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Review Article

A review on sustainable aggregate replacements in concrete

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Abstract

Concrete is the most widely used construction material and comprises cement, water, fine aggregates, and coarse aggregates. Fine aggregates are primarily obtained from river sand extraction, while coarse aggregates are produced through the mining and crushing of natural stones. However, the excessive extraction of natural aggregates has resulted in environmental degradation and the depletion of natural resources. This review paper explores various sustainable alternative materials for the partial replacement of both fine and coarse aggregates in concrete with the aim of enhancing mechanical performance while conserving natural resources. The selected replacement materials include both industrial by-products and natural waste materials. Fine aggregate replacements reviewed in this study include copper slag, quarry dust, manufactured sand (M-sand), waste foundry sand, and waste glass powder, whereas steel slag, e-waste, coconut shells, recycled concrete aggregates, and ceramic waste are reviewed as coarse aggregate alternatives. The performance of these materials was evaluated using published experimental studies covering concrete grades ranging from M20 to M50. Mechanical properties, including compressive strength, split tensile strength, and flexural strength, were comparatively analyzed at different replacement levels together with reported workability characteristics. Based on the synthesized findings, the review identifies optimum replacement ranges, compares the performance of different sustainable aggregate materials, and highlights their potential to reduce the consumption of natural aggregates while supporting environmentally responsible concrete construction.

1. Introduction

Concrete is the primary construction material and is widely used throughout the world, serving as the backbone of modern infrastructure. After water, concrete is the second most extensively consumed material due to its versatility, durability, and cost-effectiveness. In developing countries such as India, the construction industry is one of the major contributors to economic growth, driven by rapid urbanization and infrastructure development [1]. This rapid expansion has significantly increased the demand for concrete and, consequently, for its primary constituents, namely cement, aggregates, and water. Among these, aggregates constitute the largest proportion of concrete.

Aggregates account for approximately 70% of the total volume of concrete and therefore play a vital role in sustainable construction. Traditionally, natural aggregates such as river sand, gravel, and crushed stone are obtained through the extraction of materials from riverbeds and rock formations. Fine aggregates are defined as materials passing through a 4.75 mm sieve, whereas coarse aggregates are retained on the same sieve. River sand has long been the most widely used source of fine aggregate. However, excessive extraction of river sand and large-scale quarrying of natural stone for coarse aggregates have resulted in environmental degradation, ecological imbalance, and depletion of natural resources. Consequently, the continued dependence on natural

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aggregates has raised significant sustainability concerns, highlighting the need to identify suitable alternative materials for concrete production [2].

Sustainable performance, in the light of this study, can be defined as the capability of an alternative aggregate to perform in accordance with engineering requirements and standards, at the same time using less amounts of natural materials, utilizing by-products from industries, or waste materials from construction, and decreasing the environmental effects of concrete.

Against this backdrop, considerable research has been undertaken to partially replace natural aggregates with industrial by-products, agricultural wastes, and construction and demolition wastes. Industrial by-products such as copper slag, steel slag, waste foundry sand, and waste glass have received significant attention because of their wide availability and favorable engineering properties. Similarly, natural wastes such as coconut shells and palm oil shells have been investigated as lightweight coarse aggregate replacements. Construction and demolition wastes, including ceramic waste and electronic waste (e-waste), have also been explored as alternative aggregates, offering the dual benefit of effective waste management and conservation of natural resources [3]. The utilization of these waste materials in concrete is particularly beneficial in developing countries such as India, where effective waste management practices are still evolving, as it helps reduce landfill disposal while minimizing environmental pollution.

In addition to their environmental benefits, numerous studies have demonstrated that alternative aggregate materials can influence the mechanical and durability performance of concrete. The physical characteristics and chemical composition of these materials play a significant role in determining their effect on concrete properties. Several waste-derived aggregates have shown improvements in strength and durability at optimum replacement levels. However, the reported findings are not always consistent because of differences in material characteristics, mix proportions, curing conditions, and testing procedures. Therefore, a critical synthesis of the available literature is more appropriate than a simple compilation of individual research findings. Although several review articles have discussed sustainable aggregate replacements in concrete, most existing studies have focused on individual replacement materials or specific performance aspects rather than providing an integrated evaluation of their mechanical performance, durability characteristics, and sustainability. Furthermore, recent developments in life cycle assessment, carbon footprint reduction, circular economy principles, and performance optimization across different concrete grades have not been comprehensively addressed in earlier review studies. As research on sustainable aggregate replacements continues to expand, there remains a need for a comparative and performance-oriented assessment that systematically evaluates the suitability of different replacement materials.

The present review aims to address these gaps by critically examining published research on sustainable materials used as partial replacements for fine and coarse aggregates in concrete. Particular emphasis is placed on the comparative evaluation of mechanical properties, workability, durability, microstructural characteristics, and sustainability aspects of the selected materials. By synthesizing findings from recent experimental studies, this review identifies the strengths, limitations, and optimum replacement ranges of various sustainable aggregate materials, thereby providing a comprehensive reference for their effective utilization in concrete production.

2. Materials

2.1 Coarse Aggregates

2.1.1 Steel Slag

steel slag is a by-product of the steel-making process, created when iron or scrap metal are melted along with fluxes like lime in an oxidizing environment. A significant amount of air or lime is injected together with other ingredients to create the slag [16].

Slag is usually a mixture of metal oxides and silicon dioxides. Its physical and chemical characteristics make it an extremely reactive aggregate. Slag-containing concrete may be incredibly strong and long-lasting. Slag can therefore be utilized in concrete. It serves as both a strengthening agent and a filler in concrete. Iron oxide and calcium oxide also mix with the furnace slag. A denser, stronger, and less permeable concrete is the outcome of both of these processes. Up to 50, 60, and 70 percent of the coarse aggregate in this slag concrete has been substituted with furnace slag. It raises a concrete mix's water requirement. A high range water reducer will be needed for high replacement rates [17].

Fig. 1. Steel slag [129]

2.1.2 Coconut Shells

Coconut shells are the most discarded agricultural byproduct. Across the India nearly 4.7 million tonnes of coconut shells are discarded annually. The coconut shells are light weight and also offers adequate mechanical strength. So, coconut shells can be used as replacement of aggregates.

Fig. 2. Coconut shells[130]

Coconut shells are collected from farms, oil mills. The shells are cleaned to remove the fiber and sundried for atleast 10days. Then the shells are broken in small pieces of the size of 12mm or 20mm of required aggregate sizes. The coconut shells are known as light weight aggregates. The coconut shells as aggregates can provide compression, flexural and tensile strength on the basis of the percentage of replacement. The concrete mix with 5%, 10%, 20% or 40% of coconut shell aggregate is known as light weight aggregate concrete (LWAC).

2.1.3 Recycled Aggregates

Cement concrete is the most important material in the concrete industry. The concrete consists water, cement, fine and coarse aggregates. But in present conditions, there is an acute shortage of aggregates due to over usage. Recycled aggregates (RCA) are the better alternative for aggregates in concrete. According to the Hindu India annually produces 23.75 million tons of trash. According to an overall analysis 5000 tons of building trash is discarded per day throughout India and south Asia [4].

The concrete structures are demolished due to man-made and natural disasters. Recycled aggregates are collected from the demolished structures. The recycled aggregates are crushed in to small pieces to get the required shape and size of aggregates. Later the aggregates are cleaned with water to remove contaminants, and oven dried to prevent from moisture. The recycled aggregates are replaced with coarse aggregates from 0% to 100%. Generally, 10%,20%,30% and 50% of RCA is partially replaced with coarse aggregates.

Fig. 3. Recycled aggregate [131]

2.1.4 E-Waste

E-Waste is the surplus waste collected from the broken electronic devices such as TV's, mobiles, computers, washing machine etc. Due to rapid technology growth and low initial cost the resulting the fast growth of electronic waste around globe [5]. According to statistics of 2005, India accumulated 146180 tonnes of e-waste. This geometrically progressed to 800000 tonnes as per 2012 statistics [6].

Fig. 4. E-waste [132]

Traditional methods like landfill and stock pile can't be used to decompose the e-waste as plastic is not environmentally friendly. The rapid increase of e-waste causing environmental pollution. To solve the disposal of large amount of e-waste, it is incorporated in concrete as a partial replacement of coarse aggregate [7]. The e-waste in concrete provides high strength and durability. The e-waste is collected and the excessive materials like copper wires, steel and magnesium are separated and plastic is cut into small particles approximate size of 20mm.

2.1.5 Ceramic Waste

The main sources of ceramic waste are ceramic industries, building construction and building demolition. In India the 30% of daily production of ceramic production goes under the ceramic waste. The ceramic waste is not recycled or decomposed in present days. The over accumulation of ceramic waste is creating environmental pollution [8].

Fig. 5. Ceramic waste [133]

The ceramic waste can be used in concrete as a coarse aggregate because of its strength and durable properties. The ceramic products are made up of natural materials which contains earth minerals. The top surface of the ceramic tiles or waste is smooth and the remaining surfaces are rough and flaky. The ceramic waste is collected from the industries and chopped them into 20mm size to partially replace coarse aggregates. In some studies, ceramic waste powder is used as partial replacement of cement.

2.2 Fine Aggregates

2.2.1 Copper Slag

Copper slag is generated during pyro-metallurgical production of copper. copper ores consist materials such as alumina, calcium oxide, silica, etc. For every tonnage of metal production, about 2.2 tonnes of slag is generated. Such massive disposal of slag can cause environmental issues. The usage of copper slag in concrete is a sustainable alternative for the disposal of copper slag [9].

