C&D waste, the highest compressive strength obtained was 75 MPa. The samples with ceramic (40%) and coarse aggregate (60%) had compressive strengths of 40.86 MPa. For iron slag, glass, rubber, sand, and ceramic the corresponding increased compressive strength by 10.6%, 14.64%, 20.23%, and 16.77%, and 50% as compared to 30% C&D waste. Without various waste materials, other components of the mixtures were not at a constant rate. To some of the mixtures, admixtures, fly ash, and silica fume were added.

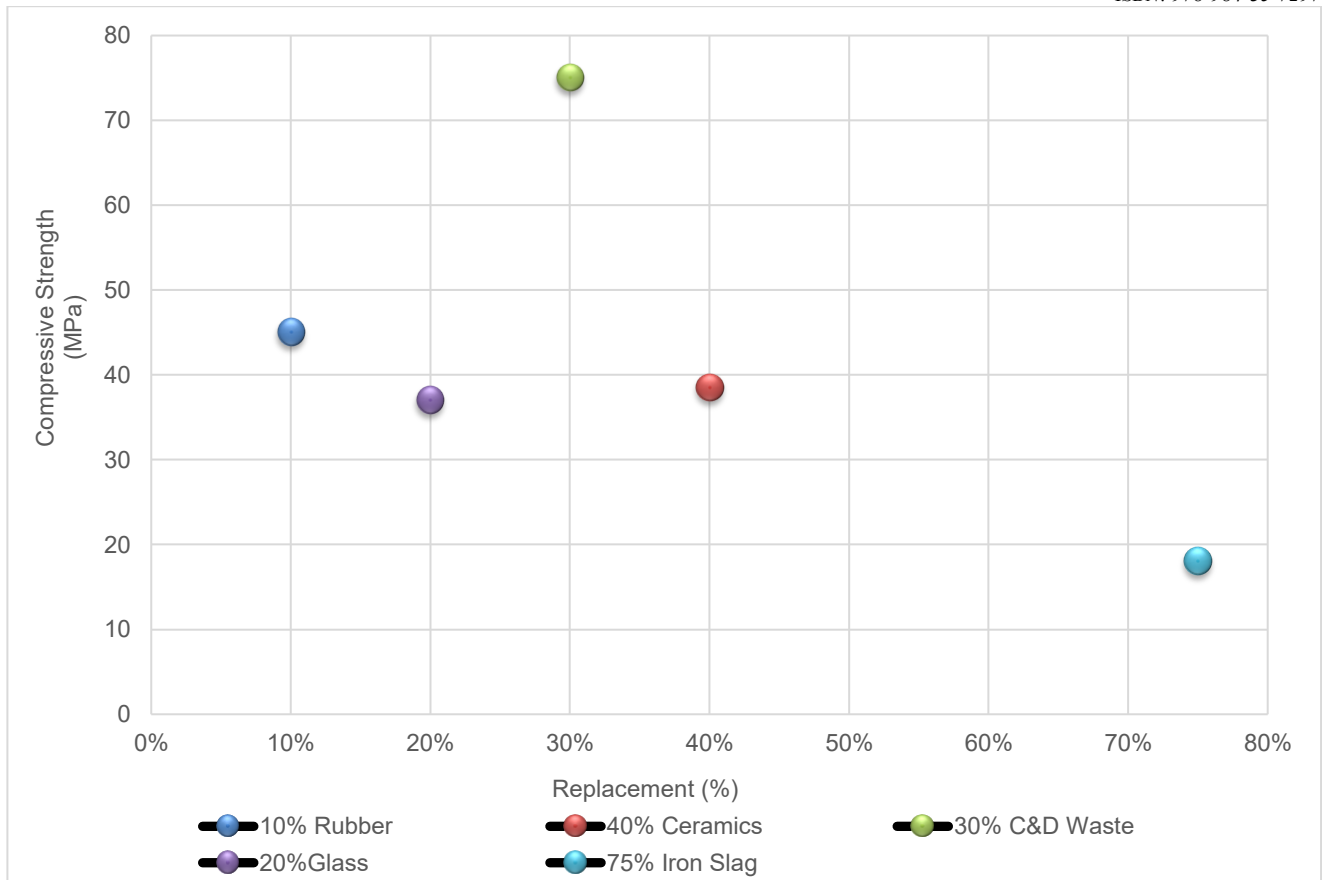


Figure 2 Effect of different waste materials as coarse aggregate replacement on compressive strength

