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Utilizing plastic waste in the building and construction industry: A pathway towards the circular economy

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ABSTRACT

The study attempts to investigate the economic and environmental feasibility of linking the plastic waste recycling industry with the construction sector as a circular economy model (CE), particularly for Egypt. The result figured out that adopting the CE approach has several substantial environmental and economic benefits. It can turn plastic waste into eco-friendly and affordable building materials besides aligning with sustainable development goals (SDGs). The study contributes to raising local awareness about the potential of waste recycling. Moreover, promoting local stakeholders to widely apply the CE model in the construction and recycling plastic waste industry for a better sustainable environment

1. Introduction

Plastic production has achieved substantial growth more than almost any other material in recent years. Because of its beneficial properties, Plastic has witnessed an extreme increase in its applications, including medical delivery systems, packaging, industrial purposes, the construction industry, etc. [1,2].

According to Kumar and Agrawal [2], The main reasons behind the massive increase in global plastic waste generated annually include the following:

- Increasing global plastic production 200-fold between 1950 and 2014, with an expected double by 2050,
- The depressingly slow growth in recycling rates and,
- The short-term use of the majority of plastics

Every year, the world generates 330 million metric tons of plastics, about 9% are recycled, 12% are incinerated, and 79% are dumped in landfills [1,3–5]. As a result, plastic waste piles up at an alarming rate, and the world is embarrassed by its failure to address this issue.

Many efforts to tackle plastic pollution have only concentrated on improving waste management or clean-up. Others have focused on plastic ban and reduction. Recent studies advocate that none of these solutions will work in isolation. We must adopt the holistic CE approach as an alternative to the current linear "take, make, use, dispose of" economy model. The CE approach is defined as a model with the ability to convert, conserve, and reallocate materials and products to responsible use in the most environmentally, functionally, socially, and cost-effective way possible [6].

The CE approach is based on three principles; reduce waste and pollution through product design, retain sources and products in use, and regenerate and preserve natural systems [7–12]. So, it contributes to preserving limited raw material resources, decreasing greenhouse gas emissions, and extending the life of products through a continuous development cycle [13].

Recycling the plastic waste in a massive industry such as the construction industry has gained notable interest among several scholars. They have investigated how plastic waste can be transformed into value-added, affordable, and eco-friendly materials. Additionally, they have explored numerous applications of plastic waste. For example;

- As a replacement to aggregates for producing concrete, as a fiber, or as a binder [14–31].
- As an additive for enhancing bituminous mixes and asphalt [32–39].
- For soil stabilization or reinforcement [40,41].
- As a complete alternative to traditional building materials, such as bricks, plasters, paving blocks, permeable pavement, and an alternative to wood, plastic tiles [42–57].
- As a thermal and water insulation material [58,59].

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- As an alternative to brick or façade cladding by reusing plastic bottles and boxes [60–70].

This prior research has documented the financial and environmental advantages of these substitute materials, such as reducing the cost, less energy and water consumption, lower carbon emissions, and conserving natural raw materials. Additionally, the results have shown an improvement in the engineering properties of these new materials, such as enhancing durability and quality, being lightweight, and more resistance to water, heat, corrosion, and cracking. All these materials have been tested and have shown their viability and structural stability under specific conditions. Other studies have introduced general reviews on different applications of plastic waste in the construction industry [71–77].

Locally, Egypt has a long-standing problem with plastic waste disposal. In 2016, Egypt generated about half of the mismanaged waste among the Mediterranean countries. It was rated fourth with 12.6% of plastic waste generation [78]. The random disposal process of plastic waste causes a constant threat to the local ecology, economy, and human health [79]. Furthermore, there is a limited recycling industry of plastic waste as an application of the circular economy approach. The other challenge Egypt faces is the high cost of building materials as a result of high energy consumption in addition to increasing the Co2 emissions that accelerates climate change.

Few studies were uncovered by the author that link recycling plastic waste with the construction sector as an application of the CE approach [6,13,80–83]. These limitations were the motivation behind conducting the current study to fill this knowledge gap. Therefore, the study intends to investigate the environmental and economic feasibility of the CE model by utilizing plastic waste in the building and construction industry. The questions the study tries to answer are how the CE approach can offer a radical and multi-faceted solution to the negative impacts of both challenges; plastic waste and the construction sector, and to what degree this approach aligns with sustainable development goals (SDGs) that Egypt seeks to adopt in its 2030 vision. So, the results are expected to encourage local stakeholders to apply this model as an affordable strategy for zero plastic waste and low carbon footprints of buildings.

2. Research methodology

The study adopted mixed methods by combining qualitative and quantitative methodology because the research purpose has multifaceted dimensions. This mixed method helps gain a holistic understanding of the research problem and enables the author to deeply answer the research question [84]. The study begins with an in-depth review of related literature to explore both challenges of plastic waste disposal and the construction industry globally and locally. The study depended mainly on recent official reports and statistics developed by global institutions and the Egyptian Government. Then the current study explored earlier works gathered through a systematic web-based search on various academic search engines, such as the Web of Science, Google Scholar, and Crossref metadata. The research process focuses on specific keywords including; plastic waste, recycling plastic waste, recycled construction materials, and circular economy. The articles that linked plastic waste with the construction sector were included then all articles published before 2000 were excluded. The study found 83 articles which then were thematically analyzed by categorizing them into main themes to conclude with the various recycled plastic-based construction materials, their general and specific potentials, limitations, and their applications. The study found only 6 articles that have addressed the utilization of plastic waste in building construction from the CE perspective. These few studies reflect a knowledge gap that the current study seeks to cover. Finally, the author used the case study method to analyze several local and global architectural projects that apply the CE model by utilizing plastic waste as construction materials. The author selected the projects that were built in the last ten years, varied in scale, type, and function, and from both developing and developed countries to gain a comprehensive evaluation of the environmental and economic potential of the CE model. Fig. 1 illustrates the research methodology.

3. Materials and method

3.1. Plastic

Plastic is the backbone of our modern society since it is widely used in diverse sectors worldwide. For example; in packaging, agriculture, the medical sector, manufacturing, transportation, and building construction.

These wide applications are due to the beneficial properties of plastic, such as lightweight, high strength, good safety, hygiene properties, durability, longevity, thermal and water resistance, and low-cost production [1,2,11,13,44].

Plastics are divided into thermoplastics, which melt when heated and harden when cooled, and thermosets, which change chemically when heated. Thermoplastics, such as Polyethylene Terephthalate (PET), Polypropylene (PE), Low-Density Polyethylene (LDPE), High-Density Polyethylene (HDPE), and Polystyrene (PS), are recyclable. The thermosets, which include phenolic and epoxy resins, are non-recyclable [76,77,83]. Plastics are also classified into six common types [67,69]. Each has a recycled identification code defined by the European Commission, as shown in Fig. 2.

3.2. The global crisis of plastic waste disposal: its causes and impacts

Producing plastics has historically outpaced that of almost every other material due to the enormous rise in the use of plastics in daily life. Fig. 3 shows the plastic production in millions of tons from 1950 until 2020. According to this statistic, 9.2 billion tons of plastic have been produced in the last fifty years. That is more than one ton for each person now on Earth [74,85].

Growing urbanization, rising populations, and changing consumption habits lead to the rapid growth of a global generation of solid waste, particularly plastic waste [2,71]. The negative issue is that plastic is non-biodegradable and remains in nature for hundreds of years [1,48].

Additionally, incineration of plastic waste or disposal in landfills and water bodies causes hazardous effects not only on human health but on the whole ecosystem [1,48,69,73,77].

According to Goli et al. [1], Singh et al. [4], Zulkernain et al. [5], da Silva et al. [13], Lamba et al. [75], and Lebreton and Andrady [86], about 300 million tons of plastic waste are generated every year globally. Only 9% of plastic waste is recycled, while approximately 70% is dumped into landfills and the marine.

The other reason that contributes significantly to increasing the problem of plastic waste is that most plastics are used for short-term or single-use applications such as packaging, while nearly a quarter is used for long-term applications. Fig. 4 shows that the packaging industry is the highest sector that generates waste in 2015, which equals 50% of global plastic waste [87]. On a global scale, 14% of plastic packaging is currently recycled, 40% is dumped in landfills, and 14% is burned in incinerators. The last 32% is dumped on sites, water bodies, or into the air, causing a great crisis to the whole ecosystem [88].

Plastic waste pollution is considered one of the greatest ecosystem threats since it has affected the environment, human health, and the economy. Environmentally, the plastic disposed into the oceans and rivers leads to water pollution due to the degradation of many toxic compounds, which cause physical hazards to marine life [5]. Toxic chemicals and CO2 emissions from burning plastic waste pollute the air and cause several diseases to humans, animals, and vegetation [19,77].

The increasing cost of landfill, the high energy used for incineration, and the related increase in greenhouse gas (GHG) emissions have forced the world to find an alternative solution to such challenges [44]. Therefore, in the last few decades, extensive studies have advocated

