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REVIEW

Sustainable construction practices with recycled and waste materials for a circular economy

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Abstract

The need to promote sustainability and reduce environmental effects has fueled a substantial increase in the use of recycled and waste materials in construction applications in recent years. Concerns about harmful environmental threats are heightened when output increases and waste generation rises. An economically viable solution to this problem could be found by using waste materials to create new products, which would reduce the burden on landfills. This analysis clarifies the wide range of waste products that can be used in buildings, including recycled concrete aggregates, fly ash, slag, waste glass, plastics, rubber, construction and demolition (C&D) wastes, and reclaimed wood. These materials can partially or completely replace natural resources like sand, cement, and gravel. As a result, there will be advantages like improved resource efficiency, decreased greenhouse gas emissions, decreased solid waste, and reduced air and water pollution. These advantages will ultimately translate to energy and cost savings. The consistency and quality of recycled and waste materials for use in construction remain a top priority. Additionally, the circular economy concept, which is closely related to the use of waste or recycled resources in construction, emphasizes the significance of waste reduction and material reuse as opposed to adhering to the linear "take, make, and dispose" model. By switching out traditional materials for recycled or discarded ones, the construction industry may take advantage of the circular economy by reducing the need for new resources and cutting down on waste production. Using recycled or waste materials in buildings is an effective way to create a more sustainable and circular economy.

Keywords Waste Materials · Sustainability · Circular Economy · Construction and Demolition Wastes (C&D Wastes) · Environmental Impacts

Introduction

The amount of waste (solid or liquid) produced worldwide is rising daily (Olukanni et al., 2014). By 2050, the volume of solid debris generated annually is expected to increase to 3.40 billion tonnes from the estimated 2.01 billion tonnes in 2016 (Kaza et al., 2018). Solid wastes are divided into several categories, including residential, agricultural and industrial wastes. The majority of industrial wastes, including steel slag, alum aluminum and used tires both highly beneficial and reusable (Arena, 2012). The Federal Highway Administration (FHWA) estimates that building destruction alone produces 123 million tonnes of construction waste per year in the United States. According to several studies, (da Conceição Leite et al., 2011; Kartam et al., 2002; Marzouk et al., 2007), construction and demolition (C&D) waste poses a major environmental threat after effects, such as growing pollution, resource exhaustion and degradation of the environment. Environmental strain from trash generation and poor disposal methods is inescapable (Hadjieva-Zaharieva et al., 2003). The impact of garbage dumping on construction costs and environmental quality is growing. Therefore, managing garbage is one of the difficult problems in the rapidly developing world because of the insufficient financial resources, tools and machinery that lead to environmental contamination (Brown & Milke, 2016; Korinjoh, 2017). Municipal solid waste (MSW) management issues

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are among the biggest ecological issues and health risks for locals (Troschinetz & Mihelcic, 2009).

Rapid infrastructure development is essential condition for meeting both human demands and a nation's economic prosperity in modern era. Due to the increasing natural resource shortage and escalating expenses for landfill disposal in many countries, construction and demolition waste management is an essential requirement that affects the entire world and is primarily motivated by ecological aspects (Aatheesan et al., 2010; Disfani et al., 2011; Puppala et al., 2011). The Construction Industry Development Board of Malaysia (CIDB) has redesigned its strategies and formulated a roadmap known as the "Industrialized Building Systems (IBS) Roadmap 2003–2010". According to the IBS Roadmap 2003–2010, IBS is a construction process that utilizes techniques, products, components, or building systems that involve prefabricated components and on-site installation. IBS along with prefabrication needs to be implemented, as suggested by Begum et al. (2010), to reduce the production and handling of waste problems. Researchers from NC A&T State University (USA), other government and academic institutions examined several green materials technologies that reduce environmental impact and incorporate recyclable materials into applications for infrastructure (Abu-Lebdeh et al., 2010, 2011; Fini et al., 2011; Hamoush et al., 2011; James et al., 2011). Materials that have undergone numerous processes to turn discarded materials into new ones are referred to as recycled materials (Brown & Milke, 2016). The majority of these materials are easily accessible in the form of garbage that was previously underutilized and 0 to 70% of them are recyclable (Perera et al., 2019). Utilizing recycled materials becomes an alternative (Manso et al., 2013) because the excessive cost and widespread use of these materials have detrimental environmental consequences (Faleschini et al., 2016). A sustainable practice is to build roadway pavements out of recycled and environmentally friendly materials (Brunner & Rechberger, 2015). Utilizing waste in the building sector not only serves to fulfill residential requirements for individuals in economically deprived areas, additionally, it also saves the environment (Hadjieva-Zaharieva et al., 2003). Consequently, the need for environmental protection has become increasingly important in our society. As a result, environmental conservation issues have grown significantly in relevance in our culture over the past few years.

In the present study, several solid waste classifications, including industrial, agricultural and household waste have been covered in detail. The majority of industrial wastes, including steel slag, aluminum dross, and used tyres, are both highly beneficial also reusable (Arena, 2012). Plastic waste is recycled by being ground into tiny bits. Glass is helpful as a geopolymer, in 3-D printing, the creation of attractive tiles, reflective beads for road safety, fiberglass insulation, and aggregate for roadbeds. One of the potential solutions to this issue has been suggested as the usage of local garbage and optimization. The utilization of materials that require a lot of construction energy (Sharma & Reddy, 2004). Materials that have undergone numerous processes to turn discarded materials into new ones are referred to as recycled materials. For instance, there are currently potential resources accessible for building highways all over the world. The majority of these materials are easily accessible in the form of garbage that was previously underutilized and only 0% to 70% of them are recyclable. Some plastic waste materials have been used to make modified bitumen for paving purposes and it has been discovered that this method is quite effective (Choudhary et al., 2014; Paje et al., 2013; Poweth et al., 2013; Safi et al., 2013). It was discovered that conventional pavement was less water-resistant than pavement created using plastic products (Kaza et al., 2018). In this study, recyclable solid wastes, such as plastic, glass, scrap metal from destruction, geopolymers, industrial waste, shingles, slag and old tyres are taken into account for pavement construction. They are taken into consideration because of some noteworthy engineering qualities that they have the traditional "take-make-dispose" company strategy has been challenged by the circular economy (CE). The greater objective is to concurrently improve social fairness, economic prosperity and environmental quality; yet, some definitions of CE make the mistake of limiting it to only recycling (Kirchherr et al., 2017). The major goal of the CE is to close the material loop by recycling high-value materials, hence minimizing waste generation, restoring and renewing material cycles and maintaining the value of materials throughout a product's life (Salmenperä et al., 2021). Keeping raw materials in the loop is the ultimate goal of the ecological economy which is aimed to maximize resource utilization, lessen the need for new ones, prevent waste and lengthen the life cycle of the products. The market for solid waste is predicted to reach \$2.01 billion by 2021 and \$3.40 billion by 2050, representing an increase of roughly 59% (Kaza et al., 2018). Furthermore, between 50 and 80 percent of garbage from building and destruction projects is recyclable or utilized again, showing that improper management of Building debris can lead to the depletion of significant financial resources (Kofoworola & Gheewala, 2009). So, by successfully enacting a waste handling strategy, managers of projects may usually restrict the quantity of garbage produced within the project and the quantity that is sent to garbage dumps. (Liu et al., 2020).

The study enlightens the area of plastic recycling which has been developed to improve the efficacy as well as the effectiveness of the recycling process. For example, chemical recycling technologies can break down plastics into their constituent molecules, allowing for the production of new high-quality plastics with construction applications. In the case of C&D wastes, new techniques are being created to enhance the quality and consistency of these materials, like sorting and processing technologies can help to separate different types of waste, allowing for the efficient Utilisation of specific materials in construction applications. Finally, in the area of construction waste application, new materials and products are being developed that incorporate recycled or waste materials, including new types of concrete are being developed that incorporate recycled aggregates and waste materials, leading to improved performance and reduced environmental impacts.

Literature review

Solid waste management is typically a municipal duty in many nations, with approximately 70% of nations establishing agencies in charge of regulatory control of trash policy creation (Reddy, 2004). The implementation of nearly two-thirds of the nation's unique solid waste management laws and regulations vary greatly. Despite governing oversight and payment transfers, local officials personally control about 70% of waste disposal offerings. Direct involvement of the federal government is also not rare (Kaza et al., 2018). Government organizations provide a minimum of 50% of the offerings, including gathering and processing, along with discharge of basic garbage, and around one-third using public–private partnerships. However, operational partnerships and profitable funding Using the private sector typically only work under specific circumstances with the right incentives and implementation systems, so they are not always the best option.