Fig. 6. Copper slag [134]

The fine aggregates can be partially replaced with copper slag with rates of 0% to 80%. The results described that the workability of cement increased with the increment in the rate of copper slag. The compressive, split and flexural strength of concrete is increased by copper slag substitution. Additionally, the durability of the concrete is improved [10].

2.2.2 M- Sand

Manufactured sand is quarry dust or crushed stone which is sieved to bring in to required size of a natural sand so as to be used as fine aggregate. It is also known as M-sand [11]. The properties of M-sand are very similar to natural sand. Due to the limiting sources of the natural sand, M-sand is used as a replacement of fine aggregate [12].

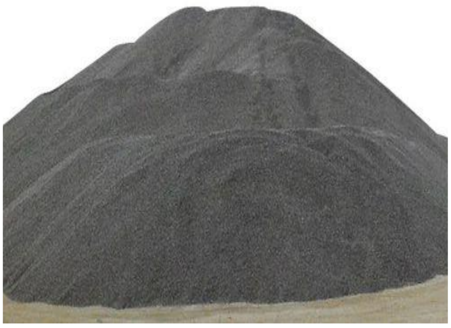

Fig. 7. M Sand [135]

M-sand is the easiest and cheapest replacement of natural sand due to the easy availability of plenty of crushed stones at every location. The mechanical properties of the concrete are increased when M- Sand is incorporated in concrete at various levels. But, the workability of the concrete is decreased with higher replacement of M-sand. It reveals that higher replacement of M-sand requires high amount of water. admixtures are added in to concrete to maintain desired workability [13].

2.2.3 Waste Foundry Sand

Foundry sand is used to cast the ferrous and non-ferrous metals in industries. This sand will be recycled and reused for several times. After certain usage the sand is not used for casting of metals and disposed as waste foundry sand. This industrial by products are non-biodegradable. so, it is expensive to dispose large quantities of waste foundry sand [14]

Fig. 8. Waste foundry sand [136]

The properties of waste foundry sand are mostly similar to the river sand. The waste foundry carries 95% of ferrous content and high quality silica. Replacement of foundry sand can provide high durability and strength properties [15].

2.2.4 Quarry Dust

Quarry dust is the industrial by-produced generated from the crushing granite stones. The disposal of the quarry dust is critical due to environmental issues. It consists of fine, angular particles rich in silica and the properties of quarry dust is similar to natural sand [16].

Fig. 9. Quarry dust [137]

Due to its low cost and potential to improve strength and durability of concrete it is used as a fine aggregate replacement in concrete. Quarry dust consists very fine particles which fills the voids and pores of concrete to improve the concrete durability.

2.2.5 Waste Glass Powder

Glass is the one of the versatile materials in world which can be used in different applications and can be recycled several times [3]. The amount of glass waste generating through glass bottle industries is increasing 0.7% annually in India [2].

Fig. 10. Waste glass powder[138]

Waste management became severe issue in present days, using waste glass powder in concrete is an innovative technique to dispose the waste glass. The composition of glass contains silica oxide, sodium oxide and calcium oxide. The glass as a fine aggregate contributes high density of concrete by reducing pore system and generating higher durability properties. The waste glass powder utility develops the mechanical properties of concrete. The waste glass preferred as an aggregate is crushed and carefully made in to tiny pieces to incorporate in concrete [1].

3. Research Framework and Methodology

3.1 Research Gap

Although several studies and review articles have investigated sustainable aggregate replacements in concrete, most of the available literature primarily focuses on individual waste materials or isolated mechanical properties. Limited attention has been given to comparative evaluation across multiple sustainable aggregate systems under varying concrete grades and replacement levels. Previous studies frequently focus on compressive strength, but tend to discuss workability properties, performance variations, and structural/non-structural application practicability as secondary features. As such, a complete synthesis of the various aspects of the mechanical performance of concrete, workability characteristics, optimal replacement ratios for different types of aggregates, and sustainability related considerations are generally found within a singular conceptual framework.

3.2 Novelty of The Study

The current review is an attempt to perform a comprehensive and systematic comparison of all sustainable alternatives to aggregates for use in concrete through the integration of results from many separate laboratory-based investigations. This study has compared the workability (e.g., flowability) and engineering properties (i.e., strength) of several types of aggregate replacements at various replacement ratios as well as for different concrete grade designations. Additionally, this study has identified the most appropriate levels of replacement that produce optimal performance characteristics, has examined the variations in the individual research findings, and will compare the relative performance of the aggregate replacements to assist in selecting suitable aggregate replacement materials. Finally, this study addresses the broad environmental implications related to natural resources conservation and waste utilization to provide additional insight into the feasibility of using alternative aggregates in concrete construction applications.

3.3 Objectives of The Review

The objective of this review is to investigate how well sustainable aggregate replacement materials perform as a substitute in concrete. The goals of this review are to:

- Analyze how several types of aggregate replacement material affect compressive, split-tensile, and flexural strengths of concrete.
- Examine the behavior of the workability of concrete made with various forms of sustainable aggregate replacements;
- Find optimal replacement ratios for different mixes and grades of concrete.
- Compare the overall performance of each type of replacement material by comparing data from experiments
- Examine and discuss both the practicality and the sustainability aspects of using alternative aggregate sources in producing concrete.

3.4 Methodology Of Literature Review

A systematic and structured approach for the literature review was followed in this study for the purpose of transparency, repeatability, and scientific integrity. The literature search for this study was carried out using the prominent online academic databases of Scopus, Web of Science, and Google Scholar, indexing top-quality peer-reviewed literature in the realms of construction materials science, sustainability studies, and civil engineering. Other relevant literature was also traced by browsing the citation lists of crucial research and review articles.

The searching process was done using selected keywords and their combination, such as sustainable aggregates, aggregate replacement in concrete, recycled aggregates, industrial by-products, agricultural waste materials, mechanical properties, carbon footprint, and circular economy in construction. Boolean operators were applied to increase the relevance of the searching process. The main focus of the study was on the literature published between the years 2009 and 2025. In order to improve the level of the review, a list of explicit inclusion and exclusion criteria was developed to be considered in the course of the article selection. Only journal articles reviewed by peers and published in the English language were considered for the purpose of the analysis. Papers which studied the partial or complete substitution of aggregates by finer or coarser ones in the course of experimental research on the outcome of the studied materials in regard to their strength characteristics and environmental impacts were included.

The screening of the literature was done through three phases. First, the titles were screened for removing obviously non-relevant literature. This was followed by abstract screening for determining the relevance of the literature within the scope of the systematic review. Then, full text screening was performed to ensure that only the literature that fulfilled the identified inclusion criteria and was methodologically sound was included. This ensured that selection bias was reduced. From the chosen literature, the relevant information was picked using the inclusion criteria, which included the nature of the aggregate replacement material, the level of replacement, proportions, mechanical characteristics such as compressive, tensile, and bending strengths, environmental characteristics such as water absorption, permeability, resistance to sulfate, and chlorides, as well as microscopic observations carried out by scanning electron microscopes. Other environmental characteristics, such as reduction in carbon emissions, embossed energy, and efficiency in waste utilization, were also picked. Based on their nature, the information was categorized into industrial by-products, agricultural wastes, and recycled construction waste.

The analyzed data was then carefully examined to find trends and ranges involved in the optimization of replacement of the mechanical properties and sustainability. Instead of writing a narrative review, a comparative synthesis analysis has been carried out to compare the results of various studies and understand variations, inconsistencies in the results. Special focus has been made on correlating the microstructural properties and variations in the mechanical properties and sustainability. Also, on understanding the sustainability benefits through life cycle assessment and carbon footprint analysis. This literature review focuses solely on aggregate replacement materials that can be used for structural concrete as well as non-structural concrete. Even though environmental factors like carbon footprint and energy content were considered for comparison, it should be noted that comparisons among different studies for such factors might be affected by differences in system boundaries, functional units, as well as geographical datasets for life cycle assessments.

3.5 Inclusion and Exclusion Criteria

The selection of studies was performed in a systematic manner to ensure the relevance and reliability of the literature reviewed. Only peer-reviewed journal articles describing sustainable materials for aggregate replacement in concrete were eligible for inclusion in the review. Workability, compressive, split tensile, flexural and sustainable performance characteristics were included. Conference proceedings, theses, duplicate studies and articles with insufficient data were excluded from the review. A total of 170 research papers were initially gathered by searching several databases. Following initial selection and elimination of unrelated studies, 150 articles were identified for detailed evaluation. Ultimately, 136 journal articles meeting the criteria for inclusion were selected for the present review.

3.6 Quality Assessment of Research Papers

The quality and appropriateness of the selected studies were assessed with respect to several criteria, including degree of clarity of experimental methodology, availability of mechanical and workability test results, definition of replacement levels and consistency of reported results. Priority was given to studies reported in peer-reviewed journals with well-defined properties of concrete mixtures, conditions of curing and methods of testing. Studies with inadequate details of methodology or with incomplete results were excluded from the final analysis. Consequently, the comparative interpretations and integrated conclusions of this review were based on a reliable and technically appropriate body of literature.

