APPLICABILITY OF VARIOUS WASTE MATERIALS AS COARSE AGGREGATE IN CONCRETE PRODUCTION: A REVIEW

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ABSTRACT

Technological advancements and modern lifestyles have increased the amount and type of waste generated in recent decades. Most of these waste materials are not biodegradable, so there are often disposal crises and environmental pollution. The growing interest in sustainable development has prompted engineers and scientists to adopt a constructive approach toward recycling waste materials across various sectors. Among the essential construction materials, concrete stands out as a cornerstone, widely utilized in building infrastructures due to its adaptability and versatility. The fundamental component of concrete, coarse aggregate, is primarily sourced from natural materials through quarrying rocks. The substantial quantities of natural aggregates consumed annually by the construction sector have raised environmental concerns. These concerns emanate from the depletion of raw materials and the deterioration of ecosystems, highlighting the pressing need for sustainable practices. The environmental and social costs associated with uncontrolled mining have further emphasized the exploration of alternative materials. To resolve these issues, research is underway to evaluate the feasibility of utilizing various waste materials, by-products, and debris instead of conventional coarse aggregates in concrete production. Many advantages are associated with replacing natural coarse aggregate in concrete production from an environmental and technical perspective. Consequently, many efforts have been made to improve concrete's physical and chemical properties to ensure its durability. This approach reduces waste disposal and promotes sustainability and economic efficiency within the construction industry. In this context, our paper delves into the prospect of using iron slag, ceramic waste, rubber tires, demolished concrete, glass, and e-waste as substitutes for natural coarse aggregates in concrete production, with a focus on supporting the construction industry's alignment with Sustainable Development Goal 12 while enhancing cost-effectiveness and environmental responsibility. According to the findings, natural coarse aggregate can be replaced with the above-mentioned waste materials up to a certain percentage to achieve similar compressive strength of conventional concrete.

Keywords: *Sustainable development, Coarse Aggregate, Waste Materials, Concrete, Civil Construction*

1. INTRODUCTION

Concrete, a composite material, is the most widely used construction material for several structures. Concrete has many advantages, including strength, ease of production, water tightness, and durability (Palankar et al., 2016). In making concrete, many extracted natural resources are used; among those, coarse aggregate is the most significant. Approximately 25 billion tonnes of concrete are consumed annually (Afroughsabet et al., 2019), and still growing. Consequently, aggregate demand will likely increase, with such aggregates accounting for approximately 70% of overall concrete volume. By 2050, 9 billion tons of aggregates will be needed (Arora and Singh, 2019). Natural aggregates are currently being extracted in a widespread manner. This scenario could hamper the rapid development of the construction industry due to the limited availability of this natural gravel. Natural gravel is scarce due to excavation and negatively impacts the environment and soil (Safiuddin et al., 2011). In light of the depletion and massive demand for natural coarse aggregate, this comes at a time when the global community is emphasizing sustainability and sustainable development more as climate change becomes more evident and acknowledged (Anderson et al., 2016). Research efforts have focused on replacing conventional natural aggregates with different waste materials in order to address the effect of natural aggregate depletion on the environment (Kwek et al., 2021). It is imperative to address the production of waste as a result of the rapid economic and industrial development of recent decades. In order to mitigate the impact of large volumes of waste or to control residues that hurt the environment, sustainable plans and programs must be designed. As a result of policies regulating the generation and management of waste in many countries, legislative frameworks have now been created. New methods for reusing, recycling, and recovering particular wastes must continue to be developed (González et al., 2014).