It is extremely difficult to finance solid waste management systems since they require continual operational expenditures rather than capital investments, which must be anticipated (Cheng & Hu, 2010). In advanced economies, the daily expenses for comprehensive waste handling, which include gathering, transporting, treatment and destruction, typically exceed $100 per tonne. According to The World Bank (Emery, 1981), the cost of garbage handling is lower in countries with low incomes (Sub-Saharan Africa), at roughly $35 per tonne, even though it is far more difficult to recoup these expenses there. Waste management requires a lot of manpower and transportation expenses range from $20 to $50 per tonne. Depending on the quantity of revenue, the cost-effectiveness of removal services varies substantially. Users' costs in low-income nations range from $35 on average per year to $170 per year, with high-income nations typically being the only ones to fully or nearly fully recover their costs (Kaza et al., 2018). Depending on the type of user invoicing, user payment models might be either fixed or variable. The national private sector provides the majority of the remaining funding for waste disposal systems, with communities typically covering about 50% of the investment expenses. Around the world, different nations produce waste in different amounts. Table 1 provides information on how different types of waste materials can be used in the production of building materials. It lists different waste materials and their applications in various building products. By repurposing these waste materials, waste can be reduced and more sustainable building materials can be created.

Types of wastes

Glass

In the Municipal Solid Waste (MSW) stream, 11.5 million tonnes of glass were produced year 2010 in the United States. Small quantities of soda ash and limestone are also used to lend uniformity to the purity and appearance of glass, which is primarily formed of silica or sand. Glass deposited in a landfill is going to require more than a million years to degrade. The addition of a glass cullet decreases the working ability of the mixture for concrete and increases the likelihood of an alkali-silica reaction. Further purposes including the creation of fiberglass insulation, aggregate for roadbeds, shining beads for safer driving, and attractive tiles may all bring positive benefits (Olukanni et al., 2014).

Table 1 Applications of significant bulk trash in the production of building stuff. (Aubert et al., 2006; Cyr et al., 2004; Diamond, 2000; Pappu et al., 2007; Xue et al., 2009; Yoshizawa et al., 2004,)

Waste materials	Waste types	Applications
Bottom ash, husk ash, fly ash from rice, fuel ash from organic fibres and palm oil	Agro-industrial	Concrete, reinforced polymer composites, supplemental cementing ingredients, particle boards, blended cement, tiles, bricks, cement boards, blocks, insulation boards, roof sheets, and wall panels
Phospho-gypsum, waste glass, waste steel slag, granulated blast-furnace slag and rubber tire	Industrial sector	Coarse and fine aggregates, bricks, blended cement, blocks, concrete, ceramic products and tiles
Dust of quarry	Mining/mineral	Bricks, coarse and fine aggregates, blocks, concrete, surface finishing materials and tiles
Debris from construction and destruction	Industrial	Sub-base pavement materials, Coarse and fine aggregates, bricks, concrete, blocks

Plastic

In 2010, approximately thirty-one million metric tonnes of trash made of plastic were generated; because these plastics take so long to degrade, disposing of them is dangerous (Li et al., 2020). Recycled plastic is used in the construction sector for a variety of purposes, including the addition of plastic strips to soil embankments, which improves the measured strength of soil reinforcement (Seghiri et al., 2017) and can even be used in concrete (Safi et al., 2013; Shihada, 2020). The Hot mix asphalt (HMA) mixture offers greater stability, lessened walkway buckling, increased endurance to fatigue, as well as better asphalt-aggregate adherence (Choudhary et al., 2014; Paje et al., 2013; Poweth et al., 2013; Raposeiras et al., 2016). As the polymer's surface area grows, ground polyethylene can be used to give a better coating or can be quickly bonded to the aggregate (Awwad & Shbeeb, 2007; Rokade, 2012; Sakale et al., 2015; Sangita & Verinder, 2011).

Slag

Slag is a by-product of the production of iron and steel. It was once derided as useless, but today it is valued as a material with several utilisation in farming and ecological concerns, the building industry and highway construction constructions (Munnoli et al., 2013; Oluwasola et al., 2014). Across concrete and asphalt mixtures, fill material for canals, as the foundation for highways and as soil-improving procedures, air-cooled coarse aggregate is employed since it is durable across a range of temperatures (Sk & Prasad, 2012). Strength in both flexure and compression of concrete is improved by using ground, pulverized slag from blast furnaces (GGBFS). By substituting 40% copper slag for the fine bituminous concrete component, the copper slag impact on the propensity for sidewalk rutting was investigated. Results indicated that it met the criteria for rutting (Fini & Abu-Lebde, 2011; Abdelfattah et al., 2018; Yi et al., 2012).

Roofing shingles

Asphalt is used as a waterproof barrier in shingles, a particular type of roof covering. It is created using the suspension process, and using it is quite affordable. In the meantime, it becomes garbage once it has outlived its usefulness as a roofing material. As a way to have a cleaner environment and sustainable construction materials, this trash generated is being used in road construction as opposed to producing environmental damage (Nam et al., 2014). It has been found that adding tear-off asphalt roofing shingles causes the mixture's binder to become stiffer, boosting the material's rigidity, stability and resistance to rutting. When 14% of the material was substituted with shingles, it was discovered that shingles waste increased the rheological characteristics of bitumen and pavement fatigue life (Cascione et al., 2015; Townsend et al., 2007).

Cement kiln dust

The cement kiln combustion gases are cleaned by air management systems, which utilize the finely ground, extremely alkaline debris known as Cement Kiln Dust (CKD), a byproduct of producing Portland cement. Soil stabilization, waste treatment, cement substitution and asphalt paving are a few applications for CKD. CKD is ideal as a soil stabilizer since it increases soil strength while requiring less labor and money. It was determined that concrete blends including low amounts of CKD (5%), could achieve nearly the same durability, bending strength, cooling and heating resistance and compressive properties as a regulating combination. CKD is an efficient waste treatment because it is a high-quality adsorbent and naturally alkaline. According to research, CKD (combined with asphalt as a mineral filler) can drastically reduce the volume of asphalt cement needed by anywhere from 15 to 25% (Emery, 1981). The addition of CKD to asphalt binder results in asphalt with poor ductility and gives the pavement resilience to peeling.

Silica fume

The need to collect and dispose of silica fumes in landfills was driven by environmental concerns. As a mineral additive in concrete, this substance may be used for the most significant purposes. To enhance the compressive property, bond endurance and resilience to abrasion of portland cement concrete, silica fume is added. These benefits occur from pozzolanic interactions between silica fume and free calcium hydroxide in the paste, as well as mechanical enhancements brought on by the combination of paste cement receiving the inclusion of an immensely fine powder (Bolden et al., 2013).

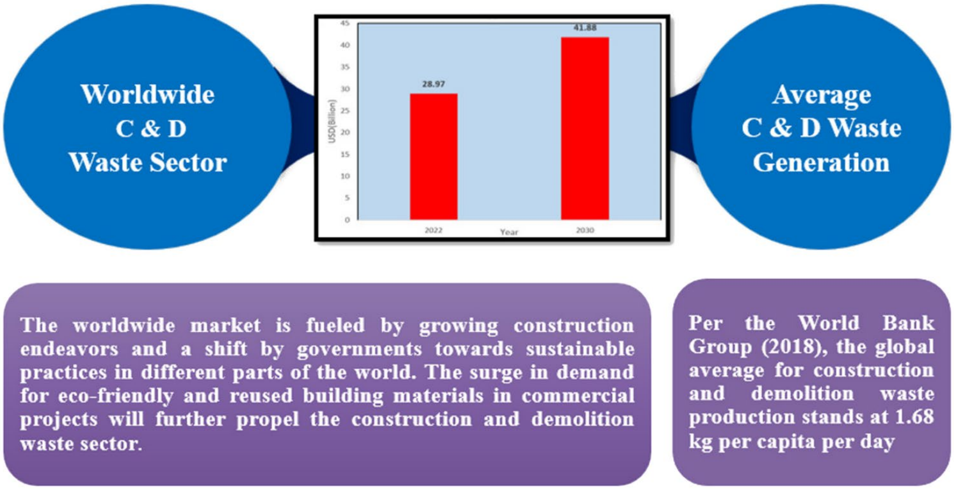
Geopolymers

Polymer serves as the basis for the term Geopolymer. Covalent bonds hold numerous smaller structural components, or monomers, together in a big molecule known as a polymer (Wietzke et al., 2011). The word "geopolymer" is used to describe a group of artificial aluminosilicate materials. It is a completely new class of building materials, which also includes waste packaging, modern adhesives for fiber composites, modern coatings and modern cement for concrete (Kua et al., 2017). They also refer to substances that produce a non-crystalline, crosslinked, semi-permanent system. Obsidian serves as a representative example of naturally occurring geopolymers (Kozhukhova et al., 2016). When reclaimed asphalt's strength and leaching effect were examined using fly ash geopolymers, it was discovered that there was less heavy metal leaking (Arulrajah et al., 2016). Early strength, a crucial component for quick road repair, was accomplished by adding geopolymer (Naik & Kumar, 2013; Ahmari et al., 2012; Neupane et al., 2018).