SPLITTING TENSILE STRENGTH

Figure-3 represents the Splitting tensile of different waste materials as fine aggregate replacement in concrete production. In 30% of Ceramic waste, the highest compressive strength obtained was 3.75 MPa. The samples with glass (20%) and coarse aggregate (80%) had a Splitting tensile of 4.50 MPa. For iron slag, glass, rubber, sand, and ceramic the corresponding reductions in Splitting tensile are 10 %, 4%,3% 3.10%, and 4.70% as compared to 30% C&D waste.

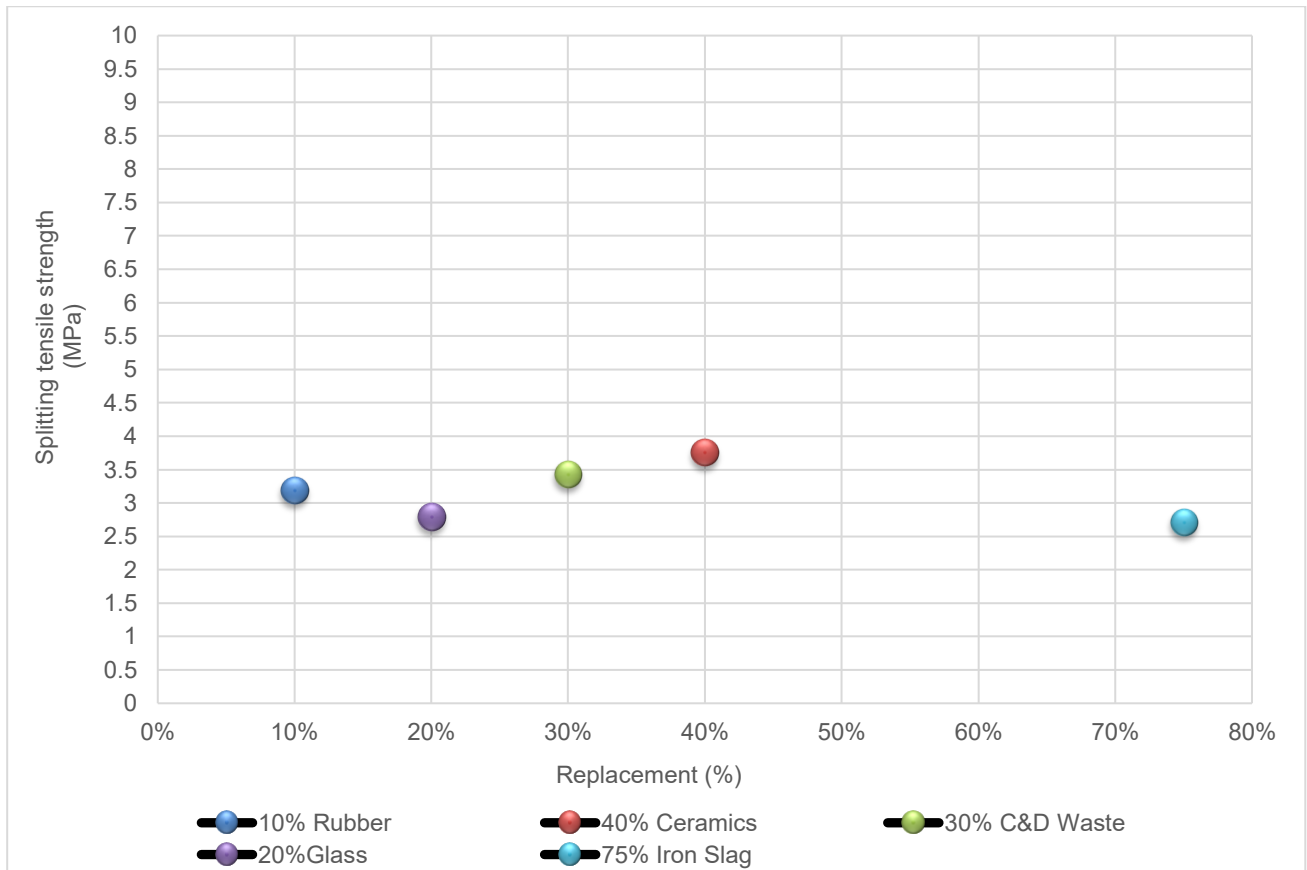


Figure 3 Effect of different waste materials as coarse aggregate replacement on Splitting tensile strength