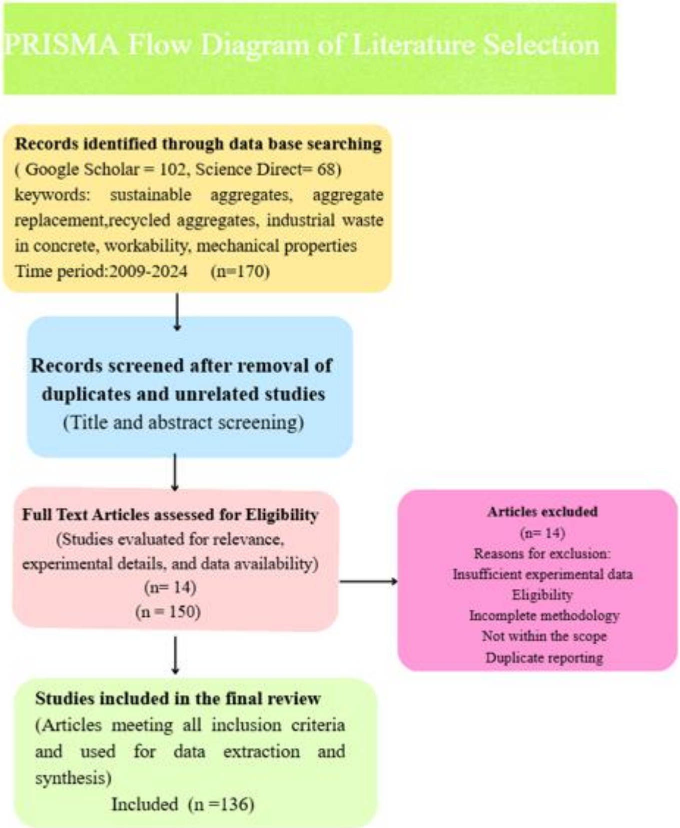

Fig. 11. PRISMA-based flow diagram of literature selection process in the present review

Table 1. Summary characteristics of the studies included in the study

Parameter	Description
Type of review	Literature review of sustainable aggregate replacement materials in concrete
Publication period	2009-2024
Databases used in the study	Google Scholar and Science Direct
Initial studies identified	170
Studies screened	150
Final studies screened	136
Type of publications	Peer-reviewed journal articles
Aggregate replacement materials reviewed	Steel slag, coconut shell, recycled aggregates, e-waste, ceramic waste, copper slag, M-sand, waste foundry sand, quarry dust, and waste glass powder
Concrete grades reviewed	M20 to M100
Replacement levels reviewed	0 to 100%
Properties evaluated	Workability, Compressive strength, Split tensile strength, and Flexural strength
Common curing periods	7 and 28 days
Common testing standards reported in literature	IS, ASTM, and equivalent international standards
Main objective of reviewed studies	Evaluation of sustainable aggregate replacements for improving resource efficiency and reducing environmental impact in concrete production

The principal features of the selected researches presented in this review are shown in Table 1. The literature selected includes a wide variety of alternative aggregate materials and grades of concrete used and different aggregate substitution levels recorded from 2009 to 2024. The main objectives of the studies under review were aimed at investigating the workability and mechanical properties of the materials tested including compressive, splitting tensile, and flexural strength. The majority of experiments involved a period of curing of 7 and 28 days using national or international testing standards.

4. Workability Studies

4.1 Steel Slag

The value of 653 mm represents slump-flow measured for self-compacting concrete as reported in the original study. However, from the research works listed under Table 2, it is revealed that steel slag causes a negative effect on concrete workability when mixed to a lower to moderate content percentage because of their angular shapes and higher water demand requirements. Satisfactory workability of concrete is generally attained only up to 10 to 30% replacement levels after which a certain decrement of slump is noticeable while preparing normal concrete mixes. However, for optimized concrete mixes of higher grades, certain positive benefits of particle packing and use of chemical admixtures may overcome this difficulty and provide satisfactory workability even up to higher replacement levels.

Table 2. Workability studies of steel slag

Authors	Grade And Replacements Levels	Optimum Levels	Workability Measurement (mm)
Sunidhi.R et al. [19]	M 25 (0% to 20%)	Up to 20%	76
V. subhathra devi et al. [20]	M20 (0% to 30%)	Up to 10%	22
Anifowose et al. [21]	M 20 (0% to 50%)	50%	35
Md jihad miah et al. [22]	M 30 (0% to 100%)	Up to 30%	210
G. Harsha et al. [23]	M 30 (0% to 40%)	Up to 20%	61
Aishwarya bhat et al. [24]	M 40 (0% to 50%)	50%	653

4.2 Coconut Shells

From the results shown in Table 3, the use of coconut shell as a coarse replacement tends to reduce the workability of concrete, and acceptable consistency values are only noted at relatively low replacement levels, typically not exceeding 5-10% replacement levels. It is mainly due to the lightweight and porous nature and relatively higher water absorption characteristics of the used coconut shells. At higher replacement levels, the workability values tend to reduce substantially, and sometimes the addition of water or admixtures might be necessary to make the mix workable.

Table 3. Workability studies of coconut shells

Authors	Grade And Replacements Levels	Optimum Levels	Workability Measurement (mm)
Alif syazani et al.	M 35 (0% to 15%)	5%	50
B. Naraindas et al. [30]	M 25 (0% to 25%)	Up to 10%	43
K. Gunasekaran et al. [31]	M 25 (0% to 100%)	Up to 70%	50
B. Damodhar reddy et al. [32]	M 30 (0% to 20%)	5%	23
B. Ranjitha et al. [32]	M 20 (0% to 30%)	10%	73
S U Azunna et al. [33]	M 30 (10% to 30%)	30%	5

4.3 Recycled Aggregates

The references cited in Table 4 above demonstrate that the workability of concrete containing recycled aggregates depends largely on the level of substitution, properties of aggregate, and grade of concrete. At low to moderate levels of substitution, the workability of concrete was found to reduce since the water absorption, surface texture, and the adhered old mortar of the recycled aggregates lead to increased internal friction and water demand. At a higher grade of concretes, there are instances where a satisfactory workability has been achieved at a higher level of substitution when adequate paste volumes and chemical admixture are used in concretes. But significant variation in the published results indicates the dependence of workability of recycled aggregate concretes on processes and mix control. From the synthesized literature, it can be concluded that the satisfactory workability of concretes can be achieved by recycled aggregates of around 10% to 30% in concretes of grade M30 to M40 grades, while for higher substitution levels, mix optimization should be carefully carried out.

Table 4. Workability studies of recycled aggregates

Authors	Grade And Replacements Levels	Optimum Levels	Workability Measurement (mm)
M. Subhamkar et al. [40]	M 25 (0% to 100%)	Up to 50%	73
Yong, P.C. et al. [41]	M 40 (50% & 100%)	100%	55
N. Siva kumar et al. [43]	M 40 (0% to 50%)	25%	80
Md. Saffiuddin et al. [45]	M 40 (0% to 100%)	Up to 100%	250
Cun hui et al. [42]	M 60 (0% to 60%)	20%	120
V. Joseph et al. [44]	M 30 (0% to 100%)	Up to 100%	60

4.4 E-Waste

The above studies represented in Table 5 provide an indication that the use of e-waste as an aggregate replacement affects the workability of concrete adversely due to the smooth surface texture, low stiffness, and irregular shape of e-waste particles. At lower levels of replacement, workability is possible, especially within higher grades of concrete due to the higher paste content and chemical admixtures used. At higher levels of replacement, workability is reduced significantly due to poor cohesion and susceptibility to segregation. To achieve acceptable workability, the evidence suggests that e-waste needs to be replaced at levels of around 5-15% for M30 to M60 grades of concrete, at which higher levels of replacement, extensive mix design modifications are required.

Table 5. Workability studies of E-waste

Authors	Grade And Replacements Levels	Optimum Levels	Workability Measurement (mm)
Prince singh et al. [51]	M 20 (0% to 15%)	15%	54
S. Needhidhasan et al. [52]	M 60 (0% to 16%)	Up to 16%	229
Chandan kumar et al. [54]	M 30 (0% to 12%)	Up to 12%	48
H. pawan et al. [55]	M 60 (0% to 60%)	Up to 15%	70
Sunil. A et al.	M 40 (0% to 30%)	Up to 25%	70
B. Shilpa et al. [53]	M 25 (0% to 30%)	30%	74

4.5 Ceramic Waste

From the investigations presented in Table 6, it could be revealed that ceramic waste has moderate workability properties with acceptable consistency over wide replacement amounts. Crushed ceramic particles are expected to be more irregular in shape with higher hardness, contributing to higher internal frictions.

Table 6. Workability studies of ceramic waste

Authors	Grade And Replacements Levels	Optimum Levels	Workability Measurement (mm)
D.J. Anderson et al. [63]	M 40 (20% to 100%)	35%	80
V. Giridhar et al. [64]	M 20 (0% to 100%)	Up to 40%	110
Basim et al. [66]	M 25 (0% to 50%)	Up to 50%	81
O. Paul et al. [61]	M 20 (0% to 100%)	Up to 50%	100
E. E. Ikponmwosa et al. [62]	M 25 (0% to 100%)	Up to 75%	80
Sherin khan et al. [65]	M 30 (0% to 50%)	Up to 30%	64

However, it can be noticed that the lower water absorption coefficient combined with higher density of ceramic waste reduces the loss of workability. In some investigations, workability could be possible at higher amounts of replacement, especially in higher concrete grades where higher paste content exists. Variations in workability properties are mainly related to variations in particle sizes, types of ceramic, and mix variables. From the synthesized data, it can be realized that ceramic waste could achieve acceptable workability characteristics at replacements ranging from 20-40% in M25 to M40 grade concrete workability, but at higher amounts of replacement.