C & D waste

Massive amounts of C&D trash are produced as a result of population increase, ongoing industrial development, infrastructure construction and housing construction activities, necessitating the urgent need for waste recycling. Natural resources are heavily consumed by the construction sector. Beginning with 21 billion tonnes in 2007 and rising to 40 billion tonnes in 2014, the world's aggregate output has increased significantly. Some of the nations with the largest growth in demand for garbage recycling are the Gulf States, Turkey, Russia, Brazil, Mexico, China, India, Malaysia, Thailand and Indonesia. Construction, refurbishment, and demolition are the three primary stages of the building life cycle that generate C&D waste (da Rocha & Sattler, 2009). Therefore, it appears that the demolition phase should be specifically taken into account when adopting more sustainable practices to provide greater proportions of the C&D waste produced. India produces over 17 million tonnes of C&D waste per year. Most of the world's C&D trash may be recovered, reusing and recycling materials can benefit the environment and the economy. In 2011, Germany's recovery of resources performance stood at 91%, while in France, 50% of the total C&D garbage created in 2014 was recycled. While the resource recovery rate in the United States was 48% in 2011, about 62% of C&D waste was recycled annually in the United Kingdom in 2011 (Randell et al., 2014). According to Pickin and Randell (2017), around 64% of C&D garbage in Australia was reused in 2014, and Tam and Tam (2008) found that the construction industry in Hong Kong is responsible for 38% of the city's solid trash. The average C&D waste generation around the globe is presented in Fig. 1 (constructed based on discussions presented by da Rocha & Sattler, 2009; Pickin & Randell, 2017; Randell et al., 2014; Tam & Tam, 2008).

Table 2 includes information on a variety of recycled building materials. Among the products mentioned are glass, concrete aggregate, plastic, slag, roof shingles, cement kiln dust, silica fume, and fly ash.



The worldwide market is fueled by growing construction endeavors and a shift by governments towards sustainable practices in different parts of the world. The surge in demand for eco-friendly and reused building materials in commercial projects will further propel the construction and demolition waste sector.

Per the World Bank Group (2018), the global average for construction and demolition waste production stands at 1.68 kg per capita per day

Fig. 1 Average C & D waste generation

Table 2 Recycled materials that have been specifically chosen for use in building (Bolden et al., 2013)

Recycled material	Hot mix asphalt	Concrete mixes	Embankments	Mineral filler	Waste water treatment	Base course
Glass	✓	✓	✖	✓	✓	✓
Concrete Aggregate	✓	✖	✓	✓	✓	✖
Plastic	✖	✓	✖	✓	✓	✓
Slag	✓	✖	✖	✓	✓	✖
Roof Shingles	✖	✓	✓	✖	✓	✖
Cement kiln dust	✖	✖	✓	✓	✓	✓
Silica fume	✖	✖	✓	✓	✓	✓
Fly ash	✓	✖	✖	✖	✖	✓

- Glass: Recycled glass can be employed as an aggregate to provide colour and texture to concrete.
- Crushed Concrete: Using crushed concrete as a substitute for traditional aggregate concrete can decrease both waste and expenses.
- Plastic: Recycled plastic can be used to create a range of building materials, including decking, fences and roofing tiles.
- Slag: Slag is a useful byproduct of the steel manufacturing industry. It can be used in construction as a substitute for ordinary aggregates, which helps to reduce waste and energy consumption.
- Roof Shingles: Recycled roof shingles can be used in both asphalt pavement and roofing materials.
- Cement Kiln Dust: Cement kiln dust, a byproduct of cement manufacture, can serve as a soil stabilising agent in construction.
- Silica Fume: Silica fume is a residue produced during the manufacturing of silicon and ferrosilicon alloy. It can be utilised as a filler in concrete to enhance its durability and lifespan.

Fly ash

Fly Ash is a byproduct of coal-fired power plants that can be substituted for cement in concrete, lowering greenhouse gas emissions and saving natural resources. By using selected recycled materials in construction projects, waste can be reduced, natural resources can be protected and the environmental impact of the building industry can be drastically reduced (Bolden et al., 2013). The various recycled materials and their applications are discussed in Table 2.

Concerns and challenges of waste management

Anything that is tossed or otherwise treated as if it were trash will be assumed to be trash until the agreement is proven and waste is described as "any material or substance about a class of waste which the owner eliminates, plans to eliminate or is required to discard." (Torgal & Jalali, 2011). Environmental strain from trash generation and poor disposal methods is inescapable (Hadjieva-Zaharieva et al., 2003). Water management and trash management have been cited by Korinjoh (2017) as two environmental protection objectives. To minimising calamities and reducing the impact on households, livelihoods, and the environmental issues in disaster management have become a significant priority (Tiwari, 2001). Construction material demand is growing faster than demolition trash production and recycling. Another difficulty is the energy requirement required in recycling demolition debris. Zhang et al. (2015) offered a solution that involved the developer, he energy service provider and the site control organization to address the energy challenge.

Around the world, waste management has become increasingly difficult due to population growth, unforeseen urban development, shortage of information and increasing living expenses. Solid waste management (MSW) issues in cities are one of the biggest environmental problems and health risks for locals. Due to environmental protection laws and the high cost of land, disposing of the growing volume of waste has proven difficult. According to studies, the disposal of 90% of MSW is improperly disposed of in open landfills, which negatively affects environmental and public health (Kumar et al., 2009). Even though the problem of building waste is becoming more severe, most nations lack accurate figures because of unlawful dumping (Pacheco-Torgal & Jalali, 2012). A typical American creates six tonnes of solid garbage annually, and because of environmental protection laws, landfilling these wastes has become prohibitively expensive and difficult (Sharma & Reddy, 2004). Reusing garbage can assist communities in maintaining their local landfills, however, creating an effective trash recycling system program in the USA is challenging (Peng et al., 1997). During industrial, mining, municipal, and agricultural operations, India produces roughly 960 million tonnes of solid waste each year (Pappu et al., 2007; Sharholy et al., 2008). Building waste management requires multidisciplinary planning, engineering and material management knowledge. A couple of major challenges facing the construction business include the building sector's inertia and the difficulty of updating building codes. Significant hurdles are also presented by uncertainty, fear of liability, and litigation related to the effectiveness of substitutes for construction materials and methods. Despite the obvious economic or environmental advantages of green building practices, the majority of them have not been rigorously measured (Torgal & Jalali, 2011). The current rapid advancement in this subject could be hampered by the absence of a consensus on the goals and rules for potential environmentally friendly structures that cover design, parts, systems and supplies. Post-disaster construction waste management poses a variety of problems because of the generation of an unexpectedly substantial amount of building materials and inadequate management capabilities in developing nations (Pappu et al., 2007). Using recycling technologies and reuse strategies, large amounts of garbage generated by disasters and other natural calamities (such as hurricanes and floods) should serve as a basis for rebuilding efforts (Xiao et al., 2012). Reducing trash and managing it properly can be seen as a useful way to assess an initiative's evolution towards a more environmentally friendly path (Kartam et al., 2002).