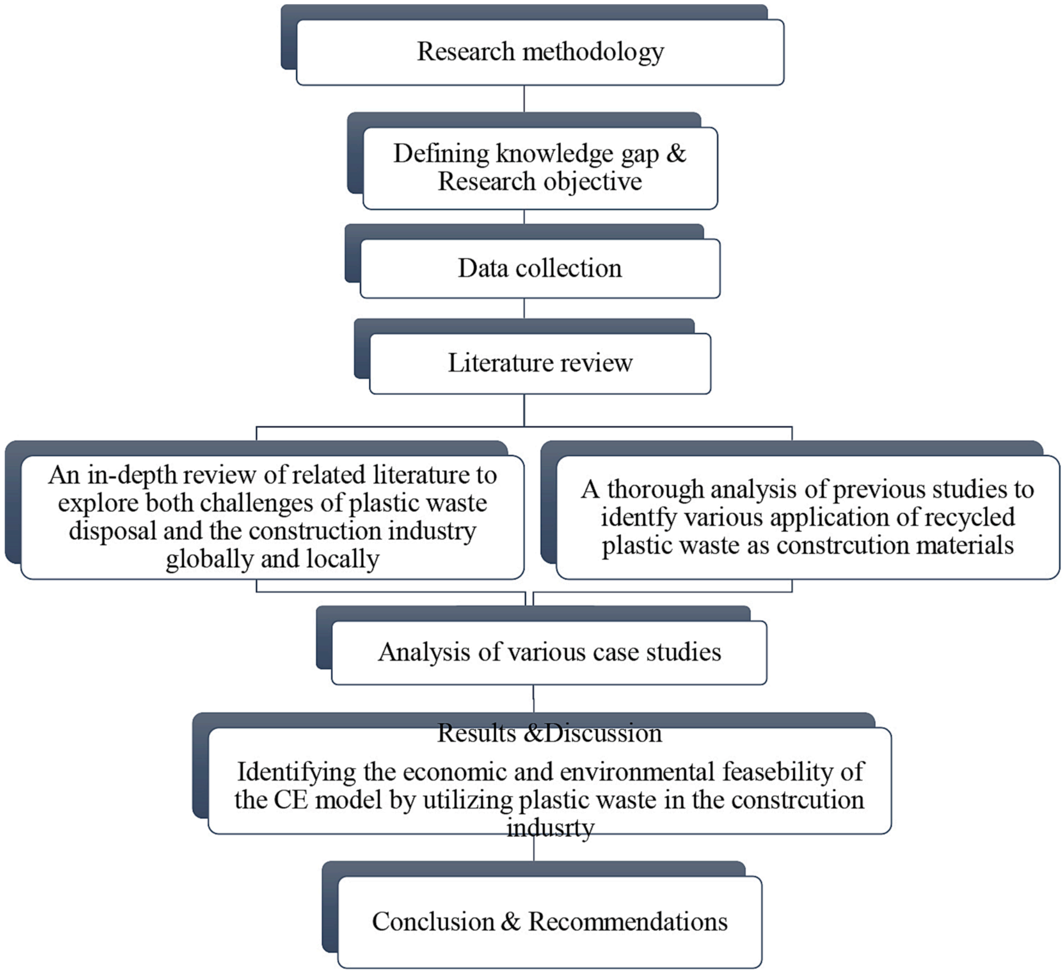

Fig. 1. Research Methodology.

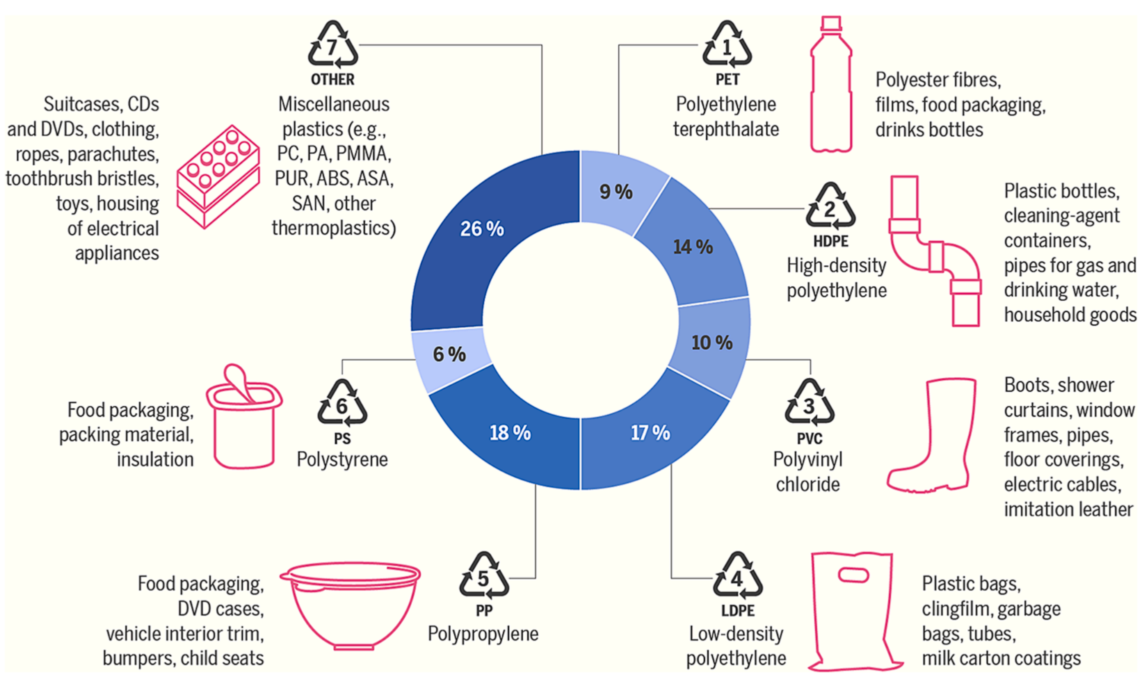

Fig. 2. Seven recycling codes, their applications, and percentage of total quantity produced worldwide, 2015 [83].

Fig. 3. Annual production of plastic worldwide from 1950 to 2020 in million metric tons [85].

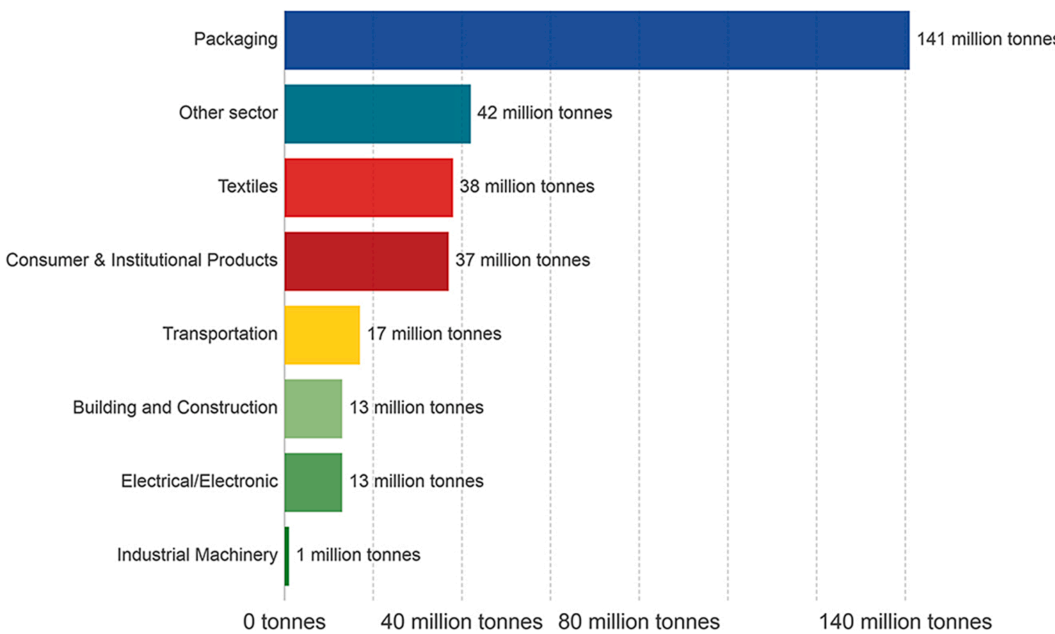

Fig. 4. Plastic waste generation by the industrial sector in 2105 [87].

recycling and reusing plastic waste as a feasible alternative to manage this problem effectively. It has been observed that recycling preserves the vast majority of the energy inherent in plastic waste when compared to incineration, where the vast majority of the energy is wasted [88], as shown in Fig. 5.

3.3. The challenge of plastic waste disposal in Egypt

Every year, Egypt generates over 90 million tons of solid waste. Municipal solid waste accounted for around 28 million tons. About 10 million tons, or 45% of this solid waste, are produced annually in the Great Cairo sector. Plastic waste constitutes about 13% of the total municipal solid waste [79]. Among the Arabic countries, Egypt ranked the highest in producing mismanaged plastic wastes that are either littered or inadequately disposed of in 2019 2019 [89], as illustrated in Fig. 6.

Globally, Egypt was the fourth biggest source of plastic polluting the Mediterranean in 2010 [78], and ranked seventh in producing ocean's plastic waste by 1 million metric tons of mismanaged plastic waste and 0.39 of plastic marine debris [90], as shown in Fig. 7.

In 2015, Egypt was among the top ten countries that generated about 1.6 million tons of globally mismanaged plastic waste (MPW). Cairo was the second largest producing urban center after Manila [86]. In 2016, among the Mediterranean countries, Egypt was the largest source of open-dumping plastic waste by total volume, dumping 1.3 million tons into open sites each year. Furthermore, Egypt, Turkey, and Italy caused 2/3 of the plastic leakage into nature [91].

According to the previous statistics, solid waste disposal in Egypt is considered a chronic challenge, causing many environmental and economic problems. It has emerged due to several cumulative causes according to State of the Environment 2016 Arab Republic of Egypt [79], as follows:

- Overpopulation; Egypt's population reached 94.8 million in 2017, with a 2.56 percent rise in population growth rate between 2006 and 2017.
- Internal migration from rural to urban regions has led to a massive increase in informal settlements and slums, which generates thousands of tons of municipal solid waste daily.
- Changing Egyptian consumption patterns, with a notable increase in fast food consumption which causes large quantities of waste.
- A shortage of capacity building and training in solid waste management.
- A lack of environmental conservation regulations, and ineffective implementation mechanisms.

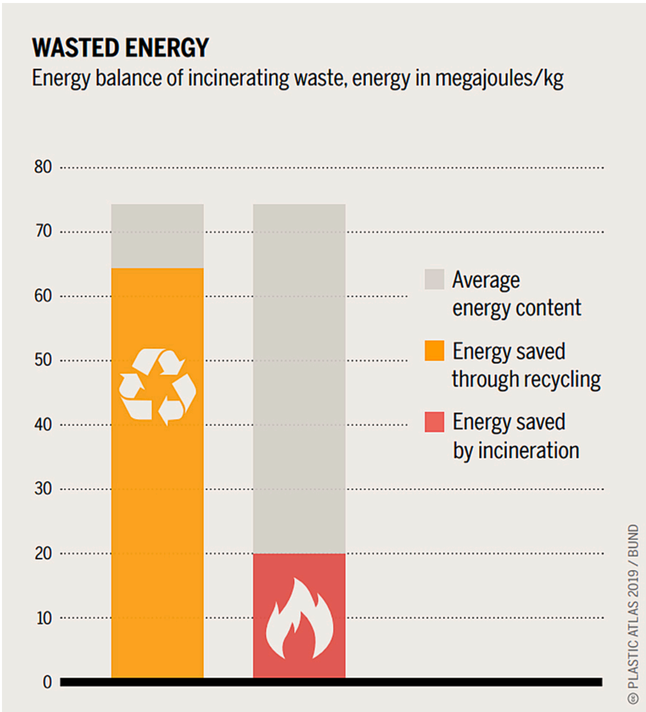

Fig. 5. Energy balance of incinerating waste, energy in megajoules/Kg [88].