FLEXURAL STRENGTH

Figure-4 represents the Flexural strength of different waste materials as fine aggregate replacement in concrete production. In 40% of ceramic waste, the highest compressive strength obtained was 5.67 MPa. The samples with rubber (10%) and coarse aggregate (90%) had a Flexural strength of 3.52 MPa. For iron slag, glass, rubber, sand, and ceramic the corresponding reductions in Flexural strength are 3.4 %, 3%,2.45% 4.11%, and 10% as compared to 30% C&D waste.

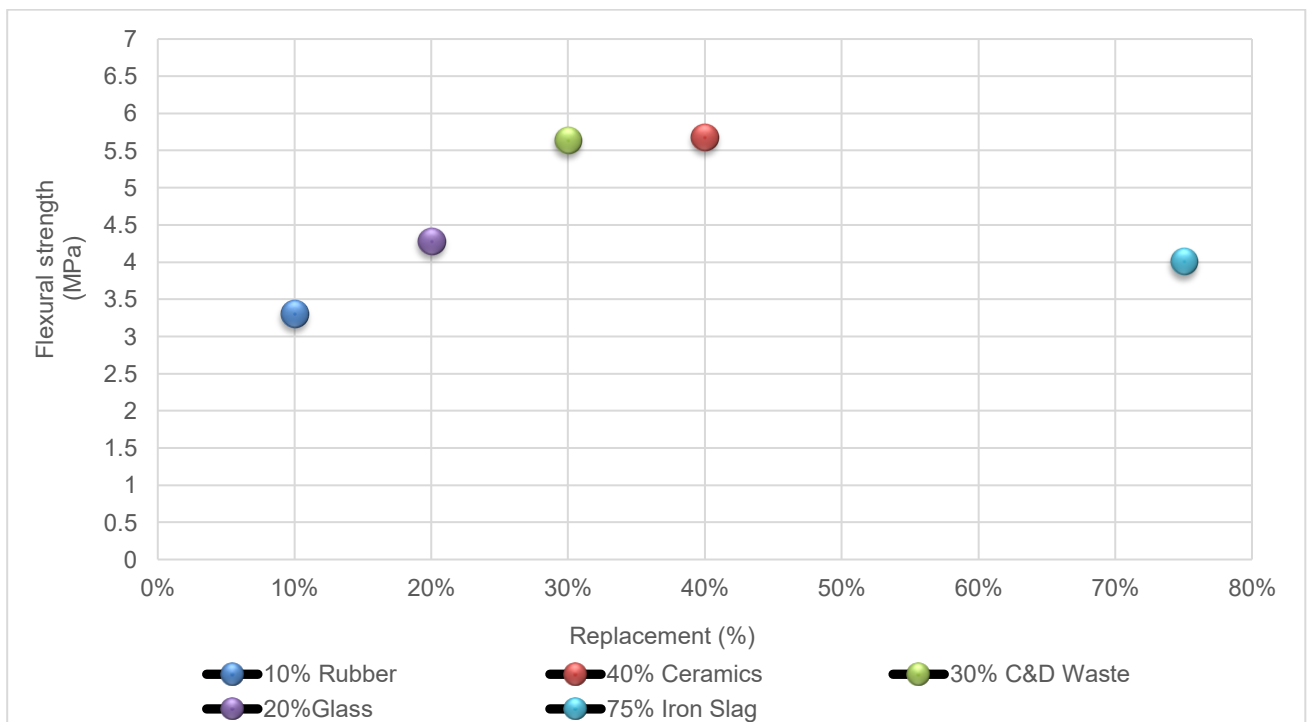


Figure 4 Effect of different waste materials as coarse aggregate replacement on Flexural strength