4.6 Copper Slag

The results represented in Table 7 reveal an overall positive effect or sustaining effect for the concrete workability over a wide range of replacement levels because of the smooth surface nature and the low water-absorbing capacity of the copper slag. The result at a relatively higher replacement rate indicates a positive effect in terms of the increased flow ability and packing efficiency because of the medium to high strength concrete. In contrast, the results show adverse effects at higher substitution levels above the medium range because the copper slag has higher densities and decreased cohesion, resulting in variable effects on concrete workability. According to the synthesized result, the copper slag can obtain effective concrete workability only through the replacement levels in the range of 20-50% for M30 to M60 grade concrete.

Table 7. Workability studies of copper slag

Authors	Grade And Replacements Levels	Optimum Levels	Workability Measurement (mm)
K.S. Al-jabri et al. [71]	M 45 (0% to 100%)	Up to 50%	130
J. Anne mary et al. [73]	M 20 (0% to 100%)	40%	83
Wu et al. [74]	M 55 (0% to 100%)	20%	75
S. chithra et al.	M 30 (0% to 3%)	2%	42
Maria. M et al. [75]	M 30 (0% to 100%)	20%	225
K.S. Al-jabri et al. [72]	M 60 (10% to 100%)	80%	28

4.7 M-Sand

From the research works listed in Table 8, it can be inferred that the workability of concrete is most influenced by particle shape, fine contents, and concrete grade when M-Sand is considered. Because of their angular nature and higher percentage of micro-fine particles, M-Sand generally decreases the workability of lower to medium grades of concrete when blended solely on their replacement levels or without using chemical admixtures. However, for medium to higher strength concrete, workability levels varying from satisfactory to higher have been reported over a broad replacement level when blended either solely on replacement levels or with the use of chemical admixtures. Variations in reported values of concrete slump testing bring out the need for careful control of fine contents and water demand. From the available collective research works, M-Sand can provide satisfactory workability when blended on a replacement basis of 25-50% for M25 to M40 grades of concrete, and 100% replacement is possible for M50 grades and higher concrete when optimized accordingly.

Table 8. Workability studies of M-Sand

Authors	Grade And Replacements Levels	Optimum Levels	Workability Measurement (mm)
A. Nadimalla et al. [81]	M 20 (0% to 100%)	Up to 100%	100
M. Yajurved et al. [83]	M 30 (0% to 100%)	Up to 20%	27
S.S. Saravanan et al. [84]	M 60 (0% to 100%)	Up to 100%	85
Nadimalla. A et al.	M 30 (0% to 100%)	25%	28
T. Mounika et al. [82]	M 25 (0% to 50%)	Up to 30%	80

4.8 Waste Foundry Sand

From the investigation results compiled in Table 9, it is found that the workability of concrete tends to decrease as the replacement level of waste foundry sand is raised, largely because of the finer size, higher surface area, and higher water demand of waste foundry sand. However, at lower to medium levels of replacement, workable mixtures can be developed, especially when waste foundry sand is properly sized and devoid of excess clays and binders. At higher levels of replacement, the resultant increase in the quantity of fines results in poor flowability, higher internal friction, and compaction problems, which are more pronounced in lower-grade concrete. Differences in workability trends among various studies can be ascribed to the different types of foundry sand, casting processes for metals, and levels of fines content. Based on the evidence compiled from various studies, waste foundry sand can attain desirable workability at replacement levels of around 10-25 percent for M25 to M40 concrete types, while at higher levels of substitution, workability needs to be ensured through controlled grading and mixing.

Table 9. Workability studies of waste foundry sand

Authors	Grade And Replacements Levels	Optimum Levels	Workability Measurement (mm)
B. Sanjay kumar et al. [90]	M 25 (5% to 25%)	Up to 20%	60
K. Jamee et al. [93]	M 30 (0% to 60%)	Up to 35%	73
S. Dileep kumar et al. [92]	M 25 (0% to 25%)	Up to 20%	105
A. Naveen et al. [91]	M 30 (0% to 20%)	Up to 15%	30
Garcia del angel. G et al. [94]	M 40 (0% to 100%)	Up to 25%	14
H. Bilal et al. [96]	M 20 (0% to 40%)	Up to 20%	30

4.9 Quarry Dust

Generally, as seen from Table 10, quarry dust reduces the workability of concrete with an increase in the replacement level, which is attributed to its angular particle shape, higher fins content, and high surface area that altogether increase water demand and internal friction. For low replacement levels, workable mixes can be obtained, especially if the quarry dust is well graded and adequate paste content is used. Beyond the moderate replacement level, excessive fins often impair flowability and compactability, particularly in the case of low-grade concretes, unless either mix design modification or chemical admixture incorporation is practiced. Variations in the reported trends in workability can be related to differences in quarry dust gradation and fins percentage. The synthesized evidences suggest that quarry dust can achieve workability similar to that obtained from conventional concrete as long as it is used at a replacement level of about 10-20% in M25-M30 grade concretes, though a higher replacement ratio demands careful control of grading combined with support from mix design or chemical application.

Table 10. Workability studies of quarry dust

Authors	Grade And Replacements Levels	Optimum Levels	Workability Measurement (mm)
Mahendra. G et al. [111]	M 30 (0% to 50%)	Up to 20%	56
Fayaz et al. [112]	M 30 (0% to 100%)	Up to 20%	44
Fayaz et al. [112]	M 20 (0% to 100%)	Up to 20%	45
D. Biswa Prakash et al. [100]	M 25 (0% to 100%)	Up to 60%	62
Ambrose et al. [101]	M 20 (0% to 50%)	Up to 20%	170
Md. Iqbal et al. [113]	M 25 (0% to 40%)	Up to 10%	55

4.10 Waste Glass Powder

The above studies, as presented in Table 11, clearly show that waste glass powder manages to retain and, in some cases, even improve workability, especially up to a moderate level of supplement, because of its smooth texture, low water absorption, and micro filler role. But in higher grades, workability levels have been acceptable over a broad spectrum of supplementation, which can be attributed to the fine nature of glass, which acts as a better paste lubricant. Higher levels of supplementation, however, have been noticed to reduce workability, especially in low-grade concretes, which lack sufficient paste. Accordingly, based on the evidence synthesized, waste glass powder can help in obtaining sufficient workability at around 20–30% supplement levels in M30-M60 grades, while in low grades, higher levels of supplement would be more prudent.

Table 11. Workability studies of waste glass powder

Authors	Grade And Replacements Levels	Optimum Levels	Workability Measurement (mm)
G. Lalitha et al. [120]	M 60 (0% to 40%)	30%	155
S. Arivalagan et al. [121]	M 20 (0% to 30%)	20%	72
D. Swarna et al. [122]	M 30 (5% to 30%)	20%	36
S. Abdallah et al. [125]	M 30 (0% to 20%)	5%	65
Md. Nabi khan et al. [126]	M 60 (0% to 100%)	Up to 100%	130
P. Lavanya et al. [124]	M 20 (0% to 40%)	Up to 30%	40

Table 12. Optimal workability grade and replacement level of sustainable aggregate replacements

Aggregate replacement material	Concrete grade with acceptable workability	Optimal replacement level for workability	Workability trend
Copper slag	M30–M60	30–50%	Improves workability
M-Sand	M25–M60	40–100%	Maintains to slightly reduces
Steel slag	M30–M60	10–30%	Slight reduction
Ceramic waste	M25–M40	20–30%	Slight reduction
Waste glass powder	M30–M60	20–30%	Maintains workability
Waste foundry sand	M25–M40	10–30%	Slight reduction
Quarry dust	M20–M40	25–40%	Moderate reduction
Recycled aggregates	M25–M40	10–20%	Moderate reduction
E-waste	M30–M60	5–15%	Significant reduction

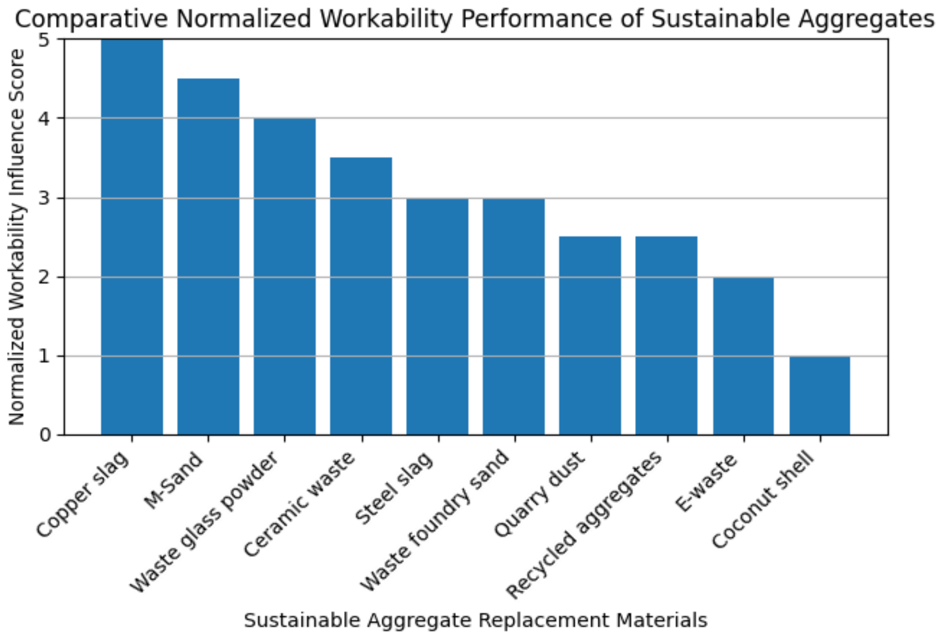

Fig. 12. Workability performance

5. Mechanical Properties

5.1 Steel Slag

In the examined literature works, steel slag has proved its effectiveness as a replacement for coarse aggregates regarding the development of compressive strength, split tensile strength, and flexural strength. The range where maximum development can be achieved using steel slag as replacement for coarse aggregates has been identified as approximately 25% to 45%. Enhanced development of compressive strength is more distinct than split-tensile strength and flexural strength. This may be attributed to the high angularity, high surface texture value along with higher density of steel slag. Moderate development can be seen in split-tensile strength and flexural strength. This may be attributed to better interlocking properties along with load distribution characteristics.