In the construction industry, materials are becoming increasingly expensive. As a result, different recycled waste replacements are becoming more attractive because they preserve natural resources for a later stage, thereby reducing the hassle of disposal. As a simple process, recycling involves gathering this waste from the site, transporting it to the desired location, and crushing and grinding it to meet the desired properties (Kishore and Gupta, 2020). Recently, there has been a growing awareness and tendency to use different recycled waste in concrete, targeting construction projects to be economically and environmentally sustainable (Tam et al., 2018; Tavakoli et al., 2018). An essential factor to consider is whether industrial waste can be compared to regular coarse aggregate with regard to its performance (Kwek et al., 2021). Numerous waste materials have been analyzed and characterized for potential use as primary coarse aggregates in concrete. In line with this, the present study reviews the previous research works that explored the applicability of some wastes, such as slag, ceramics, rubber, demolished concrete, glass, and e-plastic, recycled in concrete production. This recycling activity will allow us to save resources and contribute to protecting the environment. The application of these potential wastes in concrete production, replacing natural aggregates, can enhance green innovation and reduce environmental impact; in addition, it can achieve multiple SDG goals of the industry.

This systematic review can provide practitioners with a better understanding of current practices, limitations, and future prospects for benchmarking sustainable aspects of green concrete using different waste products. Diverse stakeholders will also be able to learn how to select waste products that will make the most suitable sustainable building materials.

2. METHODOLOGY

This literature review-based study on the application of waste materials as coarse aggregate in concrete production follows the step-by-step procedure depicted in Figure 1. In order to formulate this review paper, the methodology involves a systematic literature search, inclusion and exclusion criteria, data analysis, synthesizing and interpreting the findings.

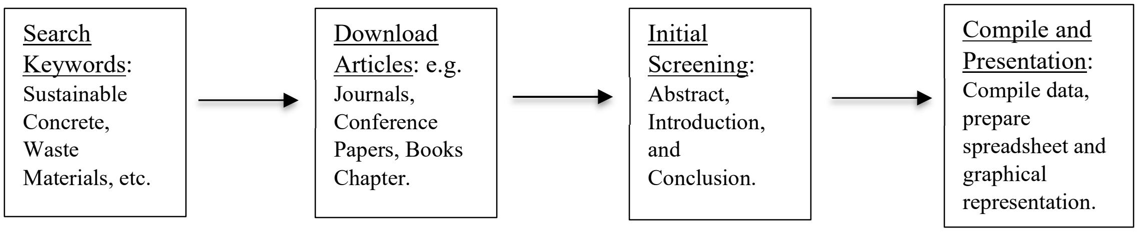

Figure 1: Research methodology for data collection and presentation.

3. CHEMICAL COMPOSITION

A waste material's chemical composition is crucial for influencing the properties of concrete as well as the environment. Concrete can be strengthened and made durable by adding wastes rich in silica, like glass and rubber. When these wastes are hydrated with calcium, they form calcium silicate hydrates (C-S-H), the primary compounds that increases strength. Table 1 demonstrates the chemical composition of different waste materials, as reported in earlier studies, note that the chemical composition for e-waste were manually converted to percentage (Rashid et al., 2023; Pitarch et al., 2017; Medina et al., 2012; Batikha et al., 2020; Alexandridou et al., 2018; Mukesh Limbachiya et al., 2007; Zhang et al., 2019; Rashad, 2014; Ismail and AL-Hashmi, 2009; Olofinnade et al., 2016; Ullah et al., 2022; Singh et al., 2020).

Table 1: Chemical composition of various alternatives for coarse aggregate.