Figure 2 displays the responses from the surveyed businesses regarding the most popular recycling. According to the companies questioned, costs accounted for 22% of

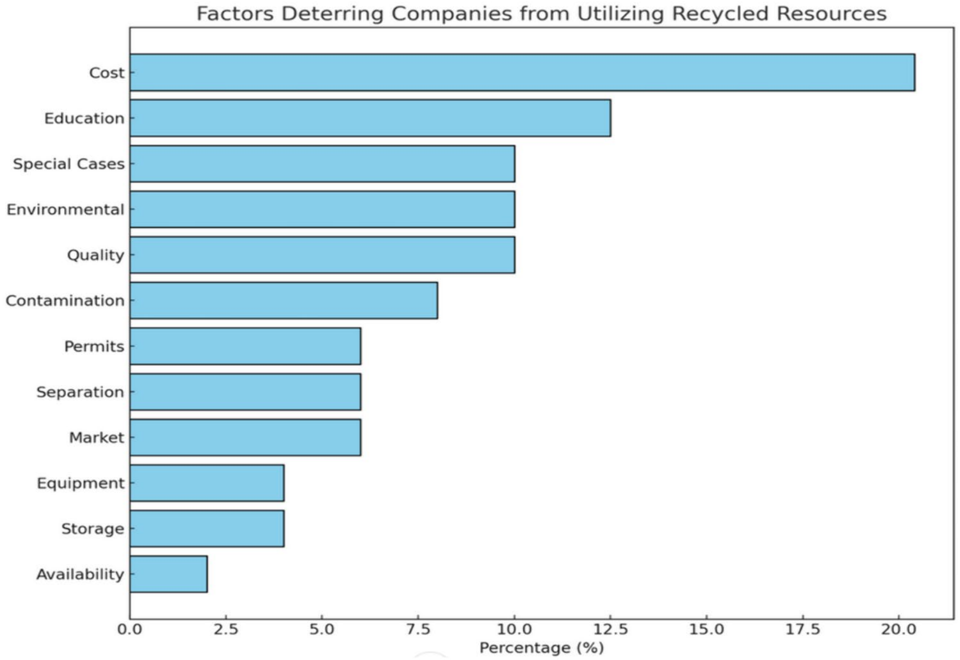


Fig. 2 Factors against utilizing recycled materials

materials (obtained from analysis carried out by Bolden et al., 2013). In this sample of businesses, recycled concrete was most frequently used (15%), followed by reclaimed asphalt (12%) and recycled wood (8%). Only 7% of the businesses used no recycled materials at all. Only a few businesses were represented in the graph. Including tyre cement kiln dust, rubber, sewage sludge, silica fume, foundry sand, glass, citrus peels, carpet, oil, date tree, animal fat, swine dung and soybeans are examples of contaminants, fewer than 2% of each recycled item was utilized by these businesses (Bolden et al., 2013).

Waste recycling and reusability

Since the nineteenth century, when rules were introduced to encourage the recycling of growing amounts of waste, waste has been recycled and reused. Utilization and recycling are acknowledged in the handling of solid waste practices that are more environmentally friendly and superior to landfilling or incineration (Etxeberria et al., 2006; Fischer et al., 2009). Plastic, glass and metallic waste products produced by metropolitan communities can be used in different methods for building construction, landscape design, utility design, paving and attractive fixtures. The collection, recycling and grinding of PET (polyethylene terephthalate) have been highlighted in Fig. 3 (drawn based on discussions presented by Bacarji et al., 2013; Pereira et al., 2020; Perera et al., 2019).

Plastic

Around One hundred million tonnes of plastic garbage are generated globally every year, but only 9% of that waste is recycled and only 14% of that rubbish is collected for recycling, based on information from the UN for the Environment (2019). Around 90% of the plastics produced on the earth are dumped in the oceans. A quarter of the plastics produced are utilized for long-term uses, such as pipelines, whereas the majority are suited for short-term applications. Brief usage has led to an annual rise in used plastic trash and, as a result, to improper environmental disposal (Awoyera & Adesina, 2020) as well as cullet waste (Al-Fakih et al., 2020).

The utilization of PET waste supplement to other construction materials has been shown in several studies (Alfahdawi et al., 2019; Mohammed & Rahim, 2020; Perera et al., 2019; Polesello, 2012), primarily for programs that don’t call for significant loads that have been placed and structured. The effects of adding plastic material to freshly laid and hardened concrete have been the subject of research (Alqahtani et al., 2017; Mustafa et al., 2019). The majority of research has found that increasing the replacement level tends to reduce workability (Akinyele & Ajede, 2018; Batayneh et al., 2007; Mustafa et al., 2019; Rai et al., 2012), but increasing the replacement ratio has been shown to increase the slump of fresh concrete (Choi et al., 2009; Ghernouti et al., 2011). The unit weight decreases as the replacement level rises, according to all investigations (Ghernouti et al., 2011; Ismail & Al-Hashmi, 2008; Juki

Fig. 3 PET waste is being **A** collected; **B** recycled; **C** ground up, and used as building materials

et al., 2013; Mustafa et al., 2019; Shubbar & Al-Shadeedi, 2017). Additionally, the majority of research (Liu et al., 2015a, Saxena et al., 2018, and Ohemeng & Ekolu, 2019) demonstrate a decrease in three different types of strength: flexural, splitting, and compressive.

Compressive strength

The compressive strength of mixes falls as the PET ratio rises with each age of curing. The standard control concrete mixture's compressive strength values were evaluated to be 30.6, 35.6, and 35.9 MPa at 7, 28, and 56 days, respectively. At replacement ratios of 10% and 20%, compression strength fell marginally, whereas, at 40% and 50%, compression strength considerably decreased by 31% and 60% at 28 days, respectively. The stresses were 18.5, 24.6, and 24.7 MPa at 7, 28, and 56 days, respectively, at a 30% replacement ratio. The main cause of this loss in strength is the composites' declining bulk density. In Fig. 4, a pattern of reduced strength can be observed, in mixes as the PET replacement ratios increase. This information combines insights from studies conducted by Remadnia et al. (2009), Kou et al. (2009), Frigione (2010), Juki et al. (2013), Ishaiba (2015), Jassim (2017) and Djamaluddin et al. (2021).

Tensile strength

At PET concentration levels of 10%, 30%, and 50%, the reference blend's tensile strength was found to be 3.11 Mpa. 3.0 Mpa, 2.01 Mpa, and 2.78 Mpa of breaking strength is reached, as shown in Fig. 5 (constructed based on research finds by Albano et al., 2009; Al-Buhaisi, 2013; Saikia & De Brito, 2014). Results for the tensile strength of splitting were assessed after 28 days of curing. As the PET replacement ratio raises, after 28 days, the inclusion of PET reduces the concrete's splitting tensile strength. The smooth, level and angular qualities of the PET sample contrast with the round, hard sand's characteristics.

The effects of incorporating plastic materials into freshly laid, hardened concrete have been the subject of recent