Table 13. Mechanical properties of steel slag

Authors	Grade And Replacements Levels	Optimum Levels	Strength Achieved (N/Mm^2)		
			Compression Strength	Split Tensile Strength	Flexural Strength
Amjad A. Sharba et al. [25]	M40 (0% to 45%)	25%	43.94	5.39	4.14
S. piraimathi. [26]	M40 (10% to 40%)	30%	59.01	-	4.92
Zahid rasool bhat et al. [27]	M35 (0% to 60%)	45%	44	4.88	4.89
K.L. ravi shankar et al. [28]	M30 (0% to 50%)	30%	38.29	-	-
V. subhathra devi et al. [20]	M20 (0% to 30%)	30%	21	2.5	4
Md jihad miah et al. [22]	M30 (0% to 100%)	Up to 100%	34.98	3.38	-
Sunidhi.R et al. [23]	M25 (0% to 20%)	15%	42.03	4.4	4.6
P. vasanthi [24]	M30 (0% to 100%)	60%	35.55	-	3.43

However, beyond the optimum range of steel slag, an increase in the amount of steel slag beyond the said range does not always ensure additional strength improvement and could potentially result in a slight degradation of tensile and bending strength. This particular behavior of steel slag could be largely attributed to the rheological constraints and the formation of free lime. Moving on, the discrepancies in the split tensile strength and bend strength results obtained by various studies clearly illustrate the design constraints and processing aspects of steel slag. Based on the synthesized results, the use of steel slag, being a sustainable material, could be considered highly effective in the reinforcement of structural concrete, but care should be taken to avoid degradation beyond the optimized range of steel slag content.

5.2 Coconut Shells

From the above studies presented in Table 14, it may be concluded that the use of coconut shell could be very effective in the partial replacement of natural coarse aggregates in low to moderate strength concretes, and the optimal content of such aggregates could vary from 5 to 15 percent. However, the compressive strength of concretes made from such aggregates has been found to be highly dependent on the contents of coconut shell, and most researchers have found improvement in strength or at least satisfactory strength retention only at low percentages of such contents. Both split tensile strength and flexural strength are also found to be dependent on the contents of the said aggregates, and there has been little improvement or stabilization at low percentages.

At higher levels of replacement, a consistent decrease in mechanical strengths has been noticed in various studies, especially in compressive and tensile strengths. This is mostly attributed to the high water absorption, lower stiffness, and coarse surface texture of coconut shell aggregates, which tend to affect workability, compaction, and bond between cement paste and aggregates. Although some studies have revealed relatively higher flexural strengths at certain levels of replacement, variations in mix proportions, curing, and pre-treatment of coconut shell aggregates tend to significantly affect these aspects. Based on the above-suggested synthesized evidence, it appears that coconut shell aggregates would be more ideally applied in applications concerning lightweight concrete, where reduced self-weight and sustainability would be preferred to high strengths. Careful replacement at lower levels would be required in such applications to maintain a balanced performance without deteriorating structural strength.

Table 14. Mechanical properties of coconut shells

Authors	Grade And Replacements Levels	Optimum Levels	Strength Achieved (N/Mm^2)		
			Compression Strength	Split Tensile Strength	Flexural Strength
B. Rajeevan et al. [34]	M 20 (0% to 35%)	30%	21.2	2.45	3.23
B. Damodhar reddy et al. [32]	M 30 (0% to 20%)	10%	13.56	1.51	4.5
B. Sandeep reddy et al. [35]	M 20 (0% to 30%)	5%	24.12	2.448	2.283
S U Azunna et al. [33]	M 30 (10% to 30%)	10%	38.37	6.5	3.04
Amarendra. Y et al. [36]	M 20 (0% to 20%)	10%	13.56	1.5	-
K. Venkateshwara Rao et al. [37]	M 30 (0% to 20%)	10%	36.7	3.6	-
B. Ranjitha et al. [38]	M 20 (0% to 30%)	5%	25.20	2.46	2.31
T. Subramani [39]	M 25 (0% to 20%)	5%	19.6	2.12	-

5.3 Recycled Aggregates

The mechanical performance of concrete with recycled aggregates, summarized in Table 15, generally reflects a broad but discernible trend of acceptable strength retention at low to moderate replacement levels, with optimum values most often reported in the range of approximately 10–30%. Indeed, compressive strength decreases with increasing content of recycled aggregate owing to adhered old mortar, higher porosity, and increased water absorption. In several cases, however, it is proved that careful mix design combined with appropriate quality control may minimize these negative effects. Low contents of recycled aggregates could even provide comparable or improved strength performance due to better particle packing and more appropriate stress distribution if properly processed and well-graded.

Table 15. Mechanical properties of recycled aggregates

Authors	Grade And Replacements Levels	Optimum Levels	Strength Achieved (N/Mm^2)		
			Compression Strength	Split Tensile Strength	Flexural Strength
Sd. Shiraz et al. [48]	M 20 (20% to 40%)	20%	42	3.52	9.5
M.Subhamkar et al. [40]	M 25 (0% to 100%)	25%	32.23	3.74	4.76
C. sabunam et al. [50]	M 30 (0% to 75%)	30%	48.49	4.98	-
Faisal ali bhat et al. [46]	M 35 (0% to 40%)	40%	52.36	-	5.40
Arul Gideon. R et al. [47]	M 25 (0% to 100%)	10%	43.9	4.8	6.55
N. Siva kumar et al. [43]	M 40 (0% to 50%)	10%	37	2.9	-
Yong, P.C. et al. [41]	M 40 (50% & 100%)	100%	65	5.2	5.5
B.A. Harish et al. [49]	M 20 (0% to 100%)	25%	32.5	4.16	26.97

Split tensile and flexural strength are more variable than compressive strength, reflecting the sensitivity of recycled aggregate concrete to interfacial transition zone quality and crack initiation mechanisms. Moderate enhancements in tensile and flexural performance at lower replacement levels reflect better aggregate interlocking and microcrack bridging as a result of combining recycled aggregates with optimized paste content. However, at higher replacement levels, strength loss becomes more significant due to weaker bonding between the recycled aggregate and the cement matrix, increased microcracking in the old mortar phase, and loss of stiffness contrast between aggregate and paste.

The large variation in the optimum replacement levels reported, including those with high values of replacement ratio, draws on the strong influence of source quality, processing methods, and concrete grade on the mechanical performance of recycled aggregates. In summary, the synthesized evidence shows that recycled aggregates can be gainfully used in structural and non-structural concretes when incorporated at controlled replacement levels and supported by appropriate mix design strategies. However, consistent performance at higher replacement levels requires advanced treatment methods combined with a strict quality assurance system to surmount the intrinsic material heterogeneity.

5.4 E-Waste

The findings presented in Table 16 suggest the use of e-waste as a partial aggregate replacement in concrete mixtures at a low replacement level, and the optimum strength level of about 5-15% has been observed to provide the best mechanical characteristics. It has also been observed in the same range that the compressive strength of the mixture has been sustained or slightly improved in the case of high-grade concrete, which suggests the ability of well-treated e-waste particles to sustain the loading capacity when mixed in combination. The split and flexural strength values have shown considerable variations depending upon the characteristics of e-waste particles.

Table 16. Mechanical properties of E-waste

Authors	Grade And Replacements Levels	Optimum Levels	Strength Achieved (N/Mm^2)		
			Compression Strength	Split Tensile Strength	Flexural Strength
D. Shobha Rajkumar et al. [56]	M 25 (0% to 20%)	10%	35.45	3.93	5.18
P. Krishna Prasanna et al. [57]	M 30 (0% to 20%)	5%	36.59	7.22	-
Prince Singh et al. [51]	M 20 (0% to 15%)	5%	19.76	-	3.11
Chandan kumar et al. [54]	M 30 (0% to 12%)	7%	45.74	3.98	6.34
Suchitra et al. [58]	M 20 (0% to 20%)	15%	35.5	3.80	6.38
Shree Lakshmi Prashant et al. [60]	M 30 (0% to 20%)	10%	29.58	-	5.66
S. Needhidhasan et al. [59]	M 20 (0% to 12.5%)	10%	27.7	1.93	6.30
S. Needhidhasan et al. [52]	M 60 (0% to 16%)	12%	67.75	4.8	4

The present study is exploring that the variable mechanical performances are mostly dependent on the low stiffness, smooth surface texture, and high polymer content in e-waste particles, intending to diminishally affect the mechanical interlocking and bonding at a higher replacement level, while at a limited replacement level, the presence of e-wastes can improve the ability of crack arrest and flexural strength in a better way because of increased energy absorption and ductility properties, while at a level above the optimal point, a continuous decline in compressive and tensile strength is noticed because of elevated void proportions, reduced quality of ITZ, and incompatibility of e-wastes with cementitious systems.