- Only 12 % of municipal solid waste was recycled, and 7% was disposed of in landfills.

3.4. The manifestation of mismanaged solid waste in Egypt

The manifestation and impacts of improper solid waste disposal in Egypt are summarized in the following section.

3.4.1. Increasing the haphazard disposal of solid waste

Depending mainly on open burning and haphazard disposal of solid waste in dumps or uncontrolled landfills, which is estimated by 81% of disposal methods, causes several negative impacts on human health and the environment. Generally, the burning of plastic waste discharges most greenhouse gases, which add to global warming and air pollution. In addition, the other toxic chemicals released from plastic waste burning include mercury, polychlorinated biphenyls, furans, and dioxins. This causes a threat to human health, resulting in many diseases like cancer, high blood pressure, and asthma [19,52,77]. It is imperative to highlight that Egypt has a growing cancer incidence rate, which was reported to be 166.6 per 1 million in 2013 and is expected to triple by 2050 [92].

Animal well-being and vegetation are also affected when such gases are emitted into the air. Soil is contaminated and degraded by the toxic chemicals released after dumping plastic waste on the ground, like phthalates and biphenyls [93].

3.4.2. Disposing of solid waste along roadsides

Disposing of solid waste along roadsides or in open spaces, particularly in slum areas and informal housing regions, is a source of airborne chemical contamination via off-site migration of gases and the particles and chemicals adhering to dust. According to Salam [94], it causes the spread of epidemics and chronic.

3.4.3. Disposing of solid waste in water streams

In urban areas, solid waste is often transported by stormwater runoff. In urban and rural areas, these items are sometimes illegally dumped directly into a waterbody or deposited along riverbanks. It causes contamination of water bodies or the groundwater source and chokes drainage. Srivastava and Chini [95] indicated that direct dumping of untreated waste into water bodies results in mercury toxicity from eating fish with high levels of mercury, the high algal population in rivers and seas, congenital malformations, and neurological disease.

3.4.4. Disposing of plastic litter in the Mediterranean Sea

plastic litter disposal in the Mediterranean Sea by the coastal cities or that generated from maritime touristic activities threatens the marine environment. This waste degrades into microplastics, causing the deaths of many marine organisms, and having massive effects on the tourism, fishing sector, and maritime industry [78].

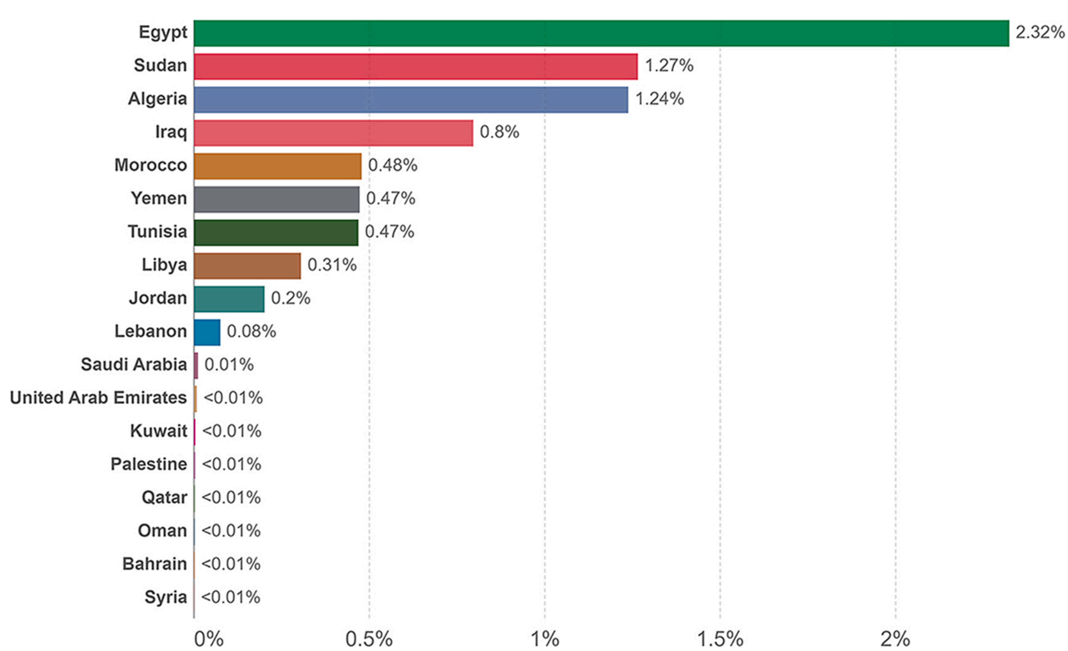

Fig. 6. Share of global mismanaged plastic waste among Arab Countries based on Meijer et al. [89].

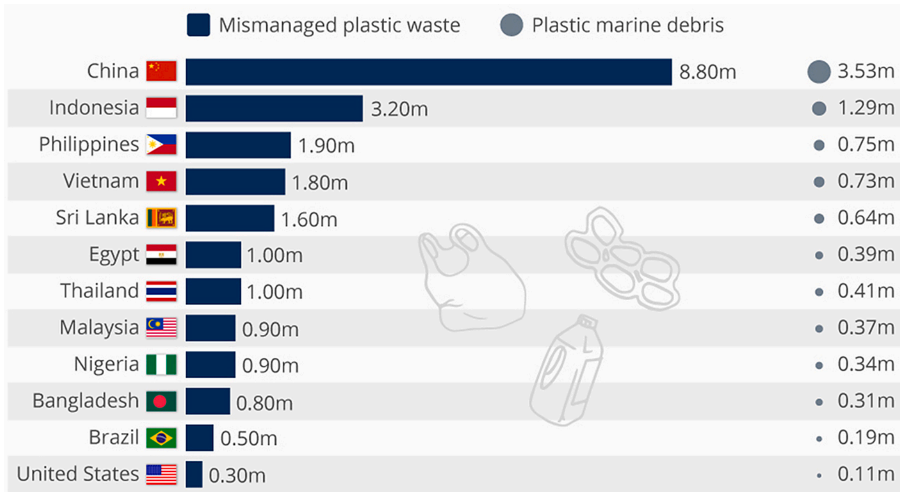

Fig. 7. The countries polluting the ocean the most measured in million metric tons annually in 2010 based on Jambeck et al. [90].

3.5. Building and construction industry and its related challenges

Regarding its contribution to the Egyptian economy, the construction industry ranked third after tourism and communications in 2017. In 2016, production from the construction industry in the Egyptian economy increased by 10.3 %. The sector contributes 5% to the Egyptian Gross Domestic Product (GDP) and employs about 11% of the total population [96,97].

3.5.1. The challenge of high cost of construction materials

Construction materials, which account for 40%–70% of total project costs, are regarded as the most cost-effective executive components, particularly in developing countries [96].

The government's subsidy removal plan coupled with the decision to float the Egyptian pound in 2016, the COVID-19 pandemic crisis in 2020, and the Russian-Ukrainian war in 2022, have all contributed to an extreme rise in energy costs reflected in the rising prices of petroleum products, electricity, and natural gas [44]. As a result, construction materials prices in Egypt have dramatically increased. For example, steal prices fluctuated to 17,750 LE/ton in July 2022 with a 22.4% growth compared with July 2021, the Portland cement price was recorded at 1325 LE/ton with a 51% growth, and the concrete prices were recorded at 1086 LE/ton with a 39.1% growth compared with the previous [98]. This accelerating growth in building materials prices has contributed to increasing the overall cost of projects.

3.5.2. The challenge of high energy consumption and greenhouse gas emissions

Shrivastava and Chini [99] categorized the energy used by a building during its life into:

- Embodied energy that used initially to produce a building, such as extraction, processing and manufacture, transportation, and assembly.
- Recurring embodied energy that is used in the restoration and maintenance process of the building.
- Operational energy which used in heating, cooling, lighting, equipment, and appliances.
- Demolition energy that used in the demolition process and transporting demolished materials to landfill or recycling centers.

European and U.S. statistics estimate the construction share to be about 7–10% of total embodied energy, which will play a substantial role in achieving sustainable construction [99].

In 2020, the building and construction sector accounted for 36% of global final energy usage, 10% of which was used by manufacturing building materials and products such as steel, cement, and glass. It also accounts for 37% of global energy-related CO2 emissions [100], as shown in Fig. 8.

The manufacture of most construction materials consumes extensive embodied energy. For example, the iron and steel industry accounted for 20% of global industrial energy use, 8% of total final energy use, 2.5% of global gas demand, and 5.5% of global electricity demand in 2019. Regarding CO2 emissions, they accounted for 2.6 Gt of direct CO2 emissions in 2019, representing about one-quarter of industrial CO2 emissions and 7% of total energy sector emissions [101].

The cement industry also consumes approximately 12–15% of total industrial energy use, accounts for 87% of the total global warming impacts, and about 8% of total global CO2 production, which is projected to rise beyond 25% by 2050 [31,102].

The latest studies indicate that concrete emits CO2 in large quantities, which undeviatingly affects climate change. Concrete and concrete-related products emit about 5% of annual anthropogenic CO2 emissions [76]. In Egypt, the building sector consumed 42% of electricity and 20% of final local energy in 2010–2011, which makes it the third biggest sector after the industry and transportation sectors [103].

The fundamental building materials, including iron, steel, and cement, consume intensive energy. For example, the iron and steel industries consume 500–650 kW/ton of electricity in the melting process and 250–300 m3/ton of natural gas [104].

Regarding greenhouse gas emissions, the latest studies state that the construction sector accounts for at least 23% of greenhouse gas emissions, where 75% of this percentage is produced by construction material production. For example, cement production accounted for about 8% of total CO2 emissions in 2015, and iron and steel accounted for 1% [105].

3.6. Utilizing plastic waste in the construction industry as a CE model

One of the most significant reasons behind the massive growth in global plastic waste is adopting the linear economic model of "take, make, dispose of," using raw materials for producing plastic products and disposing of them at the end of life. For example, plastic packaging, which constitutes a high portion of plastic waste, is produced for one-time use, causing massive waste.