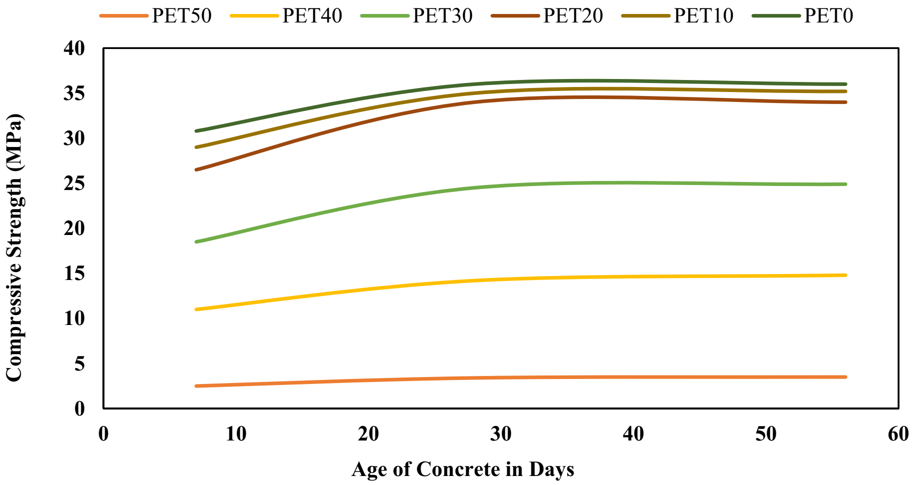


Fig. 4 Impact of recycled PET on the compressive strength of concrete

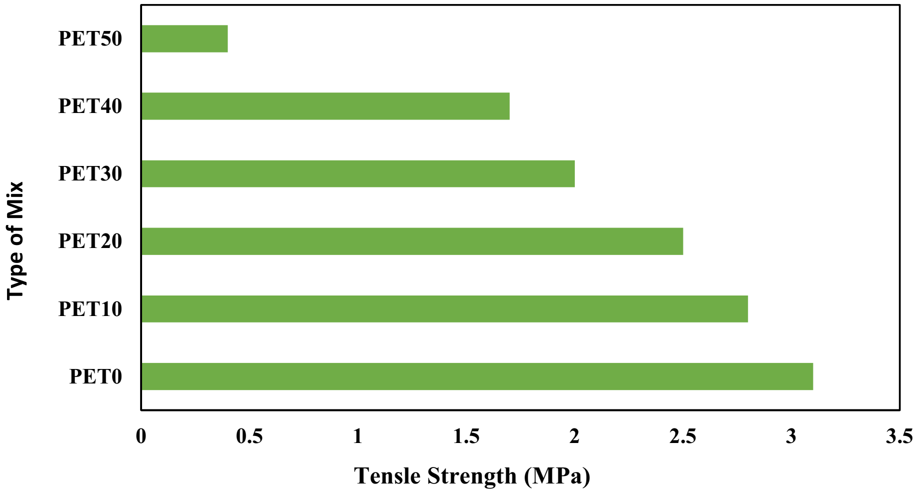


Fig. 5 Impact of recycled PET on the tensile strength of concrete

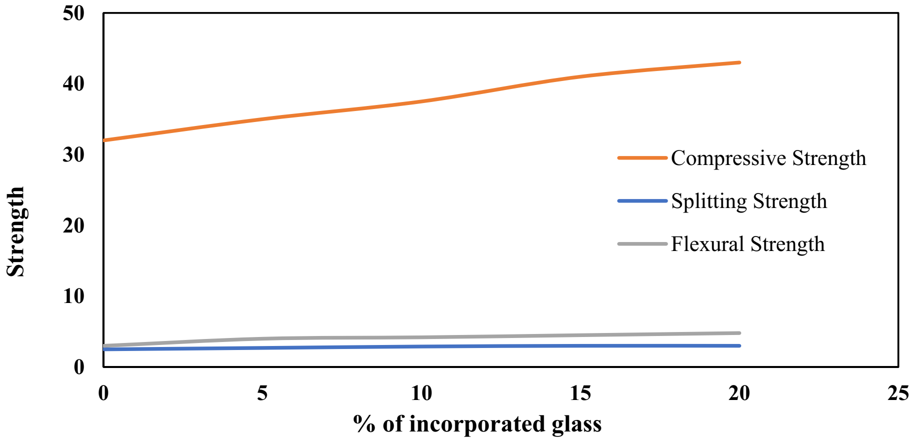
research (Liu et al., 2015b; Shubbar & Al-Shadeedi, 2017). Workability results from studies have varied, with most noting a tendency for workability to decrease as the replacement ratio increases (Akçaözoğlu et al., 2010; Batayneh et al., 2007; Mustafa et al., 2019; Rai et al., 2012). However, slump in newly laid concrete increases as the substitute ratio rises (Frigione, 2010; Marzouk et al., 2007). All studies agree that unit weight drops as the substitute level increases (Ghernouti et al., 2011; Ismail & Al-Hashmi, 2008). Additionally, the majority of studies (Ohemeng & Ekolu, 2019; Saxena et al., 2018) demonstrate a loss of flexural and compressive strength.

Glass

Recent studies have demonstrated that recycled glass (RG) can substitute as much as 20 percent of the natural aggregates in concrete while maintaining the correct mechanical qualities (Taha & Nounu, 2008). Glass debris is beneficial for the cement and concrete industry due to its chemical makeup and pozzolanic qualities (Jani & Hogland, 2014). Regardless of the color of the waste glasses, the primary grain shape of crushed glass is angular, which has a detrimental effect on the concrete's usability (Lee, 2007; Polley et al., 1998) and lowers its slump and compacting factor (de Castro & de Brito, 2013; Park et al., 2004). In contrast, a year-long trial duration conducted by Ali and Al-Tersawy (2012) revealed no noteworthy difference in the compressive strength of concrete with RG compared to the control. However, concrete's flexural, tensile, and compressive strengths all declined as glass content rose (Ali & Al-Tersawy, 2012; Park et al., 2004). Ismail and Al-Hashmi (2009) examined the characteristics of concrete using glass waste as a fine aggregate. This research assessed the strength characteristics and ASR expansion of concrete mixtures containing 10%, 15% and 20% pulverized waste glass in place of sand. The findings showed that after 28 days, waste glass provided a pozzolanic strength activity of 80%. The mix with 20% crushed glass had compressive and flexural strengths that were, respectively, 10.99% and 4.23% greater compared to the control specimen. The mortar bar test confirmed that finely crushed glass waste had 66% less expansion than the control specimen (Ismail & Al-Hashmi, 2009). The slump flow rose as the volume of recovered materials glass increased. Additionally, as the amount of recycled glass particles increased, the concrete's compressive strength, splitting tensile strength, flexural strength and static elasticity modulus all decreased. This study suggests that recycled glass particles can be used to create self compacting concrete (Ali & Al-Tersawy, 2012). Ganiron Jr. (2014) conducted exploratory research to determine how the physical and mechanical properties of the concrete mix would change if broken glass containers were used instead of coarse aggregate. Based on the findings, it is possible to substitute as much as 10% of the mass of coarse aggregate with reused glass aggregate in concrete mixes and a mix design with a 5% weight insertion produces acceptable compressive strength. Similar research was conducted by Keryou and Ibrahim (2014) on the mechanical features of newly poured and seasoned concrete incorporating window waste glass. The results show that using window glass particles in place of coarse aggregate decreased slump and fresh density due to the angular grain structure while enhancing parameters like compressive, splitting, and bending strength. Additionally, findings showed that the strength increased upto a specific limit, beyond which it dropped, as the ratio of waste glass increased.

According to Fig. 6, all strength values (compressive, splitting and flexural) for up to a 20% substitution of glass aggregate are greater than those of a typical concrete mixture. According to Batayneh et al. (2007), the increase in

Fig. 6 Substitution of crushed glass aggregate for improved mechanical strengths of concrete



strength is due to the strength and surface roughness of the glass grains compared to sand.

C & D waste

The construction sector, though smaller than other industries, consumes 12% of the world's resources by volume, primarily water, and as much as 40% of the world's energy. Construction uses 25% of all virgin timber and almost 40% of all raw resources extracted from the Earth (Yeheyis et al., 2013). Additionally, achieving zero waste is difficult due to nature of the industry and the ongoing rate of trash generation (Ulubeyli et al., 2017). Opportunities to build circular supply chains or a sustainable economy should not be disregarded as resources become more scarce (Balador et al., 2020). This indicates that increased efforts should be made to reuse, repair, and recycle resources so they can be used for longer (Bocken et al., 2016; Caldera et al., 2019). While cleaner methods of selective demolition are employed to lessen trash creation at the source (Sánchez & Lauritzen, 2004), waste management should receive more attention during the planning phase. The reduction of waste at the design stage critically depends on "modular design," "waste reduction investment," and "economic incentives" (Wang et al., 2014). Regeneration has been emphasized as a key approach to deal with environmental degradation and related contamination by reducing its effect on ecosystems, even though the reuse of waste is a reliable way to deal with construction and demolition debris (BIO, 2011; Shooshtarian et al., 2020). Multiple reports have found that the use of recovered demolition trash increases the holding power, resilience, elasticity modulus, and capacity to resist enduring deformation (Chick & Micklethwaite, 2004; da Conceição Leite et al., 2011). Xue et al. (2009) found that employing recovered demolition waste could prevent the leaching of the pavement underlays. C&D Wastes can be utilized as a component in cement, as a filler in concrete, and as a raw material in cement clinker. It can also be used as a backfill for utility trenches, shoulders, base course for foundations and sub-base for new pavements (Punthutaecha et al., 2006; Sutradhar et al., 2015). Figure 7, based on recommendations made by Saltelli, 2007, Morris, 1979, Albulescu, 2010, Freudenberg, 2003, Nardo et al., 2005) presents, comprehensively, the different stages of C & D waste management.

Applications

The application of solid waste-based building materials in real development is gaining popularity due to its potential to lessen the construction industry's environmental impacts. This includes the utilization of waste-derived materials such as fly ash, slag and recovered aggregates. These materials are used in a variety of construction applications, including building foundations, roads and pavements. The use of these materials can help reduce the demand for traditional construction supplies like natural stone and sand, which can be scarce in some places. Building materials made from solid waste offer various advantages, including lower building costs, increased durability and a lower carbon footprint. However, issues concerning quality control and the longevity of these materials must still be addressed. Overall, the use of solid waste-based materials in construction for actual development can make the building construction sector more environmental friendly and sustainable (Table 3).

Plastic

Since typical plastics have a lengthy carbon linkage and cannot biodegrade, there are several properties that provide benefits when used as a reusable material in construction. Although we often discard its use because of lack of knowledge, its sustainability in nature will provides durability in whatever work it is used. The use of PET in different building materials to increase the overall strength and durability has been discussed in Table 4.