The large variation in the values obtained to measure the strength also accentuates the significant effect that the type of e-waste, particle size distribution, pre-treatment technique, and the grade of the concrete have on the results. Even though the use of e-waste has resulted in sustainability as the recyclable materials would otherwise be disposed of in landfills, the use of e-waste in concrete should be limited to a controlled low-level replacement in non-structural or semi-structural components unless there are valid durability and leaching and long-term performance studies.

5.5 Ceramic Waste

The literature reviewed to establish the suitability of ceramic waste aggregates has proved the partial replacement of natural aggregates to positively impact the mechanical properties of concrete. The partial replacement of natural aggregates at an optimal level of 20-30% has been identified as most ideal. Based on this level of partial replacement of natural aggregates, the compressive and split-tensile strengths are maintained and slightly improved depending on the desired grade of the concrete. The improvement can be attributed to the angular particle shape and hard nature of the crushed ceramic materials. The results of split-tensile and bending strengths are significantly improved at the optimal level.

At higher levels of replacement, especially beyond the range of 30-40%, the mechanical properties tend to become more irregular. Although a few studies show acceptable values of strength retention at higher levels of replacement ratio, such results are not generally uniform and are very much dependent on the size distribution of the ceramic particles, the type of ceramic used, and the processing techniques adopted. Overabundance of ceramic waste can cause brittleness, workability, brittleness, and stress concentrations in the concrete, affecting the tensile properties marginally though the compression strength values are acceptable in most cases. The irregularities in the values corresponding to tensile properties show how sensitive ceramic waste concrete is to microstructural irregularities.

Table 17:.Mechanical properties of ceramic waste

Authors	Grade And Replacements Levels	Optimum Levels	Strength Achieved (N/Mm²)		
			Compression Strength	Split Tensile Strength	Flexural Strength
Md. Muddasir Nawaz et al. [67]	M 30 (0% to 50%)	30%	39.09	3.04	5.99
T. Aneesh et al. [68]	M 25 (0% to 30%)	10%	24.55	-	9.3
V. Giridhar et al. [64]	M 20 (0% to 100%)	20%	36.60	3.32	-
Basim et al. [66]	M 25 (0% to 50%)	30%	43.14	2.65	9
Sherin khan et al. [65]	M 30 (0% to 50%)	30%	35.75	3.69	4.45
T. Sekar et al. [69]	M 20 (100%)	100%	20.23	2.95	18.015
H.G. Shruthi et al. [70]	M 20 (0% to 30%)	30%	32.03	4.61	-
D.J. Anderson et al. [63]	M 40 (20% to 100%)	20%	47.1	3.3	5.2

In general, the synthesized evidence shows that ceramic waste is a promising material for partially replacing aggregates, particularly for structural/construction-grade concrete. The material has high abrasiveness, hardness, and angularity, which are favourable mechanical properties, although excessive partial replacement is needed for optimization against brittleness and workability. Ceramic waste has significant potential as an aggregate material for practical construction, although limitations due to partial abrasion, brittleness, and workability need attention. Ceramic waste is an environmental waste material suitable for construction work for structural/construction-grade concrete.

5.6 Copper Slag

From Table 18, the mechanical properties of concrete with copper slag show positive tendencies in terms of compressive, split, or tensile, as well as flexural strengths, with optimum replacement ratios most frequently determined to be around 30–50%. Furthermore, some studies have shown that large ratios of replacement, or even a complete replacement of natural fine or coarse aggregates, do not impact compressive strength, especially in higher-grade concrete. The significant improvement in compressive strength can be mainly related to the large density, lower water absorption, and fine surface nature of copper slag, which result in better workability, packing efficiency, or minimized void content. The split or tensile, as well as flexural, strengths also show significant improvement at the optimum ratio, indicating better resistance to fractures or increased ability to handle stresses. These can be ascribed to the better distribution characteristics of copper slag particles in Portland cement, as well as increased workability, or the development of a more compact interface transition zone. Beyond the optimum level, increased permeability, segregation, and lack of cohesivity, or decreased cohesiveness, might result because of the glass nature of copper slag's surface, as well as its higher specific gravity, despite sufficient compressive strengths.

Table 18. Mechanical properties of copper slag

Authors	Grade And Replacements Levels	Optimum Levels	Strength Achieved (N/Mm^2)		
			Compression Strength	Split Tensile Strength	Flexural Strength
K.S. Al-Jabri et al. [72]	M 60 (10% to 100%)	100%	66.3	4.1	7.2
J. Anne Mary et al. [73]	M 20 (20% to 100%)	40%	33.70	2.5	4.82
D. Akhil et al. [80]	M55 (0% to 50%)	40%	69.64	6.55	6.22
K.S. Al-Jabri et al. [71]	M 45 (0% to 100%)	50%	47.0	4.1	7.3
S. Arivalagan et al. [79]	M 30 (0% to 40%)	30%	30.76	-	4.68
B. Gopal et al. [78]	M 35 (0% to 45%)	45%	43	3.2	6
Wu et al. [74]	M 55 (0% to 100%)	Up to 40%	96.5	5.4	9.2
E. Gopi et al. [77]	M 25 (0% to 100%)	20%	48.23	-	4.3

Overall, the results from synthesized evidence prove that copper slag has a high potential as one of the most suited substitutes to address sustainability concerns in construction industry activities. Copper slag has a broad range of optimal substitution amounts and shows better strength properties compared with other waste sources with aggregate capabilities. Copper slag can be used in construction as high strength concrete if properly mixed.

5.7 M-Sand

The studies summarized for manufactured sand (M-Sand) indicate that it is a highly efficient substitute for natural river sand, with various investigations indeed showing an optimum or full replacement without any loss in mechanical performance. Compressive strength tends to increase or is comparable to conventional concrete over a wide range of replacement levels, including 100% substitution in several medium- to high-strength concrete grades. The main reason given is improved particle packing density due to the angular shape of M-Sand particles, controlled grading, and higher fines content, causing a denser cementitious matrix. The quality of the interfacial transition zone is further aided by micro-fines through filler and nucleation effects, especially in combination with supplementary cementitious materials.

The same consistency in improvement is reflected in split tensile and flexural strengths at the moderate to high replacement level, which can be a reflection of enhanced crack resistance and effective stress redistribution. Increased mechanical interlocking due to the angularity and rough surface texture of M-Sand particles improves their bond characteristics with the cement paste, thereby supporting tensile load transfer. An excessively fine or poorly graded M-Sand may adversely affect water demand and workability, which may further affect strength development if not properly controlled through mix design optimization and specifically added admixture use.

Table 19. Mechanical properties of M-Sand

Authors	Grade And Replacements Levels	Optimum Levels	Strength Achieved (N/Mm^2)		
			Compression Strength	Split Tensile Strength	Flexural Strength
V. Uma Maheshwaran et al. [85]	M 100 (100% + alccofine)	100%	110	6.13	-
C. Sudha et al. [86]	M 60 (0% to 100%)	100%	65.45	5.79	5.5
B. Vijaya et al. [87]	M 50 (0% to 100%)	40%	64.32	5.68	7.03
S. Ramkumar et al. [88]	M 20 (0% to 30%)	30%	24.57	3.56	6.2
P. Rajendra et al. [89]	M 40 (0% to 100%)	65%	53.10	6.41	5.05
M. Yajurved et al. [83]	M 30 (0% to 100%)	60%	53.99	3.44	7.4
S.S. Saravanan et al. [84]	M 60 (0% to 100%)	60%	71	6.4	7.2
A. Nadimalla et al. [81]	M 20 (0% to 100%)	100%	43	-	6.3

The synthesized evidence generally confirms that M-Sand is a technically robust and sustainable alternative to river sand, since it is able to achieve equal or superior mechanical performance across a wide range of concrete grades. Its consistent availability, reduced environmental impact, together with favorable mechanical behavior, makes M-Sand suitable for both structural and high-strength concretes, provided that particle grading and fines content are carefully regulated to ensure balanced performance.

5.8 Waste Foundry Sand

As far as the mechanical characteristics of the concrete made with the addition of the waste foundry sand, as shown in Table 18, are concerned, it is observed that this aggregate can be considered as a good addition in the replacement of the natural fine aggregates, and the optimum replacement level has been observed to be in the range of about 10-30%. At this replacement level, the compressive strength has been observed to remain unaffected or increase depending upon the grade of concrete, which indicates the good filling effect of the fines of the foundry sand.

The split tensile strength and flexural strength values show a marked improvement at the optimal replacement level, indicating improved resistance to cracks and better bonding of the interface. The improvements are brought about by better paste-to-aggregate contact and pore structure due to the micro filling action of the waste foundry sand. At higher percentages of replacement, the strength values level off or reduce due to the increased demand for water, the possibility of the presence of clay or binders, and the poor workability of the mix, thus negatively impacting the compacting and interface quality.