SUSTAINABILITY ASSESSMENT

ENVIRONMENTAL IMPACT

Table 7 indicates that the mixes with the lowest efficiency and embodied energy parameter are iron slag (15.82kg-CO₂/m³ /MPa & 94.84 MJ/m³ /MPa), ceramic (8.32 kg-CO₂/m³ /MPa & 50.49 MJ/m³ /MPa), C&D waste (18.91 kg-CO₂/m³ /MPa & 18.91 MJ/m³ /MPa), glass (9.97 kg-CO₂/m³ /MPa & 60.24 MJ/m³ /MPa) and rubber (1.24kg-CO₂/m³ /MPa & 1.67 MJ/m³ /MPa). The relationship between various mixtures' eco-strength efficiency (C_i) and compressive strength is shown in Figure 5, where lower values of C_i correspond to higher compressive strength and fewer CO₂ emissions into the surrounding environment. Comparably, less environmental impact is indicated by a lower E_f value along with massive compressive strength (Figure 6). Moreover, higher sustainability is indicated by lower values of C_i and E_f. Nonetheless, iron slag (18 MPa), ceramic (38.5 MPa), C&D waste (75 MPa), glass (37 MPa) and rubber (45 MPa) are shown to have the highest compressive strengths. By their strengths, iron slag and C&D waste are recommended for use. Although glass and rubber are substantially weaker, they are more environmentally friendly.

COST-BENEFIT ASSESSMENT

Table 7 shows the production costs for various mixes of partial replacement of fine aggregate by various waste materials. Glass and rubbers had the highest production costs and the lowest eco-strength efficiency of the five mixtures found in the environmental effect analysis. In contrast, C&D waste and iron slag exhibit higher eco-strength efficiency, high compressive strength, and cost-effectiveness. Between these two materials, C&D waste is preferred due to its lower environmental impact and production cost while maintaining compressive strength like iron slag. Thus, C&D waste is the most sustainable choice for the partial replacement of fine aggregate by various waste materials. Figure-7 shows the production cost of different waste materials with their embodied energy along with sand.

Table 6 Materials embodied energy and cost at the production stage

| Waste Materials | E-CO ₂ (kg/kg) | E. energy (MJ/kg) | Production cost (tk/kg) | Reference |
|-----------------|---------------------------|-------------------|-------------------------|-----------|
| Sand | 0.001 | 0.022 | 2.39 | [11] |
| Iron Slag | 0.011 | 0.01 | 2.8 | [39] |
| Cement | 0.83 | 4.8 | 11 | [11] |
| Water | 0.0002 | 0.022 | 2.23 | [11] |
| Ceramic | 0.0051 | 0.081 | 3 | [40] |
| C&D Waste | 0.0024 | 0.026 | 1.50 | [35] |
| Glass | 0.008 | 0.044 | 2.95 | [41] |
| CA | 0.0045 | 0.14 | 3.6 | [42] |
| Rubber | 0.0066 | 0.37 | 2.81 | [43, 44] |