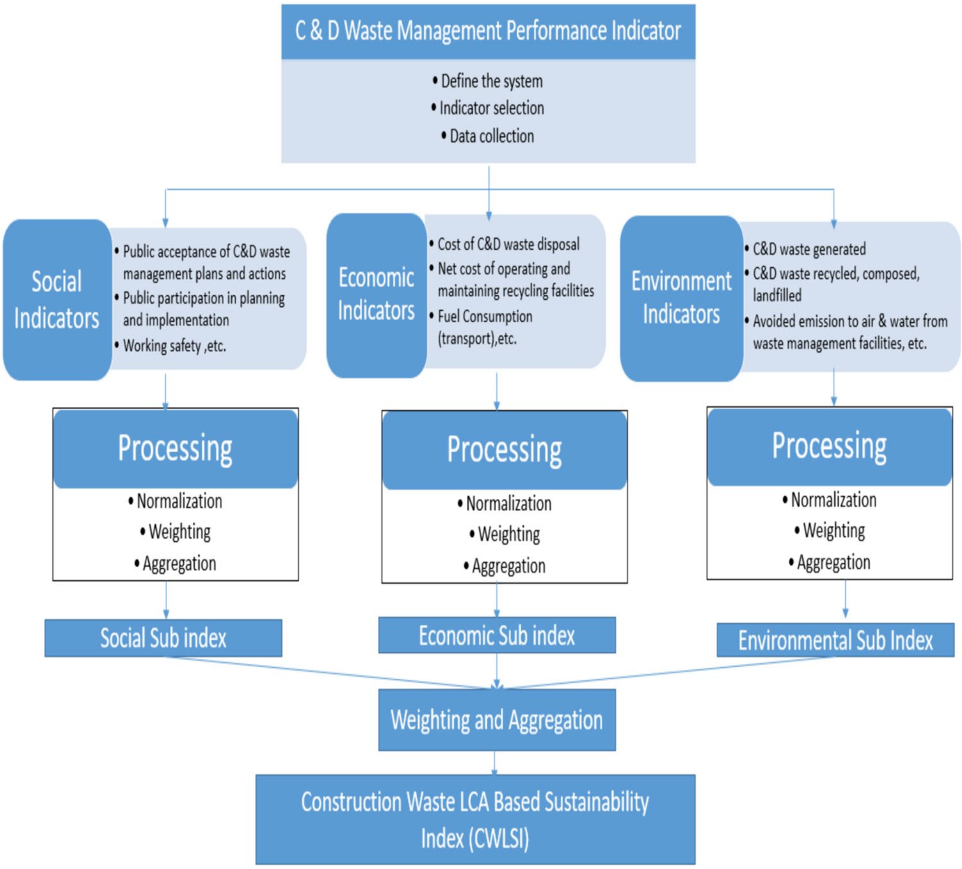


Fig. 7 A Structural determination of the CWLSI: A methodical examination

Table 3 Applications of solid waste-derived construction materials

S.no	Solid wastes	Materials used in construction	Application	References
1	Fly ash	Concrete with high performance	Water Tower, USA	Aitcin & Laplante, 2018
2	Bottom ash	Aggregates	Road sub base section, France	Bruder-Hubscher et al., 2001
3	Blast-furnace granulated slag	Concrete with high performance	Scotia Plaza, Canada	Aitcin & Laplante, 2018
4	Rice husk ash	Interlocking building blocks	Malaysian housing that is environmentally friendly	Nasly & Yassin, 2010
5	Palm oil fuel ash	Interlocking building blocks	Malaysian housing that is environmentally friendly	Nasly & Yassin, 2010
6	Bamboo fiber	Bamboo fiber-based material for composites	Low cost homes, India	Jain & Kumar, 1994
7	Waste of quarry	Aggregates	Flexible pavement's base layer, Brazil	de Rezende & de Carvalho, 2003
8	C & D wastes	Aggregates made from recycled concrete	Pearson International Air Port, Canada	Yeheyis et al., 2013

3-D printing

The approach of integrating cementitious building materials (CBM) in the 3D printing process involves extruding CBMs in layers under robotic motion control, which is also known as additive manufacturing in the construction industry (Tay et al., 2019). Over the past couple of decades, both academia and business have shown a considerable surge in interest in 3D printing technology (Gularte et al., 2017). This is mainly because automation drastically reduces the amount of time needed to create a structure by eliminating the requirement for formwork and human involvement. The 3D printing of CBMs primarily utilizes fine aggregates (Gosselin et al., 2016). The way materials are distributed, affects the amount that can be used. Among all substances, natural sand is commonly used in printing (Tay et al., 2017, 2019). By substituting sand with recycled waste glass (WG), a new market opportunity for WG can be created while

Table 4 Recent studies on PET-incorporated building materials

Title	Material types	Results	References
Aggregate from recovered concrete, Portland cement-based materials made of lighter PET composite aggregates: physiochemical and microstructure productivity, 2015	Cement mortar	PET flakes derived from recyclable packaging	(Gorak et al., 2021)
Strength of compression and water retention of soil–cement bricks made with pet waste inclusion, 2016	Block of soil–cement	Crushed PET from water bottle packaging	(Paschoalin Filho et al. 2016)
Tensile properties of environmentally friendly Strain-Hardening Cementitious Composites made of hybrid PVA and recycled PET fibres, 2018	Mortar	Surface treated (NaOH solution; silane coupling agent) PET fibers	(Yu et al., 2018)
Optimal amounts of recovered PET (polyethylene terephthalate) bottle fibre were used in concrete in 2018	Concrete	PET bottle fibres (length = 50 mm, width = 5 mm)	(Shahidan, 2018)
In a 2018 experiment, waste from PET bottles and woven plastic sacks was used to create fibre for recycled aggregate concrete	Concrete	PET bottle fibres (length = 50–60 mm, width = 2–3.5 mm)	(Bui et al., 2018)
Study on the behaviour of concrete when fine aggregate is partially replaced with waste plastics, 2019	Concrete	Water bottles, polythene bags and milk pouches	(Al-Fakih et al., 2020)
Analysis of the mechanical and physical attributes of recycled PET-added pressed concrete blocks with no structural purposes, 2019	Concrete	PET that has been recycled and shredded by a recycler	(Barreto et al., 2019)
The environmental impact of PET trash and the properties of concrete with a high strength exposed to extreme temperatures, 2019	Concrete	PET shredded bottles of water for consumption with fly ash	(Alfahdawi et al., 2019)
Using demolition trash and recovered PET mixes as building materials, 2019	Paving	C & D trash, broken PET bottles, and packaging for food	(Perera et al., 2019)
The endurance performance of a new super-high-performance PET green concrete, 2019	Concrete	PET fibres (length = 40 mm, width = 3.5 mm) were produced using a basic shredding machine	(Alani et al., 2019)
High strength concrete beams reinforced with PET waste fibre: experimental behaviour and analysis, 2020	Concrete	PET shattered from water-for-drinking bottles	(Mohammed & Rahim, 2020)
Optimisation and prediction of recycled PET aggregate concrete reinforced with steel fibres' post-fire compressive strength 2020, via RSM and GEP	Concrete	PET chips	(Nematzadeh et al., 2020)
PET blends containing demolition debris were tested for rigidity and flexural strength,2020	Paving	PET that has been recycled and shredded by a recycler	(Arulrajah et al., 2020)
Fracture and mechanical characteristics of polyethylene terephthalate (PET) granule-containing asphalt mixtures, 2020	Paving	PET granules	(Esfandabad et al., 2020)
2020 study on the acceptability of polymeric HDPE and PET wastes used to unfired clay bricks as a building material	Clay brick that has not been burned	PET flakes crushed into three sizes: < 1 mm < 3 mm < 6 mm	(Limami et al., 2020)
The 2020 mechanical characteristics of epoxy mortar that contains PET waste	Mortar	PET waste glycolisates generated by two industrial facilities	(Dębska & Lichołai, 2015)

Table 4 (continued)

Title	Material types	Results	References
Assessment of PET Material Improvement for 3D Concrete Printing, 2021	Mortar	PET granule (dia = 2–5 mm)	(Skibicki et al., 2021)
Mortar efficiency with PET, 2021	Mortar	PET wastes that have been grounded	(da Luz Garcia et al., 2021)
PET and PP plastic waste-containing AC-WC mixture's strength and toughness properties under static compression, 2021	Asphalt-Concrete mixtures	Shredded PET bottles	(Djamaluddin et al., 2021)

reducing the demand for sand, which is a limited resource. An assessment, in a study conducted by Ting et al. (2019), evaluated the 3D printing capabilities of recycled WG mortar in combination with sand. To assess the effects of aggregates, rheological and functional analyses of the mixtures were conducted. The rheological results demonstrated the benefits of using recycled CBMs with WG for printing. The reused WG mixture exhibited flow properties due to its plastic viscosity and variable yield stress compared to the original sand blend. This difference was likely caused by an amount of water in the WG mixture, leading to reduced absorption capacity of the naturally occurring sand particles. as indicated in another study (Tan & Du, 2013). Another explanations could be that recycled WG particles have a smooth surface similar to that of natural sand particles (Jiao et al., 2017).