As a result, several authors advocate the feasibility of recycling and reusing plastic waste in the construction sector and investigated various applications of plastic waste as an affordable and eco-friendly alternative to traditional construction materials for example; using plastic waste as a replacement to aggregates for producing concrete or as a

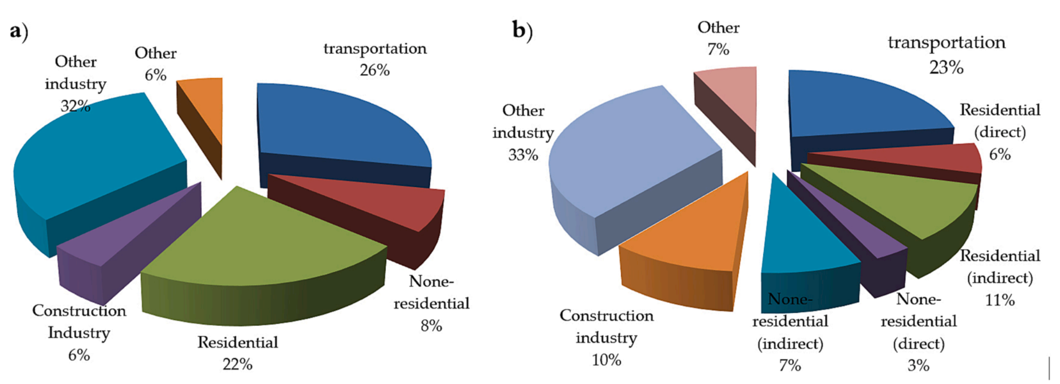

Fig. 8. (**a**) Global share of buildings and construction final energy, 2020; (**b**) buildings and construction's share of global energy-related CO2 emissions, 2018.

fiber, or a binder [14–31]. The results showed an improvement in the properties of the concrete; such as increasing ductility, initial stiffness, and compressive strength, decreasing density thereby lightweight, decreasing thermal conductivity, improving acoustic insulation, and savings in concrete and steel quantities which leads to savings in life cycle costs up to 5.9%. additionally, reducing consumption of natural materials, consequently reducing energy consumption and GHG emissions. This concrete can be used for a wide range of applications such as non-structural facades and sound barriers for highways.

Utilizing plastic waste as an additive for enhancing bituminous mixes and asphalt, this additive material has shown many advantages includes; resisting both fatigue cracking and rutting, increasing the durability and the stiffness of asphalt, improving the viscoelastic behavior of the bitumen, increasing stability, decreasing air voids, and reducing moisture absorption. This alternative material can be applied in pavement and road construction and for flexible pavement [32–39].

Utilizing plastic waste as an additive for soil stabilization or reinforcement improves the stiffness of the clay soil, and increases soil rigidity, So it can be used in roads base and sub-base [40,41].

Using recycled plastic mixed with filler materials such as fly ash, soil, and sand as a complete alternative to traditional building materials; such as brick, wood, poly-wood, and timber was investigated by many authors [43,46,48,52,56]. The results showed that alternative material is more resilient, having better quality, cost-effective and eco-friendly, lightweight, resistant to oil, salts, acids, and alkalis, reduces water absorption and energy consumption, and enhances shear resistance and load-bearing capability. These alternative materials can be used as facing brick, thin veneer brick, beams, and non-load-bearing walls.

Some studies investigated utilizing recycled plastic, particularly PET with an additive to produce an alternative to plasters which can be applied for basement or ground floors on screeds, or exterior walls [50,54,57]. The new material showed an increase in the values of stress, improving fragile behavior, and decreasing compressive and flexural strengths.

Using recycled HDPE or LDPE mixed with aggregates, gravel, ceramic waste, or sand to create paving blocks and permeable pavement investigated by ÇETIN [49]; Kumi-Larbi Jnr et al., [53]; Shanmugavalli and Gowtham [55]. The alternative material showed many advantages such as; reducing cost, resistance to heat, reduction of compressive strength, higher water resistance, and helping stormwater runoff.

Bajracharya et al. [44]; and Binhussain and El-Tonsy [47] investigated how mixing recycled PE or PVC with some materials such as cellulose fiber, wood flour, or glass fiber can produce an effective alternative to wood. The results illustrated that the new material has several economic and environmental advantages over wood including; assisting in conserving trees and decreasing carbon footprint, significant lifetime cost savings with high quality, resistance to rot, insects, algae, and fungi, longevity, durability, and is completely waterproof. The new material can be utilized in numerous applications, such as furniture applications, low-cost portable toilets, gates and doors, partitions, storage and shipping pallets, paver and block pallets, fences, and wall panels.

Utilizing Recycled plastic combined with Expanded Polystyrene (EPS) or foam as a thermal and water insulation material was investigated by Acierno et al., [58]; Moghaddam Fard and Alkhansari [59]. The results showed that alternative material improves water and fire resistance, increases durability, and long-term energy saving. It can be applied for water and thermal insulation for foundations, walls, roofs, and floors.

Reusing plastic bottles as an alternative to brick has considerable interest among several authors [60–70]. The plastic bottles were filled with soil, sand, gravel, or sand to increase their intensity and used to build a non-load-bearing wall. The results showed that plastic bottles have superior advantages over traditional brick, such as higher compressive strength and load capacity, lighter weight, higher thermal resistance, providing thermal mass storage, saving cement, water, and fittings, inexpensive relocation, no construction waste, and increasing the bearing capacity against earthquakes.

Since the 1970 s and 1980 s, the CE concept has emerged as a sustainable alternative to the linear model. It is an economical, societal, and environmental framework that aims to shift from consuming finite resources toward preserving the materials in a closed loop to retain their true benefit. It has a higher capability to minimize waste production and resource extraction, besides producing more affordable, eco-friendly, and value-added products [13,81,102].

The CE is defined as restorative by design and targets to keep products, components, and materials at their highest value, productive use, and effectiveness at all times characterizing technical and biological cycles [81]. It is also defined as an approach that can restore, retain, and redistribute components, materials, and products back into the system in the most environmentally, functionally, socially, and cost-effective way by Anwar et al. [6]; Hahladakis et al. [9]; Huysman et al. [10]; and Yhdego [12] defined CE broadly as a system-based approach to economic growth and a paradigm shift from the linear economic model of extract-produce-consume-dispose-deplete (epcd2) to a higher level of achieving zero waste. It aims to resource conservation and change concepts in production process design and material selection for a longer life cycle.

According to Nodehi and Taghvaee [102], the CE model has adopted six principles (6Rs): Reuse, Recycle, Redesign, Remanufacture, Reduce, and Recover. These principles guarantee effective plastic waste management and achieve zero waste. Fig. 9 illustrates the flowchart of the circular system of plastic products and related recommendations for efficient application.

Incorporating the CE approach of plastic with building and construction demands by utilizing plastic waste as sustainable and green building materials, as illustrated in Fig. 10 has numerous advantages.

The most significant potential of the CE lies in its compliance with

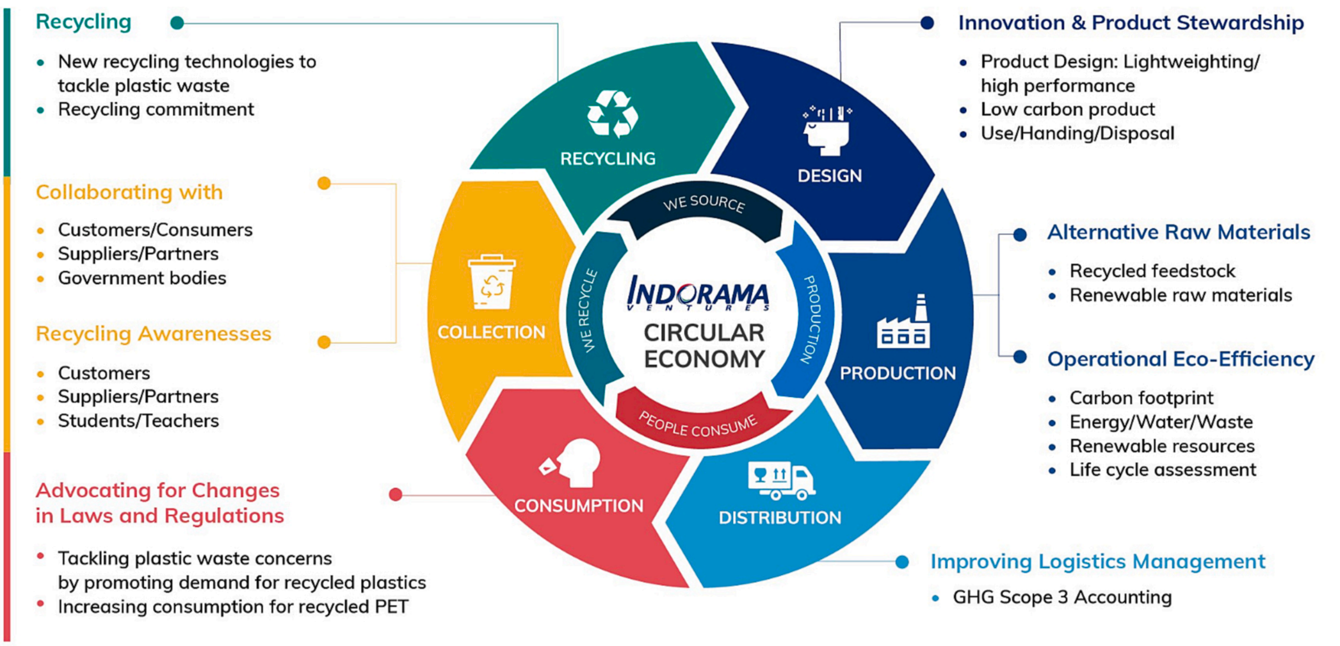

Fig. 9. The flowchart of the circular system of plastic products [6].