Waste Materials	**Slag**	**Ceramic**	**C&D**	**Glass**	**Rubber**	**E-waste**
Components			**Percentage Composition (%)**			
SiO_2	8-40	61.2-68.41	39.97-68.43	64.3-70.4	-	-
Al_2O_3	1-22	3.6-18.6	5.49-15.85	1.9-3.4	-	-
CaO	30-42	-	3.48-24.09	-	-	
MgO	5-15	0.67-25.3	1.10-2.84	0.63-10.3	-	-
MnO	0.1-8	-	-	-	-	-
FeO, Fe_2O_3	0.1-35	0.91-5	2.40-3.05	1.2-6.25	-	-
S	0.2-2	-	-	-	-	-
P_2O_5	0.1-1.7	-	-	-	-	-
TiO_2	0.4-2	-	-	-	-	-
K_2O	-	0.14-3.3	0.4-0.74	0.4-0.74	-	-
Na_2O	-	0.32-2.38	0.94-4.71	12.52-14	-	-
Rubber Hydrocarbon	-	-	-	-	45.2	-
C (black)	-	-	-	-	25.8	-
$(CH_3)_2CO$	-	-	-	-	14.2	-
C_5H_8	-	-	-	-	12.1	-
H_2O	-	-	-	-	0.8	-
Ash	-	-	-	-	0.9	-
Fiber	-	-	-	-	0.5	-
Metal Content	-	-	-	-	0.08	-
Pb	-	-	-	-	-	2.06-86.54
Cd	-	-	-	-	-	0.02-3.43
Hg	-	-	-	-	-	1.39-71.81
Cr	-	-	-	-	-	0.06-48.18
As	-	-	-	-	-	0.47-51.15
Sb	-	-	-	-	-	1.50-92.58
Be	-	-	-	-	-	0.01-2.46
Br	-	-	--	-	-	0.13-3.74

-* Not Reported

4. PHYSICAL PROPERTIES

Physical properties have several applications, including load calculation, weight-to-volume conversion, and concrete mix design. Therefore, it is vital to have a primary idea of whether the waste material can be used as a potential replacement for conventional coarse aggregate in concrete production. The following section explores the physical properties of various coarse aggregate replacements. The comparative results are listed in Table 2, as reported in earlier studies (Hainin et al., 2014; Ikponmwosa and Ehikhuenmen, 2017; Bakri et al., 2008; Awoyera et al., 2016; Xu et al., 2023; Wagih et al., 2013; Kim et al., 2022; García-González et al., 2015; Kuri et al., 2023; Liaqat et al., 2018; Harrison et al., 2020; Muthukumar et al., 2017; Kumar and Selvan 2017; Danish et al., 2023; Khern et al., 2020; Qadi et al., 2016; Yasser et al., 2023; FHWA-RD-97-148, 2016). Crumbed rubber tire is found to be the lightest, while iron slag is found to be the heaviest alternative of conventional coarse aggregate.

Table 2: Physical properties of various alternatives for coarse aggregate.

	Physical Properties						
Aggregate	**Shape**	**Size (mm)**	**Unit Weight (kg/m3)**	**Specific Gravity**	**Absorption (%)**	**Porosity (%)**	**Color**
Iron Slag	Angular, rounded	> 4.75	1600 - 1920	Maximum 3.6	Maximum 3	2.5 - 31.3	Black, off-white
Ceramic	Flaky	5 - 20	1323	1.89 - 2.16	0.55	6.3 - 37.1	Mostly gray
Rubber Tire	Irregular	4.27 - 20	900 - 1160	1.15	negligible	-	Black
C&D Waste	Rough angular	4.75 - 25	1200 - 1400	2.19 – 2.48	2.15 – 7.15	12.71-14.17	-
Glass	Angular	4.75 – 12.5	1120	1.96 – 2.41	0.55 – 1.07	-	Amber, green
E-Waste	Irregular, round	4.75 - 20	1700 - 2300	1.3	< 2	-	White, dark

-* Not Reported

5. COARSE AGGREGATE REPLACEMENT IN CONCRETE PRODUCTION

This study applied the term "waste material" to slag, broken ceramic pieces, rubber, construction and demolition waste, glass, and e-plastic waste. The applicability of these wastes in concrete production, replacing natural coarse aggregate, is assessed by evaluating the most important mechanical property of concrete, compressive strength, for brevity. It should be noted that earlier studies reviewed in this document conducted research work following a specific experimental program by fixing a target strength, mix ratio, and environment. That is why results from individual studies were not compared; instead, a general trend was highlighted compared to the control batch, where no alternative was used. Further details of the experimental program followed in each study can be found in the original documents cited in the reference section.