Geopolymerisation

In modern times, WG powders are being investigated as a possible alumina source for the manufacture of geopolymers (Cyr et al., 2012; Olawale, 2013). The study of geopolymers made from WG is a relatively recent subject of research. One study found that the mechanical characteristics of WG-based geopolymers were substantially impacted by WG particle size, curing conditions, and alkali solution content (Cyr et al., 2012). These geopolymers also attained compressive strengths equivalent to fly ash-based geopolymers. In a study investigating the effects of partially substituting WG powder for metakaolin in the manufacture of geopolymers, Novais et al. (2016) found that adding 12.5% WG improved compressive strength by over 46%. However, in a geopolymer made entirely of metakaolin, adding more WG had the reverse effect.

C&D waste

The European Union produces over 850 million tonnes of C&D waste each year (Novais et al., 2016), with France having the highest average at 349 million tonnes in 2014 (Ge & Hokao, 2006) and the United Kingdom having the lowest estimate at 90 million tonnes (Tam et al., 2018). In the US, the yearly generation of building and demolition waste is 534 million tonnes (Williams & Turner, 2011), 77 million tonnes are produced annually in Japan (USEPA, 2016), 20 million tonnes in Australia (Pickin & Randell, 2017), 200 million tonnes in China, 17 M tonnes in India, and roughly 7 M tonnes annually in Dubai and Abu Dhabi (USEPA, 2016). In 2011, Germany's recovered resource percentage was 91%, while in France, 50% of the entire amount of C&D trash created in 2014 was recycled. This is because the majority of material from C&D is recovered and repurposed for both environmental benefit and economic gain (Randell et al., 2014). While the rate of recovering resources in the United States was 48% in 2011, over 62% of C&D waste has been recycled annually in the United Kingdom. Around 64% of C&D waste in Australia was recycled in 2014 (Table 5).

Circular economy

Due to the limited availability of resources on Earth, the authors strongly support the promotion of the circular economy as a viable and forward-thinking paradigm that is environmentally sustainable. The circular economy's objective is to maintain closed loops for raw materials. Resources should be used as efficiently as possible, reducing the need for fresh ones, preventing waste and lengthening the life cycle of products. The waste of today should ideally become the raw of tomorrow. It aims to optimize assets so they operate more quickly, safely, sustainably and for longer. Projected waste generation by 2030 and 2050 has been depicted in Fig. 8 (prepared based on discussion presented by Kaza et al., 2018). Overall, a positive correlation between income level and waste generation can be observed. It has been estimated that daily waste generation per capita in high-income countries will increase by 19% by 2050, while in low- and middle-income countries, waste generation will increase by 40% compared to the present levels.

Impact of construction waste on the economy

The prices of mining and basic commodities are increasing even as the circular economy is receiving an increasing amount of focus. According to the circular economy, in 2019, 9% of the initial supplies were fully repurposed. The percentage increased slightly to 9.1% in 2018 (Musarat et al., 2022). In the circular economy, all raw materials are recycled, eliminating the need for fresh raw materials. However, achieving this scenario will take a very long time because techniques for fully recycling the components currently used in goods must be developed. Sustainability and the circular economy go hand in hand (Wilcox et al., 2007). Figure 9 provides an excellent illustration of this, showing the contributions of the circular economy in terms of Research and development (R&D), service management (SM), logistics and reverse logistics (L&RL), quality management (QM), cost management (CM), circular supply chain management (CSCM), environment management (EM), process management (PM) and strategic planning (SP) are all examples of cost management.

Table 5 Global construction and demolition waste recovery rates by country

Countries	Total C&D waste (mil. tons)	Total C&D waste recov-ery (mil. tons)	C&D waste recove-ry (%)	References
Oceania				
Australia	19.30	12.00	62.20	(Pickin & Randell, 2017)
Asia				
China	300	120.00	40.00	(Yang et al., 2017a)
Japan	77.00	62.00	80.50	(Pickin & Randell, 2017; Wilson et al., 2015)
Taiwan	63.00	58.00	91.00	(Barritt, 2016; Yang et al., 2017b)
Thailand	10.00	3.20	32.00	(Cherdsatirkul, 2012)
Europe				
Denmark	21.70	20.40	94.00	(Bürgin, 2021)
Finland	20.80	5.40	26.00	(Bürgin, 2021)
France	342.60	212.40	62.00	(Bürgin, 2021; Cazorla, 2017)
Germany	192.30	165.40	86.00	(Bürgin, 2021)
Ireland	16.60	13.30	80.00	(Bürgin, 2021)
Netherlands	25.80	25.28	98.00	(Bürgin, 2021)
Norway	1.30	0.87	67.30	(Bürgin, 2021)
Spain	38.50	5.39	14.00	(Bürgin, 2021; Vázquez-Bustelo & Avella, 2006)
Switzerland	7.00	2.00	28.00	(Bürgin, 2021)
United Kingdom	114.20	74.23	65.00	(Bürgin, 2021)
Americas				
Canada	0.66	0.20	30.00	(Pederneiras et al., 2020)
USA	534.00	256.30	48.00	(Korinjoh, 2017)
Africa				
South Africa	4.70	0.76	16.00	(Baloy et al., 2012)