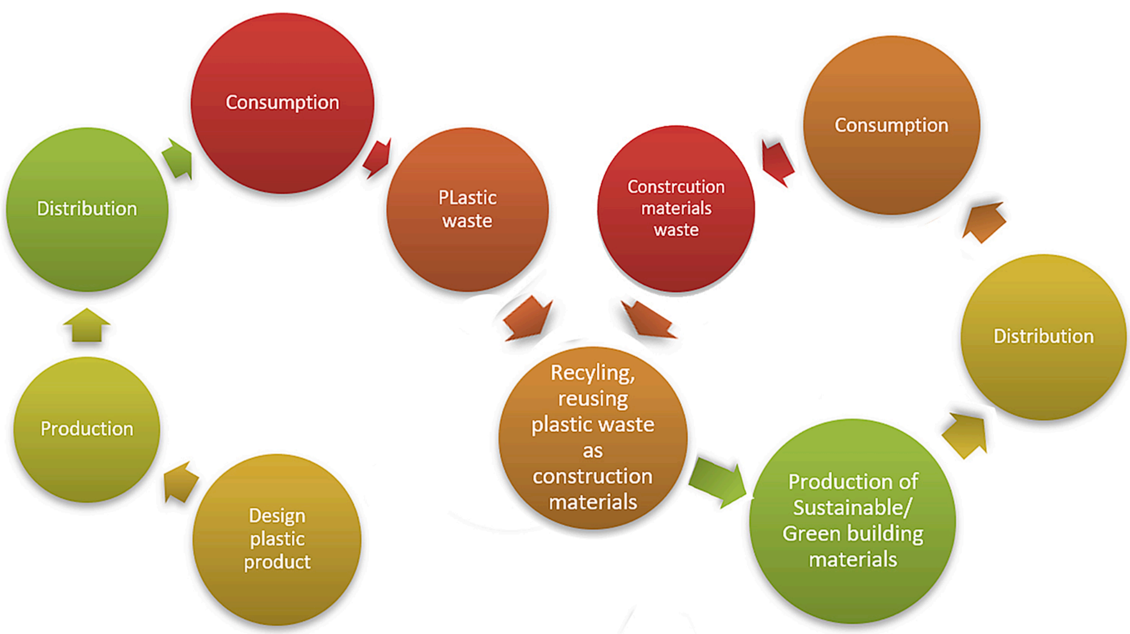

Fig. 10. The proposed flowchart of CE of plastic (open loop) incorporated with the building and construction Closed loop.

nearly half of the SDGs, directly with Decent Work and Economic Growth (SDG 8), Responsible Consumption and Production (SDG 12), and indirectly with Good Health and Well-Being (SDG 3), Climate Action (SDG 13), Life Below Water (SDG 14), and Sustainable City.

The potential of the CE in detail, as shown by Allam and Jones [80]; and da Silva et al. [13] includes:

- Allowing waste minimization and thus improving the environmental conditions.
- Promoting economic growth and enhancing the societal level by providing jobs for both the skilled and unskilled labor force. It was discovered that traditional waste disposal only provides six jobs for every 10,000 tons of solid waste, whilst recycling provides 36 jobs for the same quantity.
- Helping with raw materials conservation.
- Reducing greenhouse gases.
- Minimize the ecological footprint of buildings.

4. Analysis of the selected cases studies

4.1. Plastic bottles house in Nigeria

The Development Association for Renewable Energies (DARE) – an NGO based in Nigeria built a two-bedroom bungalow house entirely out of plastic bottles and mud. Hundreds of plastic bottles were filled with sand and then connected at the neck by a complex string network. The bottles were then carefully put and pressed down with a mixture of mud and cement, resulting in a strong construction material as compacted sand, which is also 20 times stronger than brick. The multi-colored bottle caps extending from the walls add an aesthetic dimension to the house's façade [106], as shown in Fig. 11.

Reusing plastic bottles as an alternative building material has provided an eco-friendly and affordable solution to the housing crisis in the region. The plastic bottle homes cost one-third of what a similar house made of concrete and bricks would cost [106]. Many authors advocate that reusing plastic bottle filled with sand or mud as an alternative to brick has several advantages including; Higher thermal resistance, saving cement and water, faster execution, simple and inexpensive relocation, need few indigenous workers, zero construction waste, and Increase the building's bearing capacity against earthquakes [60–70].

4.2. Temporary shelters in Guapi, Colombia

A startup company in Colombia established many houses and temporary shelters by using plastic bricks based on material collected from local recyclers and factories. Production of plastic brick begins with an extrusion process where the plastic is melted and then poured into a specific mold to create a three-kilo brick, then it is put together like Lego pieces to build walls [107], as shown in Fig. 12.

The company constructed a set of temporary shelters in Guapi for 42 families with an area of 40 m2 per unit. It accomplished the project in 28 days thanks to the cooperative work of 15 persons while recycling more than 200 tons of plastic. The cost of the project was about $6800 per unit [107]. As demonstrated by Valencia [107], the advantages of plastic brick include:

- It's stronger than traditional construction materials.
- It is easy to assemble and durable.
- It is less expensive and takes less time for the construction process.
- It has better insulation against heat and contains chemicals that slow burning.
- Its thermoacoustic and earthquake resistance are aligned with the code for Colombia.
- It is anti-seismic and does not spread flames.

4.3. A beach house in Nova Scotia, Canada

According to Canadian Plastics [108], a Canadian construction firm built a beach house in Nova Scotia with an area of 2000 square feet. The house was built using approximately 612,000 recycled plastic bottles. The construction process began with collecting the plastic bottles, which melted down into small beads. They were then subjected to an extensive extruding process, during which the bottles were shredded and heated to form plastic pellets and then placed into a hopper, where they were treated with gases that melted them into foam. Finally, the team sandwiched the foam core between fiberglass skins to create lightweight composite panels, which were assembled on-site in two days. The construction process took three months. The house incorporates 200 prefabricated PET wall panels. The smaller ones were used for the eaves. The panels were clad with aluminum and vinyl siding laser-printed with a cedar print for looks, as illustrated in Fig. 13.

Although recycled PET foam technology has been available for a while and is extensively used in the aerospace and insulation industries, this is the first time the product has been employed in composite panels for house building. The house has been ASTM certified for North America/Europe for a continuous R-30 value with no thermal breaks. The advantages of this recycled material include; resisting mold and rot; structural strength; fire resistance if special fire-rated resins are used; and high thermal insulation, which leads to maintaining internal temperatures more than twice as well as traditional buildings, yielding an energy efficiency and lowering the carbon footprint of the building [108].

4.4. Affordable housing in sub-Saharan Africa

Frank Cato Lahti, the creator of the OTHALO firm, is a Norwegian engineer who has invented patented technology that allows building systems to be made entirely of recycled plastic. He worked with Julien de Smedt, the founder of JDS architects, and has formed a collaboration with UN-Habitat in the United Nations program for human settlements and sustainable urban development to produce affordable houses, particularly in sub-Saharan Africa [109].

Lahti aims to turn plastic waste into a positive, pliable, and resilient material that can be used to create safe, sustainable, and low-cost buildings in developing countries while creating jobs and safe communities. The unique technology includes elements and construction systems that allow for simple and quick assembly. The elements may be defined as composite materials since each element is made up of multiple plastic materials with varying qualities to create a better-grade material. The technology combines plastic waste with other seasonal waste materials that may be a local or regional concern in some parts of the world to create building components such as walls, floors, and roofs. Each 60-square-meter house recycles eight tons of plastic waste. The same technology can produce storage units, modular buildings, refugee shelters, and larger structures such as schools and hospitals [109], as shown in Fig. 14.

OTHALO's system is UV-protected and has a European fire classification of E/B2 on its own, without the use of gypsum cladding. Following the completion of successful laboratory testing, OTHALO's factory in Estonia has begun the fabrication of components for the construction of three showcase homes for Nairobi in Kenya, Yaoundé in Cameroon, and Dakar in Senegal [111].

4.5. People's pavilion in Eindhoven

The People's Pavilion is a temporary building owned by the Dutch Design Foundation. Bureau SLA and Overtraders W designed the

Fig. 11. Plastic bottles house in Nigeria [106].

Fig. 12. Temporary shelters in Guapi, Colombia built in plastic [107].

Fig. 13. The beach house in Nova Scotia [108].

building with an area of 250 m2 as the primary pavilion of the World Design Event in Eindhoven for music and theater. It won the Frame Awards in the Sustainable Design category and the Dutch Design Awards in the Habitat category. It has been selected for the New Material Award and the ARC18 innovation award [110].

The pavilion adopted the CE approach, where 100% of the building materials have been borrowed from suppliers, producers, and residents of Eindhoven. Piles, façade elements, wooden beams, plastic cladding, glass roof, and lighting have been borrowed and will be returned to the owners after the end of the event. Leftovers that were used for the glass portion of the façade were from a refurbishment of BOL.com's headquarters and will be reused for new office space [110]0.100% borrowed materials mean a construction site without screws, glue, drills, or saws and thus zero waste. Facade cladding was constructed of multicolored plastic tiles with an artistic look, produced from recycled plastic domestic waste, which was collected by residents [110], as illustrated in Fig. 15.

4.6. Utilizing plastic waste in road construction in India

The fast degradation of pavement infrastructure and the substantial amount of raw materials needed each year make roadway construction energy intensive in addition to the sizable financial expenditure needed for road maintenance and rehabilitation. These facts have encouraged the world to look for more economical and ecologically friendly paving materials and technology [112].

Several studies investigated the potential of using waste plastics in road construction as an eco-environmental alternative. Recycled plastic can replace aggregates or serve as a binder modifier. The results showed an improvement in stability, fatigue life, resistance to deformation, and strength, thus improving pavement performance, durability, and longevity [32–38,113].

India has the most apparent experience with waste plastics in road construction. India has advocated using plastic waste in bituminous mixes for the construction of its national highways and rural roads, in