Table 7 Literature on replacing coarse aggregate with various waste materials

| Waste Materials | E-CO ₂ (kg-CO ₂ /m ³) | E. energy (MJ/m ³) | Mixture production cost (tk /m ³) | Compressive Strength, f _c (MPa) | C _i (E-CO ₂ /f _c) (kg CO ₂ /m ³ /MPa) | E _f (EE/f _c) (MJ/m ³ /MPa) | Mixture Production Cost Index (tk /m ³ /MPa) |
|-----------------|---|--------------------------------|---|--|---|--|---|
| Iron Slag | 284.77 | 1707.26 | 7222.55 | 18 | 15.82 | 94.84 | 401.25 |
| Ceramic | 320.70 | 1944.20 | 8514.35 | 38.5 | 8.32 | 50.49 | 221.15 |
| C&D Waste | 230.96 | 1418.81 | 7901.65 | 75 | 3.07 | 18.91 | 105.35 |

| | | | | | | | |
|---------------|--------|---------|----------|----|------|-------|--------|
| Glass | 369.09 | 2228.99 | 9513.256 | 37 | 9.97 | 60.24 | 256.11 |
| Rubber | 50.41 | 75.04 | 295.42 | 45 | 1.24 | 1.67 | 6.56 |

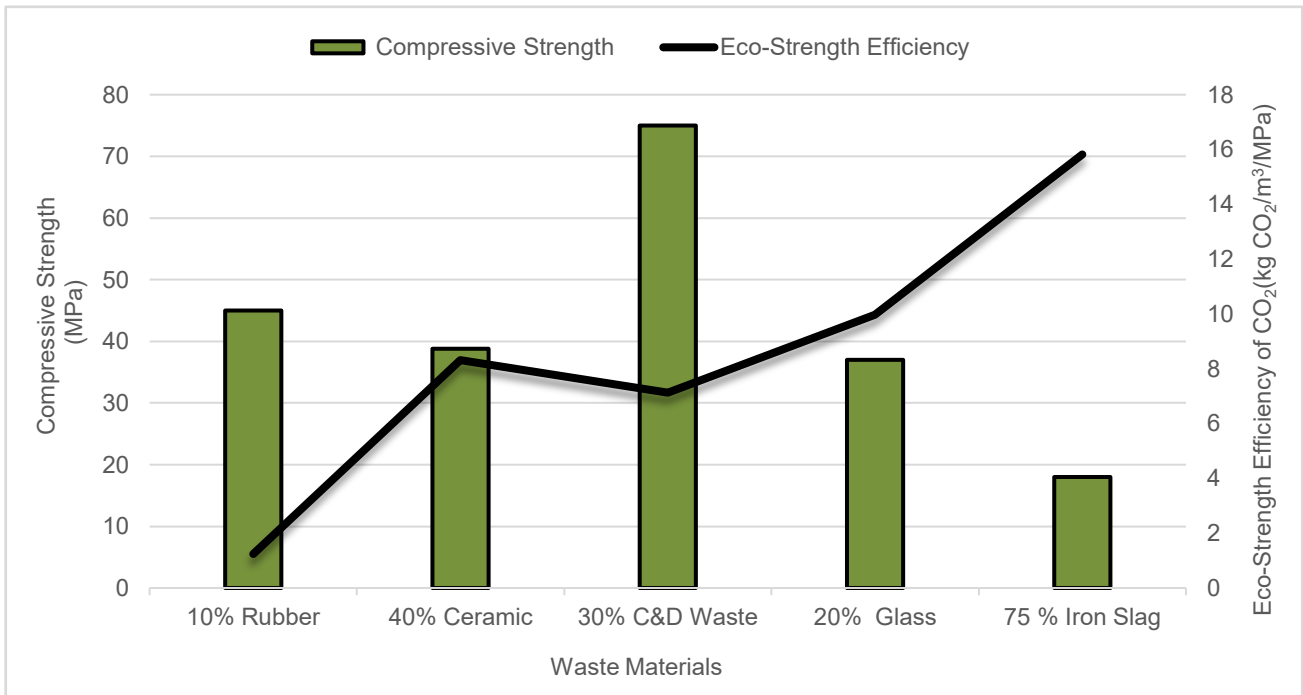


Figure 5 Eco-strength efficiency of CO₂ with respect to the compressive strength

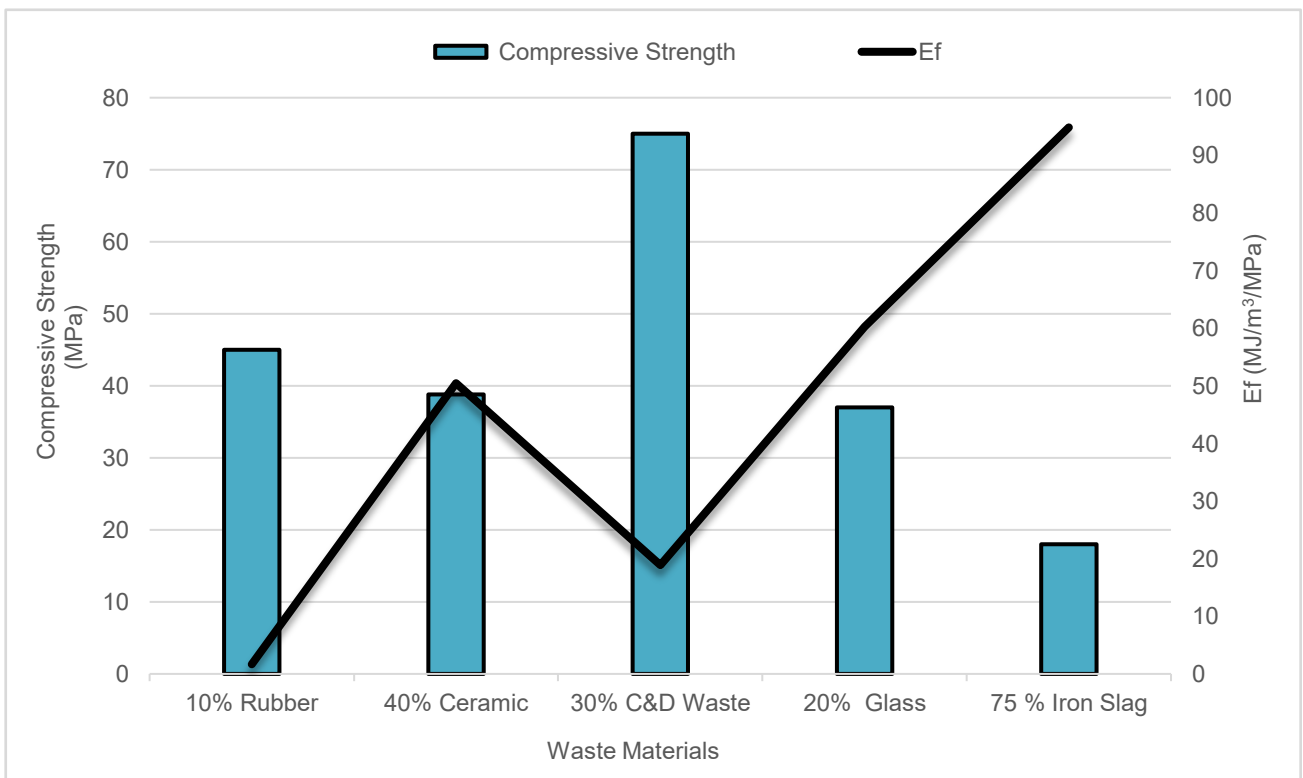


Figure 6 E_f (MJ/m³/MPa) with respect to the compressive strength

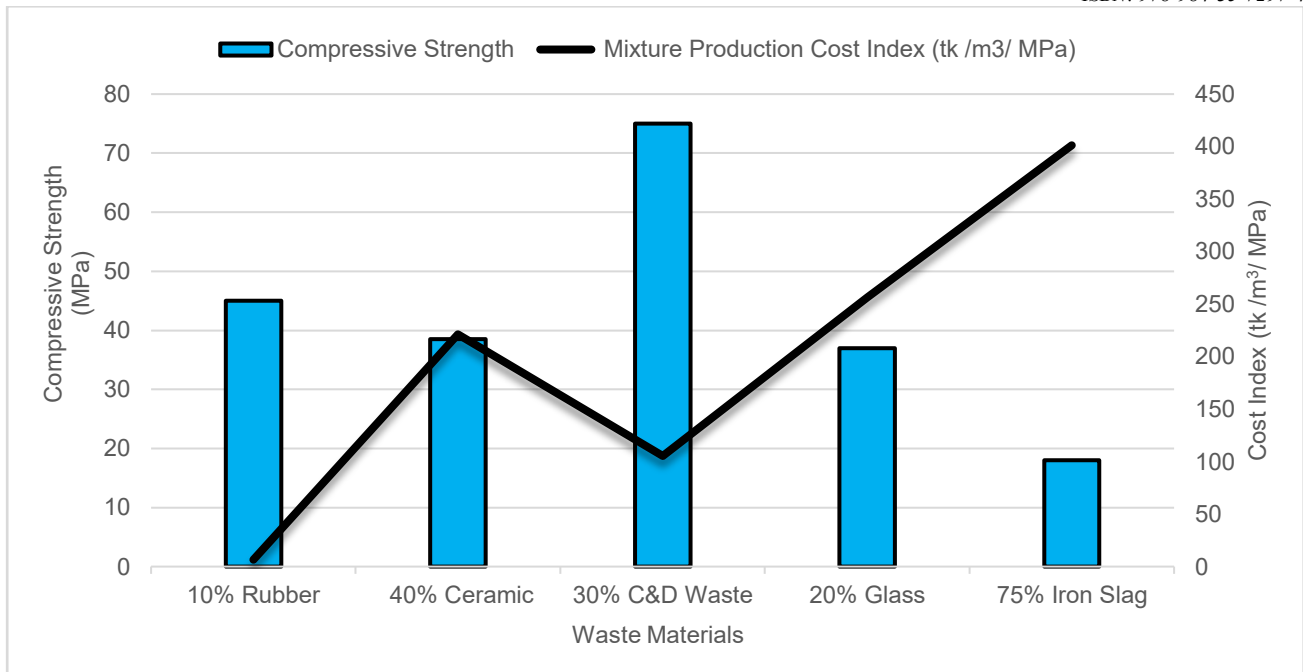


Figure 7 Mixture production cost index (tk/m³/MPa) with respect to the compressive strength

CONCLUSION