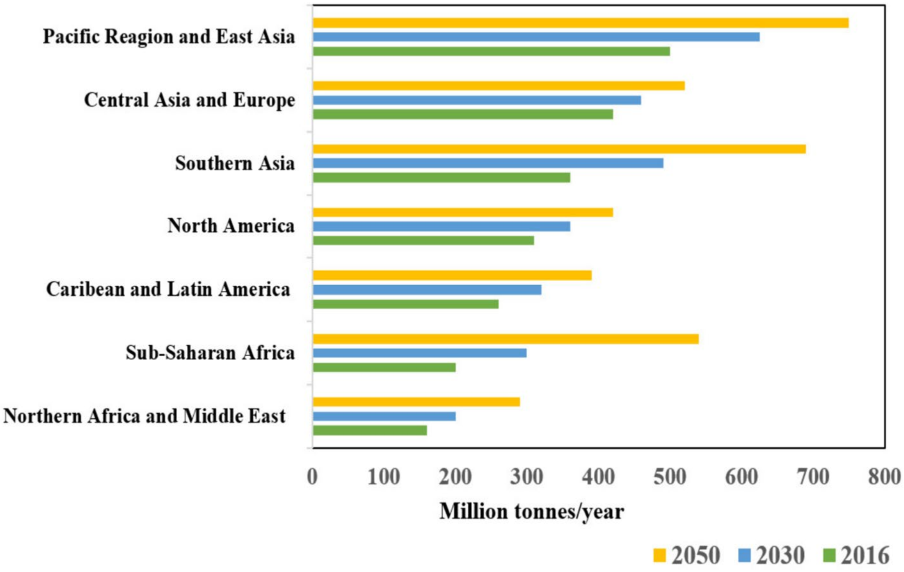


Fig. 8 Projected waste generation trends in various global regions

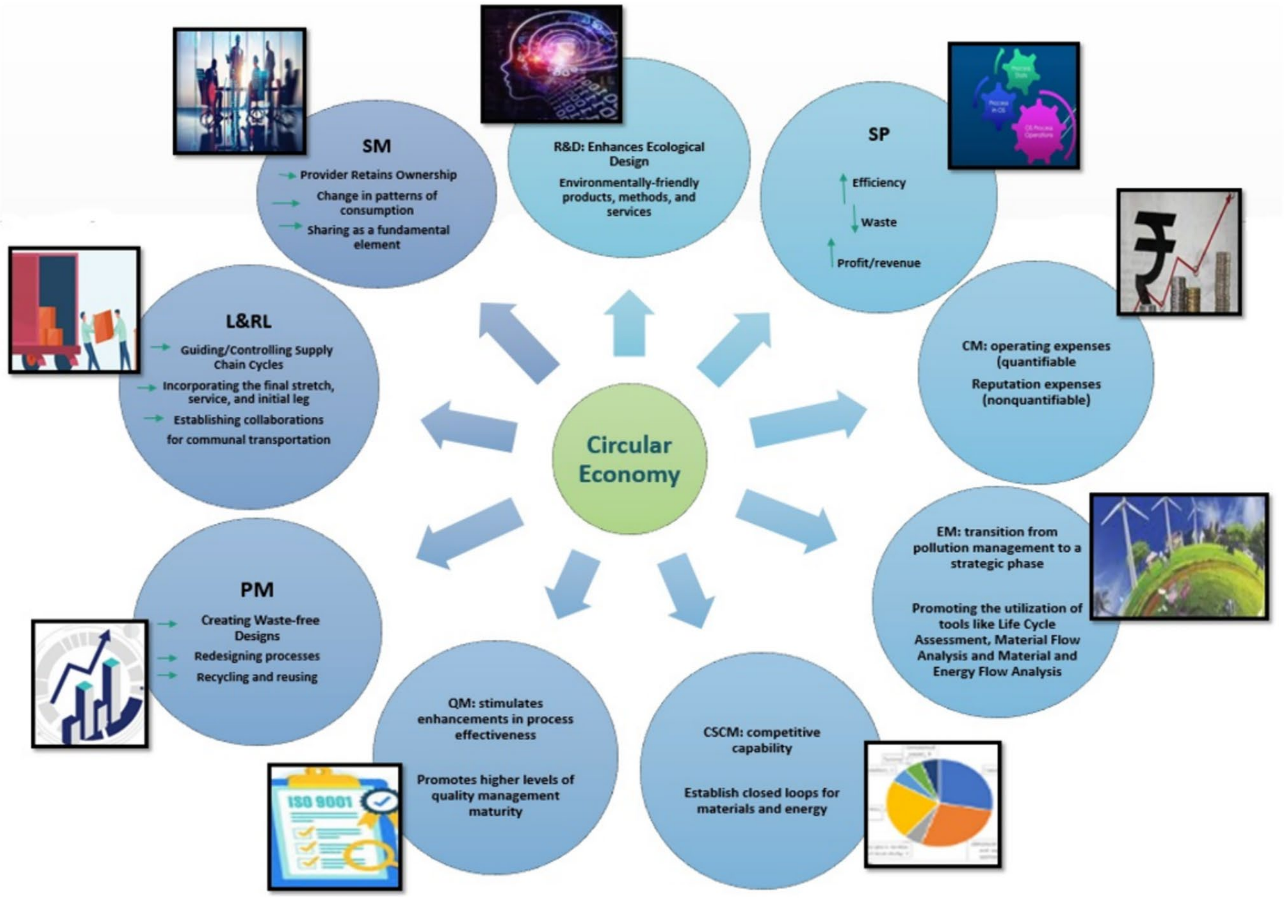


Fig. 9 Contributions of the circular economy to sustainable development

Figure 10 further emphasizes the circular economy prospects by 2030, which was previously underlined as an economic opportunity from the circular economy.

According to the United Nations Environment Programme (UNEP) (Musarat et al., 2022), increased resource efficiency could result in roughly $2 trillion in economic

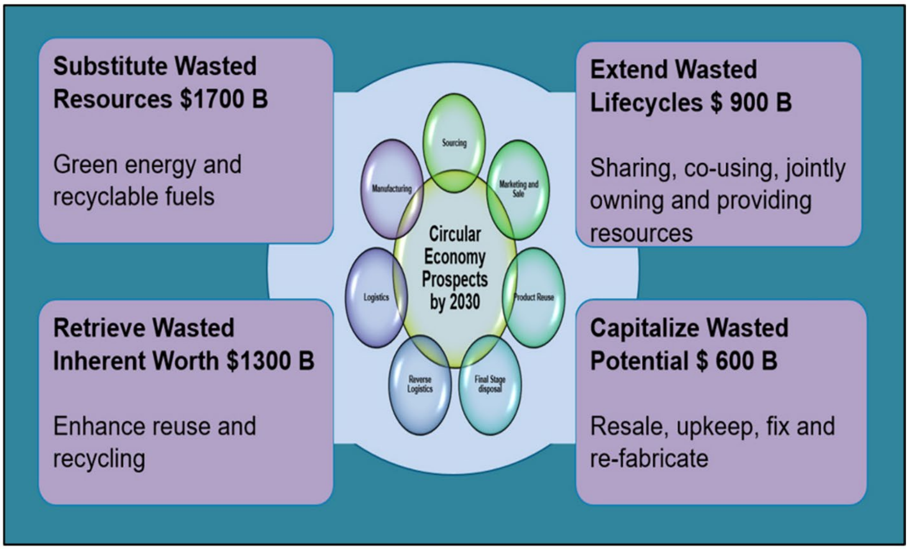


Fig. 10 Anticipated economic shifts within the circular economy of 2030

benefits annually by 2050. This can be achieved by developing more functions using the same amount of resources and production capability while also raising revenue from new circular activities. These circular items require a specialized staff for their creation, manufacture, and maintenance, which expands job opportunities. On the other hand, as raw material extraction and processing become less necessary, less specialized labor becomes available (Sulich & Sołoducho-Pelc, 2022).

Conclusion

Utilizing recycled or abandoned materials in construction projects is becoming a more popular strategy to promote sustainability and lessen negative environmental effects. To ensure the caliber and consistency of these materials, however, several concerns must be resolved:

1. One key challenge is the lack of standardization in waste management practices. The absence of norms and procedures for disposing and recycling construction waste can lead to dumping and inadequate waste management practices, which can harm the environment and public health. Establishing rules and regulations for waste management in the construction industry is essential to ensure disposal of waste and effective utilization of recycled materials.
2. Recycling plastics into pellets for construction materials such as pipelines, insulation and roofing tiles has been successful in reducing waste and its environmental impacts. However, specialized facilities and technologies are necessary due to the complexity of plastic recycling. Encauragement and motivation in using plastic in construction investments in infrastructure and technology that facilitate plastic recycling are vital.
3. Construction and demolition (C&D) projects generate an amount of waste for the building sector. Utilizing C&D waste in construction can benefit the environment by reducing reliance on virgin resources and minimizing waste generation.
4. To meet the standards for performance, it is necessary to implement quality control methods and standardized testing techniques when dealing with construction and demolition (C&D) wastes due to their varying quality and consistency.
5. The use of building wastes, such as fly ash and slag, as substitutes for materials like cement and sand can lead to reduced impact improved resource efficiency and cost savings. Further research is needed to optimize the utilization of these materials in construction practices while ensuring their consistency and quality.
6. Adopting a circular economy approach offers a method for waste management by promoting resource redistribution and waste reduction. By designing products with a circular economy mindset, it becomes feasible to redistribute resources times while minimizing waste generation and the reliance on resources.

Incorporating recycled or discarded materials in construction projects has the potential to enhance sustainability reduce harm and improve resource efficiency. For these materials to be used effectively, issues with waste management, recycling, and quality control procedures must be addressed. The sustainable recycling and reuse of waste materials in construction will be supported by advancing clear waste management legislation and guidelines, making investments in recycling infrastructure and technology, and creating quality control processes.

Author contributions Bishnu Kant Shukla: As the main author and supervisor, Bishnu Kant Shukla played a pivotal role in conceptualizing the study, leading the research design, and overseeing the entire project. He was also instrumental in the analysis and interpretation of data and contributed significantly to the writing and editing of the manuscript. Additionally, Bishnu Kant Shukla is the corresponding author, responsible for communicating with the journal and addressing reviewers' comments. Gaurav Bharti: Contributed to the revision stage of the manuscript by creating high-quality figures and assisting in content creation. He played a significant role in enhancing the visual representation of data and concepts, ensuring clarity and effectiveness in conveying key findings. Additionally, Gaurav Bharti provided valuable input during the revision process, contributing to the overall improvement of the manuscript's quality and presentation. Pushpendra Kumar Sharma: Contributed to the data collection and analysis, particularly focusing on the aspects of sustainable materials and circular economy. He also assisted in drafting parts of the manuscript related to these areas. Manshi Sharma: Played a key role in the literature review, particularly in gathering and synthesizing information on recycled and waste materials in construction. She also contributed to writing the introduction and background sections of the manuscript. Sumit Rawat: Focused on the methodological framework of the study, contributing to the development of research methods and data analysis. He also assisted in the interpretation of results and drafting relevant sections of the manuscript. Neha Maurya: Actively involved in compiling case studies and practical applications of recycled materials in construction. She contributed to writing and revising the sections that discuss these applications. Risha Srivastava: Assisted in the environmental impact assessment part of the research, analyzing the data on greenhouse gas emissions and pollution reduction. She contributed to writing and revising the sections detailing these impacts. Yuvraj Srivastav: Provided support in graphical representation and visualization of data. He also contributed to the final editing and formatting of the manuscript to ensure compliance with journal guidelines.

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