5.1 Concrete production from iron slag

According to research, concrete can be produced using coarse iron slag instead of natural coarse aggregate. Figure 2 presents the effect of iron slag on the compressive strength of concrete, applied in different doses replacing natural coarse aggregate. It should be noted that up to 40% replacement of coarse aggregate with iron slag gained comparable compressive strength with the control batch. A mix ratio of 1:1.65:2.92 and w/c ratio of 0.45 was used in the research by Raza et al., 2014. Stone chips were replaced with coarse iron slag at 10%, 20%, 30%, 40%, and 50%. It was found that up to 40% of the coarse aggregates can be replaced by iron slag. Karim et al. (2022) reported similar findings. A concrete batch containing 50% to 70% coarse slag has higher compressive strength (35.33 MPa to 34.45 MPa) compared to the control batch (33.55 MPa) (Subramani and Ravi, 2015). Furthermore, partially replaced test specimens have a higher compressive strength than regular concrete (Kumar and Kumar, 2013). Similarly, Gokul et al. (2012) replaced stone chips with iron slag at 20% intervals up to 100%. It achieved a compressive strength of 27.16 MPa after 28 days. Another study by Karim et al. (2023) concluded that iron slag can be a better choice over brick chips for concrete production.

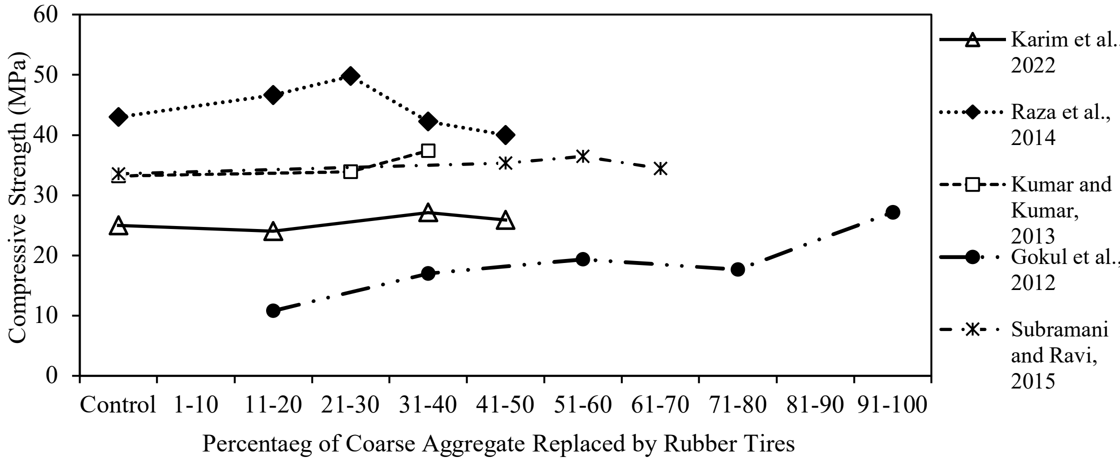

Figure 2: 28 days compressive strength using iron slag as coarse aggregate replacement.

5.2 Concrete production from ceramic waste

Ceramic waste can be used in concrete as coarse or fine aggregate. Figure 3 shows that up to 20% of coarse aggregate replacement by crushed ceramic tiles increases the compressive strength of concrete (Bommisetty et al., 2019). O et al. (2018) reported that with partial replacement of coarse aggregate with broken ceramic tiles in concrete production, the strength of concrete decreases with increasing percentages of broken tiles. Another study on reusing sanitary ceramic wastes as coarse aggregate in concrete production showed that compressive strength increased with up to 25% replacement of sanitary ceramic wastes (Medina et al., 2012). Hilal et al. (2020) studied concrete composed of limestone and ceramic tile waste exposed to high temperatures. Ceramic tiles were replaced from 10% to 100% at 10% increments with a mix ratio of 1:1.5:3 and a w/c ratio of 0.50. The result showed that up to 60% replacement increased the strength of concrete at room temperature. Gallardo et al. (2017) on the other hand, analyzed concrete mixed with waste ceramic tiles at 37.5%, 56.25%, and 75% and 25% fly ash.