This paper provides an extensive review of the use of various recycled wastes as coarse aggregate substitutes in the production of sustainable concrete in the construction industry.

- Iron slag can be used as a coarse aggregate replacement when proper mix design ratios are maintained. Existing results indicated that iron slag can replace up to 75% of natural coarse aggregate, but iron slag using concrete has the lowest compressive strength (18 MPa) and maximum production cost compared to others. That's why, iron slag is not sustainable alternative of coarse aggregate.
- For ceramic waste replacement, compressive strength (38.5 MPa) is considerable compared to iron slag and also lower production cost. Considering flexural strength and splitting tensile strength, ceramic waste is the best recycled waste materials among all the waste materials mentioned above, making its suitable for coarse aggregate replacement.
- Construction and demolition waste can be used as an alternative of natural coarse aggregate in concrete production. 30% natural coarse aggregates can be replaced by construction and demolition waste having the maximum compressive strength (75 MPa) compared all the wastes. Also, it has lowest embodied energy and production cost compared to other wastes making it's the best partial waste material with coarse aggregate.
- Glass waste in concrete production yield a marginal decrease in the compressive strength (37 MPa) also production cost and embodied energy is higher than C&D waste. However, glass waste can replace up to 20% natural coarse aggregate without compromising the compressive strength of concrete.
- Rubber can be replaced up to 10% with natural coarse aggregate with compressive strength of 45 MPa. Also rubber has the minimum production cost and embodied energy compared to the among all wastes. Considering sustainability, rubber is the best partial replacement with coarse aggregate without compromising concretes compressive strength.

The above sections prove that the various recycled wastes can be easily used to replace certain percentages with the natural coarse aggregate in sustainable concrete production, thereby establishing a circular economy. Further research into using modern technology to recycle wastes and using waste materials in large-scale projects in a way that doesn't damage the concrete properties, resulting in low environmental clean-up, which can be a step towards sustainable growth, is required.

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