Table 20. Mechanical properties of waste foundry sand

Authors	Grade And Replacements Levels	Optimum Levels	Strength Achieved (N/Mm^2)		
			Compression Strength	Split Tensile Strength	Flexural Strength
A.Yogesh et al. [96]	M 35 (0% to 60%)	30%	31.81	2.46	5.34
Naveen. A et al. [91]	M 20 (0% to 20%)	Up to 10%	33.33	-	4.08
B. Sanjay kumar et al. [90]	M 25 (5% to 25%)	15%	41.15	13.94	4.06
S. Dileep kumar et al. [92]	M 25 (0% to 25%)	20%	52	4.3	7.7
Mahmadareep.N et al. [97]	M 30 (0% to 25%)	15%	31.56	6.17	15
Jaya Chandra et al. [98]	M 40 (0% to 35%)	25%	48.17	4.02	6.8
K. Jamee et al.[93]	M 30 (0% to 60%)	35%	33.40	-	4.20
D. Pradeep et al. [99]	M 25 (0% to 100%)	50%	33.56	3.56	7.98

The variability in the values of tensile and flexural strength reported in various studies points out to the significant effect of the source of foundry sand, method of metal casting, or pre-treatment on concrete properties. Thus, the integrated body of literature summarized in this study indicates that waste foundry sand is a practical, useful, and sustainable alternative material in concrete production, either in structural or non-structural work, provided certain limits in replacement level are maintained.

5.9 Quarry Dust

Mechanical performance of concrete incorporating quarry dust, as summarized in Table 21, reveals that quarry dust may be effectively used as a partial replacement of natural fine aggregates, with optimum replacement levels most often within the range of about 25-50%. Within this range, compressive strength is generally maintained or moderately improved across different concrete grades, largely due to the fine particle size, angularity, and filler effect of quarry dust, contributing to improved particle packing and reduced void content in the concrete matrix. These characteristics promote a denser microstructure and an improved load transfer under compressive loading.

It can be observed that the split tensile and flexural strength test results, when compared to the compressive strength gain, reflect moderate improvement at optimum replacement levels. These aspects in turn signify the underlying improvement in bond strength and crack resistance as a result of better paste-aggregate interlocking. However, improvement in tensile-related properties is less consistent compared with the compressive strength gain. This is a reflection of the sensitivity of quarry dust concrete to particle grading, fines content, and workability. Excessive fines at higher replacement levels could lead to increased water demand and loss of workability, resulting in improper compaction and poor quality of the interfacial transition zone.

Clearly, particle size distribution, fines percentage, and mix design parameters may contribute significantly to the mechanical performance variability observed in several studies. On the whole, the synthesized evidence indicates that quarry dust can be a promising and sustainable fine aggregate replacement that may substitute structural and non-structural concrete against specific controlled replacement limits. Its practicality as an alternative, considering its widespread accessibility and reducing reliance on river sand, depends on the right optimization of mix proportions with regard to the balance between strength and workability.

Table 21. Mechanical properties of quarry dust

Authors	Grade And Replacements Levels	Optimum Levels	Strength Achieved (N/Mm^2)		
			Compression Strength	Split Tensile Strength	Flexural Strength
Mahendra. G et al. [111]	M 30 (0% to 50%)	40%	43.79	3.44	4.65
V. Aishwarya Lakshmi et al. [115]	M 20 (0% to 30%)	30%	32.86	3.11	-
Kannan. A et al. [119]	M 20 (0% to 100%)	40%	45	5.8	10.8
Amar. R et al. [116]	M 25 (0% to 100%)	50%	35.617	3.475	3.122
T. Subbalakshmi et al. [117]	M 40 (50% & 100%)	50%	47.33	-	6.59
Vijaya kumar. A et al. [118]	M 20 (0% to 75%)	25%	37.99	3.04	3.456
Fayaz et al. [112]	M 30 (0% to 100%)	40%	37.78	3.70	3.90
G. Bala Murugan et al. [114]	M 25 (0% to 100%)	50%	30.07	3.63	4.10

5.10 Waste Glass Powder

The results shown in Table 22 illustrate that waste glass powder has consistently positive effects on the mechanical properties of concrete as a partial replacement for natural aggregates. The optimum content shown for the different combinations usually falls within the range of 20-30%. Within this range, the results show that the strength of different concrete strength categories is improved, especially for medium- to high-strength concrete. This is mainly due to the filler effects, amorphous silica content, and fine size distribution of waste glass powder, which result in increased densification of the cement matrix. On the other hand, the pozzolanic activity introduced by the fine grinding of glass particles also results in the secondary hydration process, allowing more calcium silicate hydrate to be formed.

Results for split tensile and flexural strengths also demonstrate significant improvement at the optimal replacement dosage, signifying improved resistance to cracking or enhanced ability to handle stress. Such improvements can be attributed to the finer microstructure or better paste-aggregate bond work brought about by the microfilling action and pozzolanic action of glass powder. Nevertheless, beyond a certain dosage, a plateau or degradation in mechanical properties might occur, mostly owing to enhanced brittleness, possible reductions in workability, or the possibility of alkali-silica reaction if the glass aggregates were not fine enough or if their dosage were uncontrolled.

Table 22. Mechanical properties of waste glass powder

Authors	Grade And Replacements Levels	Optimum Levels	Strength Achieved (N/Mm^2)		
			Compression Strength	Split Tensile Strength	Flexural Strength
G. Lalitha et al. [120]	M 60 (0% to 40%)	30%	74.48	6.52	8.80
J. Premalatha et al. [122]	M 40 (0% to 50%)	30%	53.8	4.6	-
S. Arivalagan et al. [121]	M 20 (0% to 30%)	20%	27.11	3.46	4.60
P. Pooja et al. [123]	M 50 (0% to 50%)	30%	74.31	5.8	8.5
K. Deepak et al. [128]	M 20 (10% to 30%)	20%	26.75	4.02	4.07
J. Premalatha et al. [122]	M 30 (0% to 50%)	30%	39.60	4.03	-
S. Abdallah et al. [125]	M 30 (0% to 20%)	20%	34	3.2	5.5
P. Lavanya et al. [124]	M 20 (0% to 40%)	30	30%	4.5	6.1

The fairly consistent optimal range revealed by this data emphasizes the reliability of waste glass powder as an optimal substitute in this field. On the whole, the synthesized data suggests that waste glass powder is an attractive substitute for structural concrete in terms of improvement in mechanical properties as well as sustainability advantages. However, size parameters and optimal percentage levels require very precise control to optimize benefits along with minimizing any potential durability concerns.

6. Variability and Contradictions in Reported Findings

However, despite the fact that many investigations found enhancements in workability and mechanical performance of concrete using sustainable aggregates as a replacement, the results obtained from different papers did not always match in the literature. The discrepancies were noticed between compressive strength, split tensile strength, flexural strength, and workability values even in cases when the same replacement material and percentage of substitution were used. This discrepancy could have occurred because of the following reasons such as difference in the material origin, difference in particle size distribution, difference in aggregate shape and texture, water absorption properties of aggregates, as well as different concrete mix proportions. Different curing regime, sample preparation procedure, and testing method were other factors that could influence the variability of performance. Moreover, the physical and chemical properties of industrial by-products and waste materials could vary depending on the type of waste and its treatment, thus causing inconsistent results in case of concrete mixture preparation.

Variations based on material properties were also observed in the various studies reviewed. In particular, it is clear that steel slag and recycled aggregates had varied strength performances based on the quality of the aggregates, mortar remaining, and moisture status. Copper slag tended to improve workability since it has a smooth surface finish and low water absorption capacity; but high levels of substitution sometimes led to decreases in strength as a result of bleeding and segregation. For coconut shells and e-waste materials, the variations were highly dependent on their density, shapes, and bonding properties at the paste-aggregate interface. Ceramic wastes, quarry dust, waste foundry sands, and waste glass powders also had different optimum replacement levels based on gradation, fineness, and mix design parameters. These variations within the different studies show that there is no one material that can be considered to be universally the best in all scenarios. The effective use of the sustainable aggregates is dependent on the correct material characterization, mixing, and the extent of the replacements.

7. Comparability of Concrete Grade

The grades used in the studies considered were M20 through M100, which made mix ratios, quantity of cement, w/c ratio, and compressive strength target variable. Hence, comparison of properties among different studies cannot be directly made. Higher grade concretes tend to have higher w/c ratios, more binders, and in most cases admixtures or supplementary cementing materials, making the strength increase and longevity independent of the nature of the aggregate substitute. On the other hand, low grade concretes are more prone to changes due to the fact that performance is dependent on simpler mixes. As such, differences in concrete grades might affect the increase or decrease in strength of the same aggregate substitute. This explains why this review focuses on optimum range and performance trends rather than direct numerical comparison of strength levels.

In spite of all these differences, there are some observations which remain common to all reviewed literature. The optimum level of sustainability of most of the sustainable aggregate replacement materials is observed in case of replacement within a certain range for any grade of concrete. Although the values of the strengths are different in case of concrete of grades M20, M30, M40, M60, and other higher grades of concrete, yet the general trend remains the same. Hence, this literature review considers general properties and optimum levels of replacements.