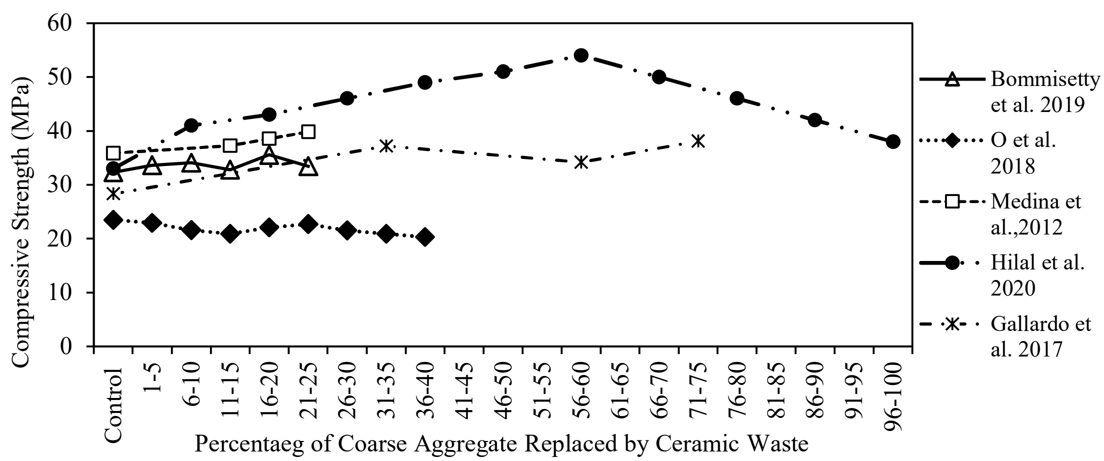

Figure 3: 28 days compressive strength using ceramic waste as replacement

5.3 Concrete production from rubber tires

Mudabheer and Siddiqui (2016) partially replaced natural aggregate with rubber aggregate at 5%, 10%, and 15% in concrete. Tests conducted at 7 and 28 days show that the concrete strength reduced significantly. Similarly, Toutanji (1996) replaced stone chips with rubber aggregate at 25%, 50%, 75% and 100%. M-31.9 grade concrete mix was selected with a 0.5 w/c ratio. The experimental result showed a notable reduction in the compressive strength of concrete. On the other hand, Etefa and Mosisa (2020) used M-25 and M-30 grade concrete; both experiments showed that at 30% replacement, the compressive strength reduced to 26.72 and 30.83 MPa, respectively. Experiments conducted by Luong et al. (2017) concluded that a replacement proportion of fine rubber particles at 30-50% by volume improved the workability of rubberized concrete, and a replacement proportion of coarse rubber particles at 10-30% by volume improved the workability of fresh rubberized concrete. Figure 4 represents the compressive strengths of concrete produced using different doses of rubber in earlier studies mentioned above.