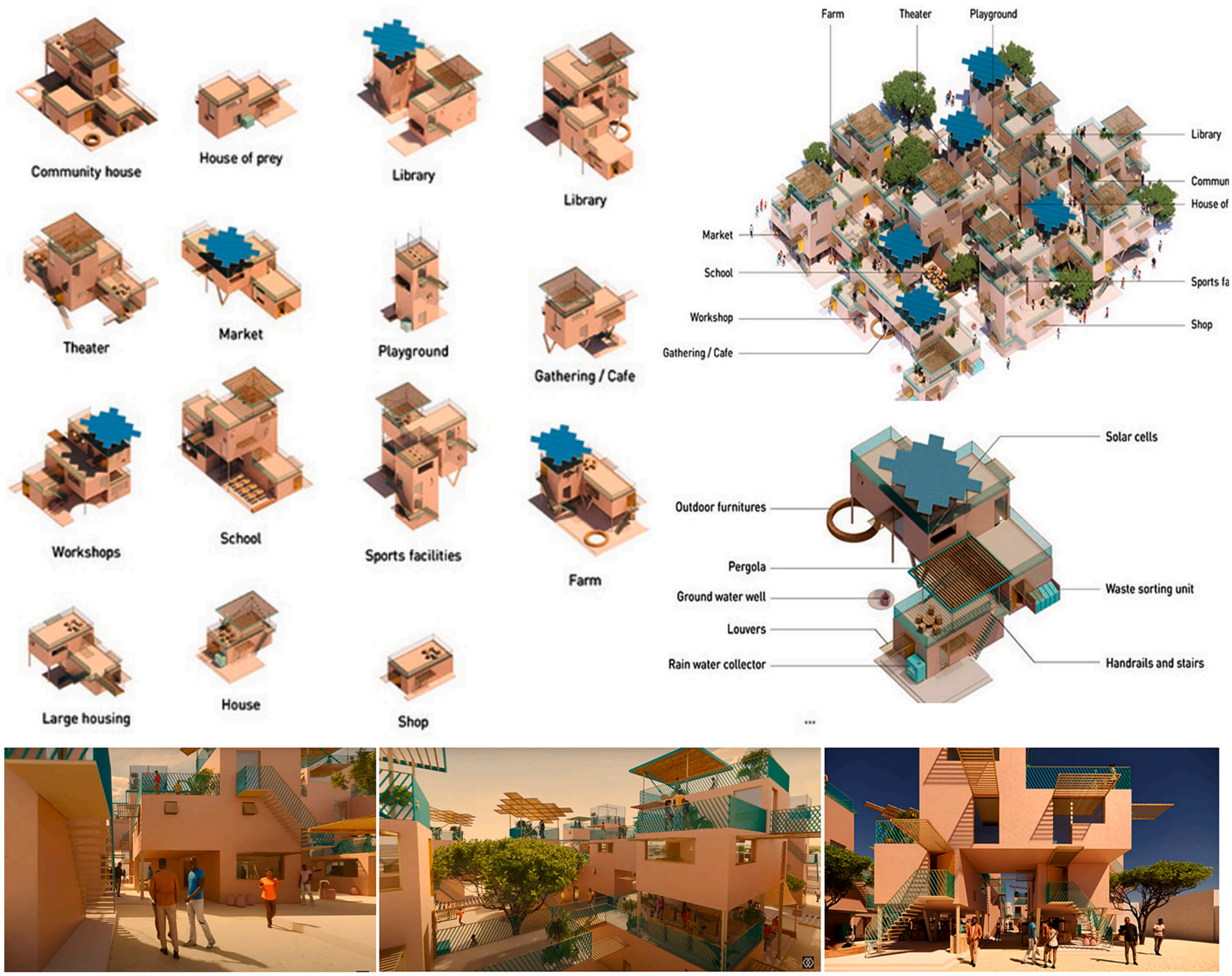

Fig. 14. The design proposal for affordable housing was developed by JDS architects [110].

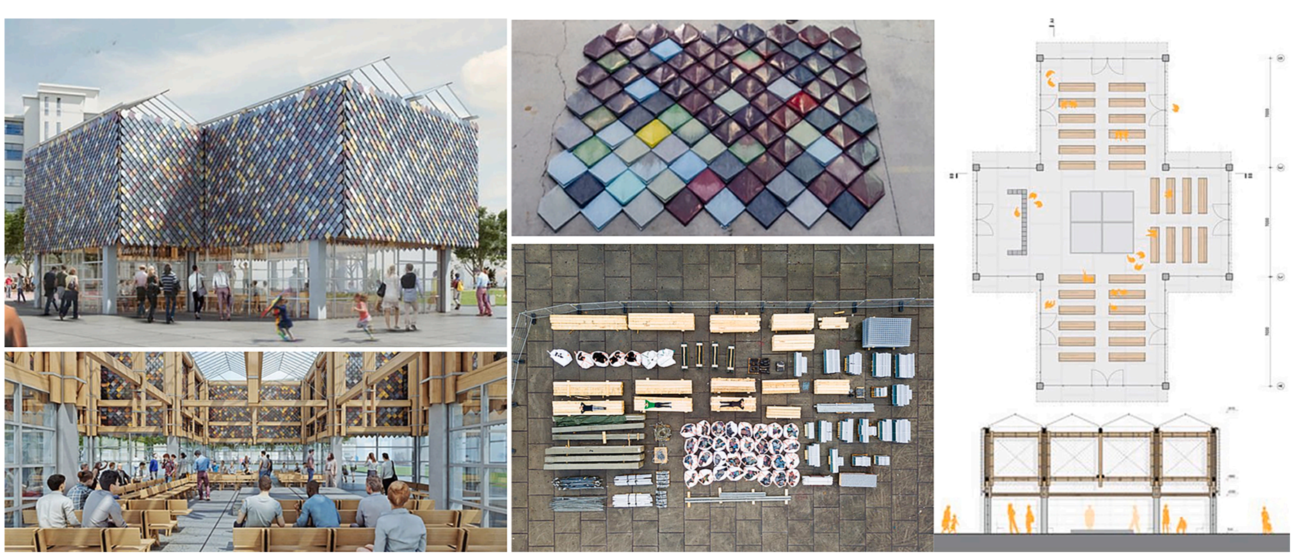

Fig. 15. People's Pavilion in Eindhoven [110].

addition to approving it as the default method of periodic renewal with hot mixes for roads within 50 km of urban areas with more than 500,000 inhabitants. More than 2500 km of roads have been constructed since 2002 using waste plastic, and 10 years later they were still running well without potholes, raveling, or rutting [114]. For every kilometer of road constructed, a ton of waste plastic was utilized, resulting in a 3 tons/km reduction in carbon dioxide emissions compared to conventional building methods, the cost saved by using plastic waste in road construction was estimated at $670 per km in 2012 ([113].

4.7. The recycled plastic bridge over River Tweed, Scotland

The Easter Dawyck bridge over the Tweed is Europe's first of its kind. It was finished in 2011 and replaced an earlier bridge constructed in 1920. This new 30-meter-long bridge is the world's longest bridge made of recycled materials. It can support weights of up to 44 tons.

The structure uses 50 tons of thermoplastic composite material made from post-consumer recycled high-density polyethylene bottles and the end-of-life vehicle recycling. It has the same inherent benefits as other plastic materials in terms of natural resistance to environmental threats, does not require finishing, requires little maintenance, and is recyclable, with a life span that extends to years. When compared to traditional building materials, thermoplastic composites resulted in a $3,300 per square meter cost reduction [115].

The Ecocrib retaining wall is made of intrusion molded recycled plastic, with a header width ranging from 500 mm to 3000 mm, and no steel reinforcement is required. In 2012, the British Board of Agreements certified Ecocrib to have a Design Service Life of more than 120 years [115].

Molding technology can turn plastic waste into a strong, lightweight building material that may be used instead of wood or concrete. Because it does not need chemical additives and is unaffected by moisture, microbiological assault, and acid soil, recycled waste plastic is perfect for applications that contact the earth and water. The capacity to make the big cross-sectional and non-uniform shape is a significant advantage of intrusion molding, which leads to recycled plastic being utilized in applications as varied as underground utility chambers, biofilter floors, and drop curbs [115]. According to Waghorn and Sapsford [116], the advantages of Ecocrib are summarized as follows:

- It offers a design service life equivalent to steel-reinforced concrete crib walls and doubles that of a timber alternative.
- Recycled plastic does not need maritime transportation or chemical additives.
- It helps in reducing CO2 emissions from concrete manufacture.
- Its headers and stretchers are significantly lighter than their concrete equivalents, resulting in cheaper shipping and installation costs.
- The production or installation process doesn't generate waste.
- It has a resistance to termites, micro-biological attack, rot, moisture, and acid soil.
- It doesn't require regular maintenance and is recyclable.

4.8. Using recycled plastic as railway sleepers on network rail tracks

Recently, reinforced polymer sleepers, also known as composite sleepers, have been recognized as viable replacements for timber sleepers. Reinforced polymers can be made to behave similarly to timber, require nearly no maintenance, and are more environmentally friendly [116]. Several companies manufacture composite sleepers made from 100% recycled plastic, including plastic coffee cups, plastic bags, laundry detergent bottles, milk jugs, etc., such as Axion, USA; I-Plas Ltd., United Kingdom; and Tufflex Sleeper, South Africa [117].

The first composite railway sleepers have been placed on the main line tracks that cross the Sherrington Viaduct by the UK's Network Rail. Sicut, a manufacturer of sustainable infrastructure products, produces these new sleepers from plastic waste collected nearby. Compared to timber sleepers, recycled sleepers will have a longer service life and require less maintenance, which will help lower total expenses. Moreover, it has a lifespan of around 50 years, is more resistant to rot, insects, fungi, and moisture offers superior resistance to plate wear, and can be recycled or reused [117].

5. Results

Based on reviewing related literature, the study categorized the utilization of plastic waste in the building and construction industry into main six types, as summarized in Table 1. The table also shows the type of recycled plastic, the products, their applications, and their characteristics.

The results of the analytical part revealed that the selected case studies in the developing countries applied the CE approach by recycling plastic waste or reusing plastic bottles as an alternative to traditional brick for buildings, especially houses. This solution has a significant impact on confronting both plastic waste disposal and the housing problem in these countries. It's affordable, clean, and doesn't need advanced technology.

The additional environmental benefits derived from the case studies are as follows:

- Minimizing plastic waste quantities will reduce the toxic chemicals and CO2 gas released from plastic waste burning, resulting in less air pollution, thereby protecting humans, animals, vegetation, and the whole ecosystem.
- Minimizing the disposal of plastic waste in oceans, rivers, and other water bodies and thus protecting the water and marine life from contamination.
- Gradually reducing the use of traditional construction materials, thereby lowering CO2 emissions, greenhouse gas emissions, and other pollutants produced by manufacturing and transportation processes. So, it will help mitigate climate change.
- Conserving the natural resources consumed in the construction sector from depletion.

The economic feasibility of applying the CE by utilizing plastic waste as construction materials is outlined below:

- Reducing the cost of plastic waste landfilling and the energy used for the incineration process.
- Promoting economic growth and enhancing the social level by creating an extra source of revenue for all stakeholders.
- Reducing both the embodied energy used in manufacturing traditional construction materials and the energy consumed during building operation due to the thermal insulation properties of recycled plastic-based materials.
- The low price of recycled and processed materials and the low transportation cost of plastic waste, which are available everywhere in contrast with the raw construction materials, yield a reduction in the entire cost of the building.

6. Discussion

Egypt like other developing countries suffers from the solid waste disposal problem coupled with the high cost of construction materials and the high energy consumption by the construction industry. However, Egypt seeks to enhance the management of waste disposal and expands to using renewable energy in the last few years, these strategies need high costs and take a long time to have their direct results. On the other hand, adopting the CE by recycling and reusing plastic waste in the construction and building industry has proven its effectiveness in solving related problems, particularly in developing nations besides various economical and social benefits. This new approach is appropriate for the Egyptian context as it is affordable and provides fast, radical, and

Table 1
Types of utilization of plastic waste in the building and construction industry, the final products, their applications, and their specifications.