8. Comparative Performance Evaluation of Sustainable Aggregate Replacements

Table 23. Comparative ranking of sustainable aggregate replacements based on mechanical performance

Aggregate replacement material	Typical optimum replacement (%)	Compressive strength performance	Tensile & flexural performance	Overall mechanical suitability
Copper slag	30-50	High improvement	High improvement	Excellent
M-Sand	40-100	High improvement	Moderate–high improvement	Excellent
Ceramic waste	20-30	Moderate-high improvement	Moderate improvement	Very good
Steel slag	25-45	Moderate-high improvement	Moderate improvement	Very good
Waste-glass powder	20-30	Moderate improvement	Moderate improvement	Very good
Waste-foundry sand	10-30	Moderate improvement	Moderate improvement	Good
Quarry dust	25-50	Moderate improvement	Slight–moderate improvement	Good
Recycled aggregates	10-30	Slight-moderate reduction	Variable	Fair-good
E-waste	5-15	Slight improvement	Variable	Limited
Coconut shell	5-15	Reduction beyond low levels	limited	Non-structural

9. Comparison Synthesis and Results of The Review

A comparison study on the sustainable materials used for replacement based on the reviewed research work shows various hierarchy levels for their performance and suitability for a specific area of applications. Of all materials used in their research work, copper slag and M-Sand have emerged as materials having better performance in terms of mechanical properties like split tensile strength, compressive strength, and flexural strength for various replacement levels. Their better performance can be ascribed to their superiority in density and packing properties.

Ceramic waste material, steel slag, and waste glass powder have good potential in the moderate substitution range typically in the 20-45% level. This is due to their angular and hard nature as micro-fillers or pozzolanic materials. The properties related to tensile strength are also satisfactorily improved. But in these types of waste materials, care has to be taken in terms of processing and substitution level to avoid brittleness or other deficiencies. Foundry waste sands and quarry dusts have medium mechanical strength contributions when considered as partial substitutes of fine aggregates in mixed concrete, largely because of the filler action and increased density. Suitability in conventional construction concrete is readily feasible in the case of non-structural or normal concrete work, but the increased fine content and demand of water may become detrimental in the case of higher percentages of replacement. Recycled aggregates demonstrate acceptable strength retention in the case of lower percentages of replacement, but the inhomogeneous material, mortar content, and increased porosity demonstrate variation in the case of tensile or bending strength.

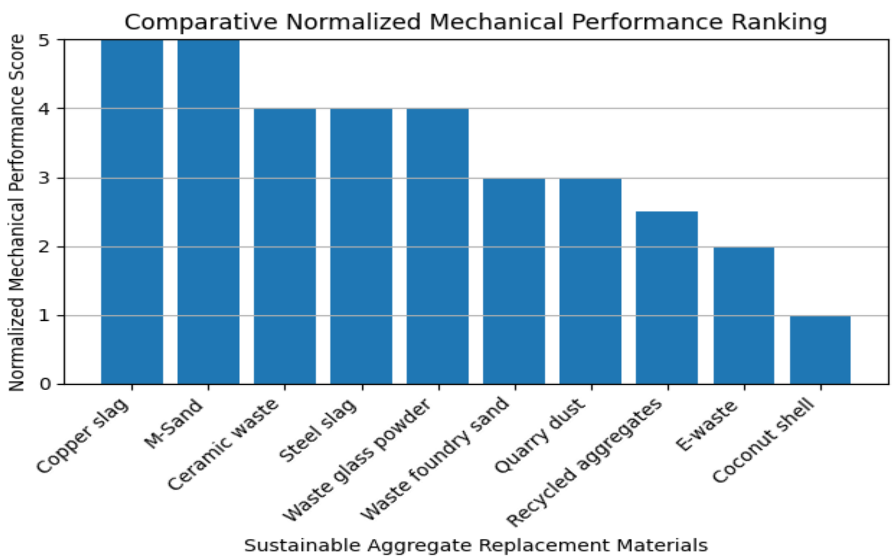

Fig. 13. Mechanical performance

The material properties of e-waste and coconut shell display limited mechanical applicability, and the ideal percentages are restricted to low replacement. Even though such materials are of great ecological advantage through waste recycling and the consequent reduction in the requirement of natural aggregate, the lower elastic modulus and increased porosity hinder their applicability to structural applications. In summary, this synthesizing study has clearly demarcated a performance-level prioritized ladder with respect to the sustainable aggregate replacements, emphasizing the imperatives of optimizing each individual material in contrast to following universally agreed approaches for replacements. These results would help in deciding on suitable possible aggregates applicable in accordance with mechanical requirements, fulfilling an important deficiency in the present literature related to aggregate-related reviews.

10. Limitations and Future Scope of Research

Although this literature review contains an exhaustive compilation of sustainable alternatives to aggregates in concrete, there are some shortcomings. These shortcomings are primarily based on the variability of experimental setups in investigated literature, such as concrete type, mix proportioning procedure, curing regimes, and testing standards. These factors limit a quantitative comparison of results among different investigations. In some investigations, workability and strength characteristics of concrete were affected by chemical admixtures and supplementary cementitious materials. The characteristics of these admixtures and cementitious materials were not reported uniformly. Moreover, long-term durability factors like resistance against freeze-thaw action, carbonation depth, alkali silica reactions, and chloride ion diffusion permeability were not investigated fully in all cases of concrete made by different sustainable alternatives to aggregates. This limits a comprehensive assessment of long-term performance of concrete in field conditions. Moreover, LCA and carbon content values were not provided in all cases of sustainable alternatives to aggregates.

Future research should concentrate on formulation and development of standardized test models that can allow deep comparison of sustainable aggregate replacement levels among different research works. More emphasis is necessary on long-lasting strength and environment impact assessment of alternatives, especially through rigorous life cycle analyses and carbon footprint analyses. Hybrid aggregate systems consisting of two or more types of waste materials may provide synergistic benefits related to strength improvement, workability improvement, and sustainability improvement and need serious research investigation. Modern material analysis tools such as SEM, XRD, and Micro-CT need to be adopted to comprehensively study transition zone behavior and failure patterns of composite materials. Furthermore, coupling of research models involving data science applications such as machine learning algorithms and decision-making models for optimizing multifaceted system objectives can provide future directions towards developing predictive models for optimized replacement levels of sustainable materials. Finally, future research needs to make their experimental works meaningful from a real-world perspective regarding large-scale adaptability of research results towards practical cost analyses and integration of sustainable aggregate models into national building codes and standards.

11. Conclusions

This review critically assessed the suitability of various industrial by-products, waste materials, and alternative aggregates as partial replacements for natural aggregates in concrete, with particular emphasis on workability and mechanical properties. The synthesized findings demonstrate that sustainable aggregate replacement materials can substantially reduce the dependence on natural resources while maintaining satisfactory concrete performance when appropriate replacement levels, material characteristics, and concrete grades are considered. The review further highlights that the successful application of these materials depends on selecting suitable replacement percentages and optimizing the concrete mix design according to the intended application.

The performance of coarse aggregate replacement materials varied with concrete grade and replacement level, indicating that optimum replacement percentages should be selected according to the intended application. Among the materials reviewed, steel slag exhibited promising mechanical performance at replacement levels of 20%–45%. Although its angular shape and rough surface texture tend to reduce workability, proper mix proportioning can improve compressive, split tensile, and flexural strengths within the optimum replacement range. Coconut shell aggregate showed comparatively lower mechanical performance beyond low replacement levels, with optimum results generally obtained below 15%. Owing to its lightweight and porous nature, it is more suitable for lightweight and non-structural concrete applications than for structural concrete. Recycled concrete aggregates demonstrated satisfactory strength retention at replacement levels of approximately 25%–40%, particularly in medium-grade concrete, making them a viable and sustainable alternative for the partial replacement of natural coarse aggregates.

E-waste and ceramic waste exhibited distinctly different performance characteristics. E-waste performed satisfactorily at low replacement levels (5%–15%); however, further increases in replacement generally reduced both strength and workability because of poor interfacial bonding and particle incompatibility, limiting its suitability to non-structural applications. In contrast, ceramic waste demonstrated satisfactory mechanical performance and workability at moderate replacement levels of 20%–35% owing to its hardness and angular particle shape. Replacement beyond the optimum range generally resulted in reduced workability and increased brittleness, emphasizing the importance of proper mix design and admixture selection.

Among the fine aggregate replacement materials, copper slag and manufactured sand (M-sand) emerged as the most effective alternatives to natural river sand. Copper slag significantly improved workability and mechanical properties at replacement levels of 20%–50%, particularly in medium- and high-strength concretes, owing to its smooth surface texture, higher density, and improved packing characteristics. M-sand demonstrated excellent potential as a partial or complete replacement for river sand, with optimum performance generally observed between 40% and 100% replacement, provided that appropriate grading and fines content were maintained. Waste foundry sand and quarry dust exhibited satisfactory performance at replacement levels of approximately 20%–40%, whereas higher replacement levels generally reduced workability and bond strength. Waste glass powder improved compressive, split tensile, and flexural strengths at replacement levels of 20%–30% because of its micro-filler effect and pozzolanic activity, while excessive replacement adversely affected both strength and workability.

The comparative synthesis presented in this review establishes a clear performance hierarchy among sustainable aggregate replacement materials based on their workability and mechanical performance. Copper slag and M-sand demonstrated the highest overall performance and are suitable for structural and high-performance concrete applications. Ceramic waste, steel slag, and waste glass powder also exhibited reliable performance at optimum replacement levels and can be effectively used in structural concrete with appropriate mix design. Recycled concrete aggregate, quarry dust, and waste foundry sand provided moderate performance and are suitable for controlled replacement applications. In contrast, coconut shell and e-waste are more appropriate for lightweight and non-structural concrete, where sustainability benefits are prioritized over high mechanical strength. Overall, the findings of this review provide practical guidance for selecting sustainable aggregate replacement materials based on workability requirements, mechanical performance, replacement level, and intended concrete application, thereby offering a comprehensive reference for sustainable concrete production.

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