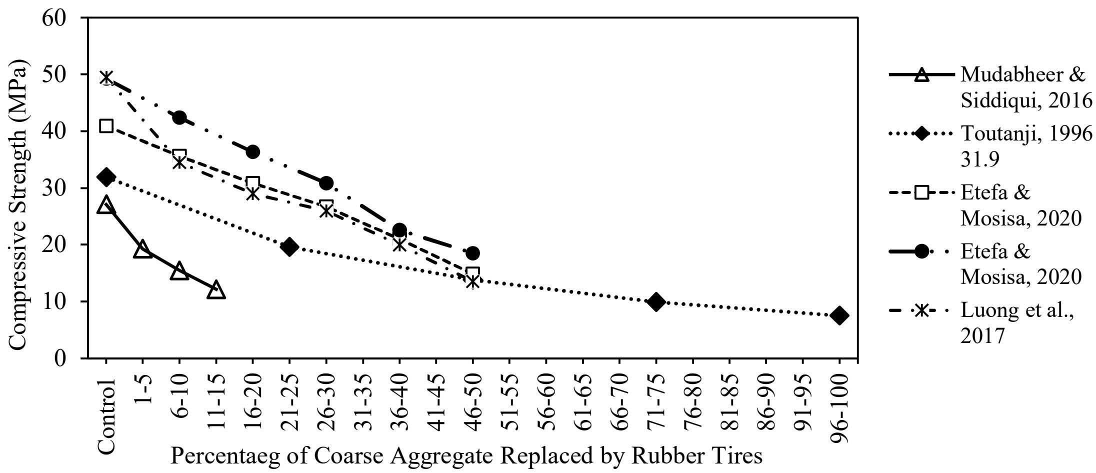

Figure 4: 28 days compressive strength using rubber tires as replacement

5.4 Concrete production from construction and demolition waste

Research conducted by Duan et al. (2020) substituted crushed stone aggregate with 25%, 50%, and 100% concrete and demolition (C&D) waste and 10% recycled powder. Kalpavalli and Naik (2015) studied the durability properties of C&D waste as coarse aggregate and analyzed the compressive strength of concrete at 10%-40% replacement. Similarly, experiments conducted by Zheng et al. (2018) showed that up to 25% replacement gives comparable compressive strengths to M-50 grade concrete. Vijai et al. (2010) studied the strength of concrete incorporating aggregates recycled from demolition waste. For M-20 grade concrete, natural coarse aggregates were replaced with crushed C&D waste aggregates up to 100% at 20% interval. The results showed a gradual decrease in compressive strength. Zega and Di Maio (2011) also reported a similar trend. Figure 5 shows that compressive strength decreases with increasing replacement percentage and a replacement percentage of up to 30% C&D waste yield comparable compressive strength when compared with conventional coarse aggregate.