Utilization of plastic waste	Type of Recycled Plastic	Products	Applications	Specifications	Ref.
A replacement to aggregates (sand/ gravel) for producing concrete based-materials/ As a fiber/ As a binder	• PET HDPE PVC LDPE PP PE Expanded polystyrene (EPS) Glass Reinforce plastic fiber Polyurethane (PUR)	• Polymer concrete Fiber reinforced concrete Green concrete	• Temporary or light construction Outdoor floors Concrete footpath construction Concrete pavement Decorative concrete	• A reduction in the bulk density An increase in strength and toughness An improvement in thermal insulation Low acoustical and electrical conductivity Preventing crack A reduction in the splitting tensile strength Enhancing the compressive strength and modulus of rupture An increase in the ductility of concrete Improving impermeability and resistance to deicer salt scaling A reduction in the abrasion resistance	[14–31]
	• PET	• Geopolymer Mortar		• An improvement in the flowability and mechanical properties Having almost the same workability and flexural strength A decrease in compressive strength and tensile strength	[22,31]
An additive for enhancing bituminous mixes and asphalt	• HDPE LDPE PP PE PS		• Pavement construction Flexible pavement Roads construction	• Resisting both fatigue cracking and rutting An increase in durability Increasing the stiffness of asphalt Improving the viscoelastic behavior of the bitumen increasing stability and decreasing air voids Reducing moisture absorption	[32–39]
A soil stabilization/ reinforcement	• PET	• Soil stabilizer	• Roads/Highway base and sub-base	• Improving the stiffness of the clay soil An increase in soil rigidity	[40,41]
A complete alternative to the traditional building materials: Brick, Wood, Poly-wood Timber	• Only recycled plastic Recycled plastic mixed with fly ash /soil. Scrap plastic waste mixed with foundry sand LDPE /HDPE/ PET mixed with sand)	• Plastic/green brick	• A non-load-bearing walls Building brick Facing brick Thin veneer brick	• More resilient. Better quality. A reduction in water absorption. Cost-effective and eco-friendly. Consuming lower energy. Some types require no water. Resistant to oil, salts, acids, and alkalis. Tough and have higher ductility. and thermal conductivity than concrete. Lightweight. Low energy and water. requirements. Enhancing shear resistance, stiffness, and load-bearing capability.	[43,46,48,52,56]
	• recycled PETand additives)	• Lightweight plasters	• For basement floors or ground floors on screeds walls with recesses Exterior walls	• Increasing the values of stress. Improving fragile behavior. A decrease in the compressive and flexural strengths.	[50,54,57]
	• HDPE and aggregates /gravel/ceramic waste. LDPE and sand	• Paving blocks Permeable pavement	• In non-traffic and light traffic road Pedestrian and cycleway	• Reducing cost Good heat resistance. A reduction of compressive strength Higher water resistance An increase in compressive	[49,53,55]

(*continued on next page*)

Table 1 (*continued*)

Utilization of plastic waste	Type of Recycled Plastic	Products	Applications	Specifications	Ref.
				and tensile strength. help stormwater runoff.	
	• PE/PVC/ PS and cellulose fiber/ wood flour/glass fiber/palm leaves waste	• Alternative to wood Plastic lumber	• Furniture applications Low-cost portable toilets Gates and doors Partitions Storage and shipping pallets Roofing sheets Porch Canopy Shuttering formworks Paver and block pallets Fences Wall cladding/ panels Solar shading.	• Aiding in conserving trees, which serve as carbon sinks. Low cost with high quality. Resistant to rot, insects, algae, and fungi. UV protection against fading. Easy to clean. Longevity and durability. Completely waterproof Splinter free. Not require painting. Significant lifetime cost savings. Low carbon footprint.	[44,47]
	• HDPE/PET Recycled plastic and filler such as fly ash Recycled plastic and recycled glass + sand	Plastic tiles	For Floor, wall, and ceiling finishing.	• Better mechanical strength. Decreasing flammability. Resistant to strong acids and bases and organic solvents. Lightweight. Resistant to heat and water. Safety for human use High durability	[42,45,51]
As a thermal and water insulation material	• Recycled plastic combined with Expanded Polystyrene (EPS) or foam	A thermal and water insulator	Water and thermal insulation for foundation, walls, roofs, and floors	• Improving water and fire resistance Durability Long-term energy saving	[58,59]
Reusing plastic bottle	• PET	Bricks plastic bottles filled with soil/ sand + gravel/ Sand + mud	A non-load-bearing walls	• Higher compressive strength and load capacity. Lighter in weight. Thermal mass storage is provided. Higher thermal resistance Saving cement, water, grinder, and fittings. Faster execution. Simple and inexpensive relocation. Few indigenous workers. There is no construction waste. Increase the building's bearing capacity against earthquakes.	[60–70]

multifaceted solutions to the waste disposal mismanaged as well as the high cost of construction materials.

7. Conclusion

The current study sheds light on the most pressing global challenge today, the negative impacts of both plastic waste disposal and the building and construction industry. It explored their manifestations, causes, and effects on the environment with a focus on the Egypt case. The study also investigated the concept of CE and its potential as a multi-faceted solution to these chronic challenges as well as a pathway to achieving SDGs. The study advocates incorporating the recycling and reusing of plastic waste with the construction industry demands while presenting an assembly of recycled plastic construction materials showing their advantages, limitations, and different applications in the construction sector.

Additionally, the study analyzed the significance of eco-friendly architectural projects that adopted the circular economy model to achieve sustainability in the 21st century.

The study highlighted the environmental and economic feasibility of the CE model, particularly in developing countries, which encourages policymakers and stakeholders in Egypt to embrace this model as the most efficient economic and environmentally friendly alternative toward a more sustainable environment. The study also calls on the local government to establish rigorous rules and regulations to prevent the haphazard disposal of plastic waste in landfills or water bodies. Finally, the study recommends further research on the potential and challenges of implementing CE in Egypt by linking the recycled plastic industry with the demands of the local construction sector.

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CRediT authorship contribution statement

Nadia Ahmed: Conceptualization, Methodology, Data curation, Writing – original draft, Visualization, Investigation, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

[1] V.S.N.S. Goli, A. Mohammad, D.N. Singh, Application of Municipal Plastic Waste as a Manmade Neo-construction Material: Issues & Wayforward, Resour. Conserv. Recycl. 161 (2020), 105008, https://doi.org/10.1016/j.resconrec.2020.105008.

[2] A. Kumar, A. Agrawal, A Review on Plastic Waste Assessment and Its Potential Use as Building Construction Material, in: K. Thirumaran, G. Balaji, N.D. Prasad (Eds.), Sustain, Urban Archit., Springer Singapore, Singapore, 2021, pp. 37–52, https://doi.org/10.1007/978-981-15-9585-1_3.

[3] L.C.M. Lebreton, J. van der Zwet, J.-W. Damsteeg, B. Slat, A. Andrady, J. Reisser, River plastic emissions to the world's oceans, Nat. Commun. 8 (2017) 15611, https://doi.org/10.1038/ncomms15611.

[4] N. Singh, D. Hui, R. Singh, I.P.S. Ahuja, L. Feo, F. Fraternali, Recycling of plastic solid waste: A state of art review and future applications, Compos. Part B Eng. 115 (2017) 409–422, https://doi.org/10.1016/j.compositesb.2016.09.013.

[5] N.H. Zulkernain, P. Gani, N. Chuck Chuan, T. Uvarajan, Utilisation of plastic waste as aggregate in construction materials: A review, Constr. Build. Mater. 296 (2021), 123669, https://doi.org/10.1016/j.conbuildmat.2021.123669.

[6] M.K. Anwar, S.A.R. Shah, H. Alhazmi, Recycling and Utilization of Polymers for Road Construction Projects: An Application of the Circular Economy Concept, Polymers 13 (2021) 1330, https://doi.org/10.3390/polym13081330.

[7] J. Cámara-Creixell, C. Scheel-Mayenberger, PetStar PET Bottle-to-Bottle Recycling System, a Zero-Waste Circular Economy Business Model, in: M.-.-L. Franco-García, J.C. Carpio-Aguilar, H. Bressers (Eds.), Zero Waste, Springer International Publishing, Cham, 2019, pp. 191–213, https://doi.org/10.1007/978-3-319-92931-6_10.

[8] S. Guran, R.L. Mersky, S.K. Ghosh, Status of Plastics Waste in Circular Economy in the USA, in: S.K. Ghosh (Ed.), Circ. Econ. Glob, Perspect., Springer Singapore, Singapore, 2020, pp. 413–421, https://doi.org/10.1007/978-981-15-1052-6_21.

[9] J.N. Hahladakis, E. Iacovidou, S. Gerassimidou, Plastic waste in a circular economy, Plast. Waste Recycl., Elsevier, in, 2020, pp. 481–512.

[10] S. Huysman, J. De Schaepmeester, K. Ragaert, J. Dewulf, S. De Meester, Performance indicators for a circular economy: A case study on post-industrial plastic waste, Resour. Conserv. Recycl. 120 (2017) 46–54, https://doi.org/10.1016/j.resconrec.2017.01.013.

[11] J. Payne, P. McKeown, M.D. Jones, A circular economy approach to plastic waste, Polym. Degrad. Stab. 165 (2019) 170–181, https://doi.org/10.1016/j.polymdegradstab.2019.05.014.

[12] M. Yhdego, The Circular Economy in Tanzania: A Self-referential System, in: S. K. Ghosh, S.K. Ghosh (Eds.), Circ. Econ. Recent Trends Glob, Perspect., Springer Nature Singapore, Singapore, 2021, pp. 69–112, https://doi.org/10.1007/978-981-16-0913-8_3.

[13] T.R. da Silva, A.R.G. de Azevedo, D. Cecchin, M.T. Marvila, M. Amran, R. Fediuk, N. Vatin, M. Karelina, S. Klyuev, M. Szelag, Application of Plastic Wastes in Construction Materials: A Review Using the Concept of Life-Cycle Assessment in the Context of Recent Research for Future Perspectives, Materials. 14 (2021) 3549, https://doi.org/10.3390/ma14133549.

[14] H.M. Adnan, A.O. Dawood, Recycling of plastic box waste in the concrete mixture as a percentage of fine aggregate, Constr. Build. Mater. 284 (2021), 122666, https://doi.org/10.1016/j.conbuildmat.2021.122666.