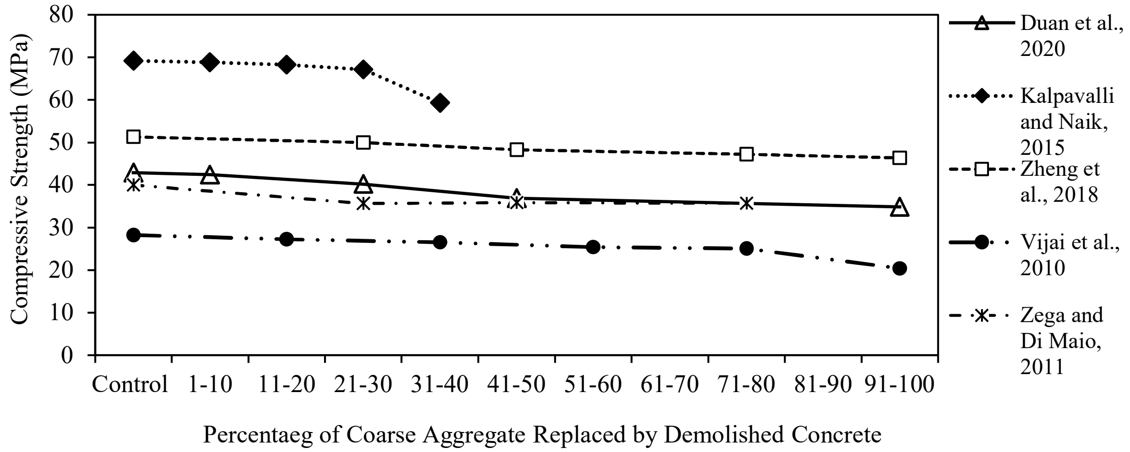

Figure 5: 28 days compressive strength using demolished concrete as replacement

5.5 Concrete production from Glass waste:

Recycled glass can be used to replace both coarse and fine aggregates in concrete production. Figure 6 presents the effect of glass waste on the compressive strength of concrete, applied in different doses replacing natural coarse aggregate. It was found that up to 20% natural coarse aggregate can be replaced by glass waste without compromising the compressive strength of concrete. Gerges et al. (2018) replaced coarse aggregates with green bottles at one-third, half, two-thirds, and 100%, with a water-cement ratio of 0.55. Compressive strength seemed to decrease with an increase in percentage replacement. Srivastava et al. (2014) replaced stone chips with glass waste at 10%-50% with a mix ratio of 1:1.67:3.33 and w/c ratio of 0.50. The observed result indicated an increase in compressive strength at 28 days with 10% replacement. However, a marginal decrease in strength is observed at 10 to 40% replacement. Similarly, Omoding et al. (2021) replaced coarse aggregate in concrete with a w/c ratio of 0.52 for 12.5%, 25%, 50%, and 100%. The results showed a gradual decrease in compressive strength. Kuri et al. (2023) replaced stone chips with waste glass at 10%, 20%, 30%, and 40%, with a 0.38 w/c ratio. Compared to the control batch, the 28-day compressive strength of the recycled glass aggregate concrete decreased by 0.21%, 3.00%, 10.28%, and 20.99%. The strength of concrete made from glass waste substituting natural coarse aggregates by 10%, 20%, 30%, and 40% is determined by Malik et al. (2013). The compressive strength improved at 10% and 20% replacement and marginally decreased later.

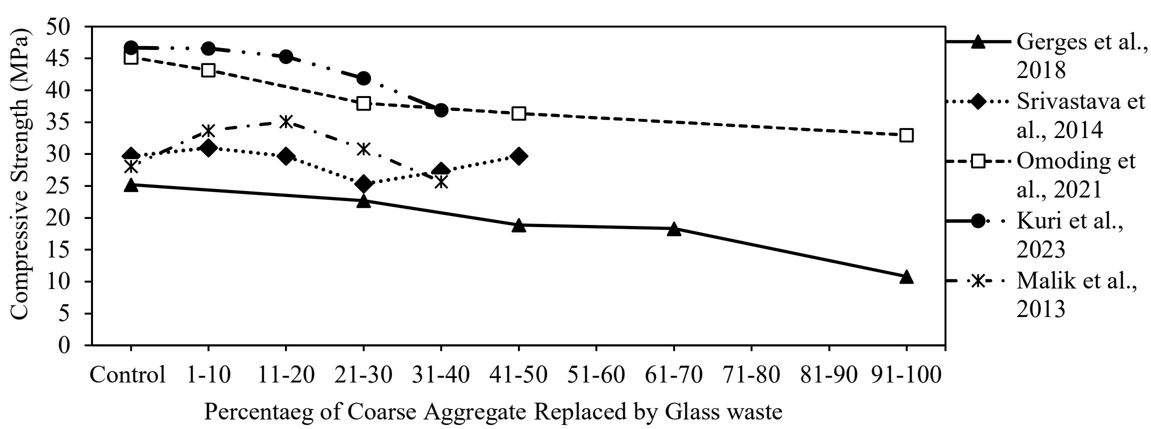

Figure 6: 28 day's compressive strength using glass waste as replacement

5.6 Concrete production from E-waste:

The potential of e-waste as a partial replacement of coarse aggregate in concrete production has also been investigated in earlier studies. Shilpa et al. (2019) replaced coarse aggregate with E-waste at 10%, 20%, and 30%. The result showed that up to 20% replacement fulfills the compressive strength requirement of M25 concrete. The substitution of E-waste as coarse aggregate at 10%, 20%, 30%, 40%, and 50% was studied by Zarbade et al. (2015). M-40 grade concrete is used with a water-cement ratio of 0.4. Results showed a decrease in strength with an increase in percentage replacement. Needhidasan et al. (2020) focused on replacing conventional coarse aggregate ranging from 0 to 12.5% with E-waste for M-20 grade concrete. The results showed a gradual decrease in compressive strength but showed promising results for M-20 concrete. Another study demonstrated the limited substitution of coarse aggregate with E-waste at 8%, 12%, and 16% (Needhidasan and Sai, 2020). The ratio of mixed concrete is 1:3.77:3.95 with a water-cement ratio of 0.28, and fly ash is used as an admixture for better workability. The result showed that average compressive strength at 28 days improved up to 12% replacement. After that, strength decreased for 16% replacement (Needhidasan and Sai, 2020). For M-40 grade concrete, natural coarse aggregate in concrete was replaced with 5%, 10%, 15%, 20%, and 25% of E-waste aggregate and 10% fly ash was added. Compressive strength decreased (49.79-41.42 MPa) with an increase in the replacement percentage (Dawande et al., 2015). It should be noted that E-waste may be used in concrete if it is appropriately processed. Figure 7 presents the compressive strengths of concrete produced using E-waste in earlier studies. It was found that up to 15% natural coarse aggregate can be replaced by E-waste without compromising the compressive strength of conventional concrete.

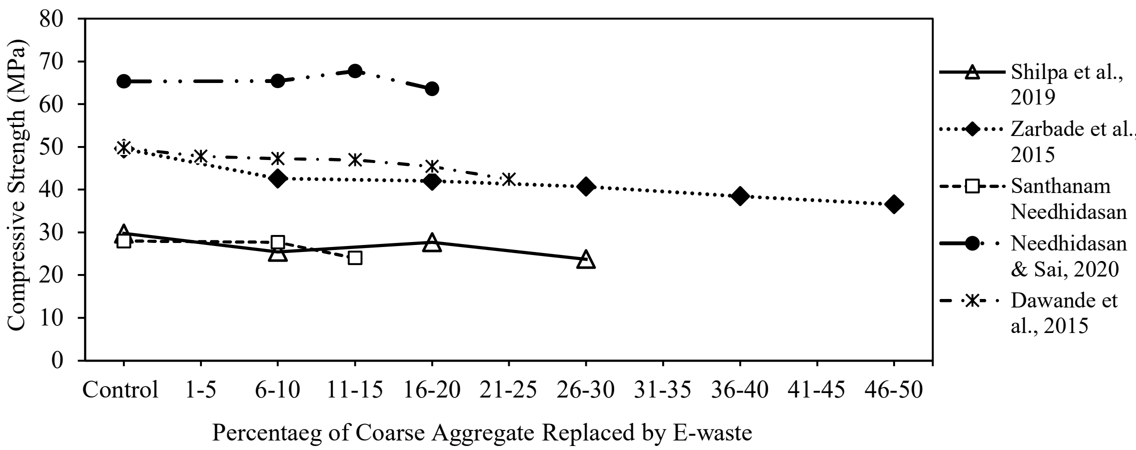

Figure 7: 28 days compressive strength using E-waste as replacement

6. CONCLUDING REMARKS

This literature review-based study aims for a sustainable alternative to natural coarse aggregate in concrete production. Earlier studies explored the possibility of developing sustainable concrete from an endless variety of waste materials. According to the study's objectives and the availability of the materials, this study has explored the potential of iron slag, ceramic waste, rubber tires, demolished concrete, glass, and E-waste as replacements for natural coarse aggregate, a major constituent in concrete production. A comprehensive review of the effect of alternative coarse aggregates in concrete production has been thoroughly conducted in this paper. Based on the review, the following conclusions are drawn:

- 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 40% of natural coarse aggregate, maintaining the desired performance of concrete in terms of compressive strength.

- For ceramic waste replacement, some variation is found in the existing literature. If broken ceramic tiles are used in concrete production, the strength of concrete decreases, but the application of sanitary ceramic wastes shows an increase in the concrete strength for up to 25% replacement.
- Research works reviewed in this study indicated that crumb rubber can cause a reduction in the compressive strength of concrete if applied as aggregate replacing natural coarse aggregate.
- 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 to produce comparable compressive strength.
- Glass waste in concrete production yield a marginal decrease in the compressive strength. However, glass waste can replace up to 20% natural coarse aggregate without compromising the compressive strength of concrete.
- E-waste can replace up to 15% of natural coarse aggregate in concrete production to yield comparable compressive strength.

It should be noted that the findings stated above are based on the earlier research works reviewed in this study. The compressive strength of concrete is considered the controlling parameter to assess the performance of individual waste alternatives and other parameters are considered out of scope for brevity. The above sections prove that the various environmental wastes can be easily used to replace certain percentages of the natural coarse aggregate in concrete production, thereby establishing a circular economy.

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