[15] F.K. Alqahtani, I.S. Abotaleb, M. ElMenshawy, Life cycle cost analysis of lightweight green concrete utilizing recycled plastic aggregates, J. Build. Eng. 40 (2021), 102670, https://doi.org/10.1016/j.jobe.2021.102670.

[16] M. Belmokaddem, A. Mahi, Y. Senhadji, B.Y. Pekmezci, Mechanical and physical properties and morphology of concrete containing plastic waste as aggregate, Constr. Build. Mater. 257 (2020), 119559, https://doi.org/10.1016/j.conbuildmat.2020.119559.

[17] E. del Rey Castillo, N. Almesfer, O. Saggi, J.M. Ingham, Light-weight concrete with artificial aggregate manufactured from plastic waste, Constr. Build. Mater. 265 (2020), 120199, https://doi.org/10.1016/j.conbuildmat.2020.120199.

[18] X. He, W. Li, Y. Su, Z. Zheng, J. Fu, J. Zeng, H. Tan, Y. Wu, J. Yang, Recycling of plastic waste concrete to prepare an effective additive for early strength and late permeability improvement of cement paste, Constr. Build. Mater. 347 (2022), 128581, https://doi.org/10.1016/j.conbuildmat.2022.128581.

[19] M.A. Kamaruddin, M.M.A. Abdullah, M.H. Zawawi, M.R.R.A. Zainol, Potential use of Plastic Waste as Construction Materials: Recent Progress and Future Prospect, IOP Conf. Ser. Mater. Sci. Eng. 267 (2017), 012011, https://doi.org/10.1088/1757-899X/267/1/012011.

[20] V. Kathe, A. Gangurde, A. Pawar, Green concrete using plastic waste, IJETT 19 (2015) 1–3.

[21] M.I. Khan, M.H. Sutanto, M.B. Napiah, K. Khan, W. Rafiq, Design optimization and statistical modeling of cementitious grout containing irradiated plastic waste and silica fume using response surface methodology, Constr. Build. Mater. 271 (2021), 121504, https://doi.org/10.1016/j.conbuildmat.2020.121504.

[22] G. Lazorenko, A. Kasprzhitskii, E.H. Fini, Sustainable construction via novel geopolymer composites incorporating waste plastic of different sizes and shapes, Constr. Build. Mater. 324 (2022), 126697, https://doi.org/10.1016/j.conbuildmat.2022.126697.

[23] X. Li, T.-C. Ling, K. Hung Mo, Functions and impacts of plastic/rubber wastes as eco-friendly aggregate in concrete – A review, Constr. Build. Mater. 240 (2020), 117869, https://doi.org/10.1016/j.conbuildmat.2019.117869.

[24] A. Mohammadinia, Y.C. Wong, A. Arulrajah, S. Horpibulsuk, Strength evaluation of utilizing recycled plastic waste and recycled crushed glass in concrete footpaths, Constr. Build. Mater. 197 (2019) 489–496, https://doi.org/10.1016/j.conbuildmat.2018.11.192.

[25] J. Pablo Ojeda, A meta-analysis on the use of plastic waste as fibers and aggregates in concrete composites, Constr. Build. Mater. 295 (2021), 123420, https://doi.org/10.1016/j.conbuildmat.2021.123420.

[26] A. Poonyakan, M. Rachakornkij, M. Wecharatana, W. Smittakorn, Potential Use of Plastic Wastes for Low Thermal Conductivity Concrete, Materials. 11 (2018) 1938, https://doi.org/10.3390/ma11101938.

[27] A. s,, Experimental Study on the Properties of Green Concrete by Replacement of E-Plastic Waste as Aggregate, Procedia Comput, Sci. 172 (2020) 985–990, https://doi.org/10.1016/j.procs.2020.05.145.

[28] K.K. Sahoo, M. Gupta, R. Sahu, K. Mudgal, Y.S. Shankar, in: Experimental Investigation for the Feasible Applications of Processed Recyclable Plastic Waste in Construction Sector, Adv. Waste Manag., Springer Singapore, Singapore, 2019, pp. 155–169, https://doi.org/10.1007/978-981-13-0215-2_11.

[29] N. Saikia, J. de Brito, Use of plastic waste as aggregate in cement mortar and concrete preparation: A review, Constr. Build. Mater. 34 (2012) 385–401, https://doi.org/10.1016/j.conbuildmat.2012.02.066.

[30] R. Siddique, J. Khatib, I. Kaur, Use of recycled plastic in concrete: A review, Waste Manag. 28 (2008) 1835–1852, https://doi.org/10.1016/j.wasman.2007.09.011.

[31] M. Thiam, M. Fall, Mechanical, physical and microstructural properties of a mortar with melted plastic waste binder, Constr. Build. Mater. 302 (2021), 124190, https://doi.org/10.1016/j.conbuildmat.2021.124190.

[32] S. Aldagari, S.F. Kabir, E.H. Fini, A comparative study on efficacy of waste plastic and waste Rubber in bitumen, Constr. Build. Mater. 325 (2022), 126724, https://doi.org/10.1016/j.conbuildmat.2022.126724.

[33] A. Almeida, S. Capitão, R. Bandeira, M. Fonseca, L. Picado-Santos, Performance of AC mixtures containing flakes of LDPE plastic film collected from urban waste considering aging, Constr. Build. Mater. 232 (2020), 117253, https://doi.org/10.1016/j.conbuildmat.2019.117253.

[34] J.K. Appiah, V.N. Berko-Boateng, T.A. Tagbor, Use of waste plastic materials for road construction in Ghana, Case Stud, Constr. Mater. 6 (2017) 1–7, https://doi.org/10.1016/j.cscm.2016.11.001.

[35] S. Haider, I. Hafeez, Jamal, R. Ullah, Sustainable use of waste plastic modifiers to strengthen the adhesion properties of asphalt mixtures, Constr. Build. Mater. 235 (2020) 117496. doi: 10.1016/j.conbuildmat.2019.117496.

[36] S. Heydari, A. Hajimohammadi, N. Haji Seyed Javadi, N. Khalili, The use of plastic waste in asphalt: A critical review on asphalt mix design and Marshall properties, Constr. Build. Mater. 309 (2021) 125185. doi: 10.1016/j.conbuildmat.2021.125185.

[37] R. Manju, S. Sathya, K. Sheema, Use of Plastic Waste in Bituminous Pavement, Int. J. ChemTech Res. 10 (2017) 804–811.

[38] A. Shaikh, N. Khan, F. Shah, F. Shukla, G. Kale, Use of Plastic Waste in Road Construction, IJARnD. 2 (2017) 14–19.

[39] R. Vasudevan, A. Ramalinga Chandra Sekar, B. Sundarakannan, R. Velkennedy, A technique to dispose waste plastics in an ecofriendly way – Application in construction of flexible pavements, Constr. Build. Mater. 28 (2012) 311–320. doi: 10.1016/j.conbuildmat.2011.08.031.

[40] M. Hafez, R. Mousa, A. Awed, S. El-Badawy, Soil Reinforcement Using Recycled Plastic Waste for Sustainable Pavements, in: S. El-Badawy, J. Valentin (Eds.), Sustain. Solut. Railw. Transp. Eng., Springer International Publishing, Cham, 2019: pp. 7–20. doi: 10.1007/978-3-030-01911-2_2.

[41] V. Mallikarjuna, T.B. Mani, SOIL STABILIZATION USING PLASTIC WASTE, IJRET. 5 (2016) 391–394.

[42] K. Akinpelu Olujide, E.O. Anaele, G. Keres Okereke, H., Osita Omeje, Production of Ceiling Tile with High Density Polyethylene (HDPE) and Polyethylene Terephthalate (PET) Plastic Wastes as Main Ingredients, J. Eng. Appl. Sci. 15 (2019) 114–127, https://doi.org/10.36478/jeasci.2020.114.127.

[43] F.I. Aneke, C. Shabangu, Green-efficient masonry bricks produced from scrap plastic waste and foundry sand, Case Stud. Constr. Mater. 14 (2021) e00515.

[44] R.M. Bajracharya, A.C. Manalo, W. Karunasena, K. Lau, An overview of mechanical properties and durability of glass-fibre reinforced recycled mixed plastic waste composites, Mater. Des. 1980–2015 (62) (2014) 98–112, https://doi.org/10.1016/j.matdes.2014.04.081.

[45] D. Behera, Y. Damtew, A. Mola, Experimental investigation on recycling of plastic wastes and broken glass into construction material, IJCRT 6 (2018) 1658–1667.

[46] T. Belay Wendimu, B. Neguse Furgasa, B. Mohammed Hajji, Suitability and Utilization Study on Waste Plastic Brick as Alternative Construction Material, J. Civ. Constr, Environ. Eng. 6 (2021) 9, https://doi.org/10.11648/j.jccee.20210601.12.

[47] M.A. Binhussain, M.M. El-Tonsy, Palm leave and plastic waste wood composite for out-door structures, Constr. Build. Mater. 47 (2013) 1431–1435, https://doi.org/10.1016/j.conbuildmat.2013.06.031.

[48] W.K. Biswas, X. Zhang, Techno-Assessment of the Use of Recycled Plastic Waste in RE, Sustainability. 13 (2021) 8678, https://doi.org/10.3390/su13168678.

[49] ÇETIN, M., Using Recycling Materials for Sustainable Landscape Planning, in: Environ. Ecol. Begin. 21st Century, St. Kliment Ohridski University Press, Turkey, 2015: pp. 783–788.

[50] V. Corinaldesi, J. Donnini, A. Nardinocchi, Lightweight plasters containing plastic waste for sustainable and energy-efficient building, Constr. Build. Mater. 94 (2015) 337–345, https://doi.org/10.1016/j.conbuildmat.2015.07.069.
[51] R. Dhawan, B.M.S. Bisht, R. Kumar, S. Kumari, S.K. Dhawan, Recycling of plastic waste into tiles with reduced flammability and improved tensile strength, Process Saf. Environ. Prot. 124 (2019) 299–307, https://doi.org/10.1016/j.psep.2019.02.018.
[52] R.S. Kognole, K. Shipkule, M. Patil, L. Patil, U. Survase, Utilization of Plastic waste for Making Plastic Bricks, IJTSRD. 3 (2019) 878–880.
[53] A. Kumi-Larbi Jnr, R. Galpin, S. Manjula, Z. Lenkiewicz, C. Cheeseman, Reuse of Waste Plastics in Developing Countries: Properties of Waste Plastic-Sand Composites, Waste Biomass Valorization. (2022), https://doi.org/10.1007/s12649-022-01708-x.
[54] K. Salim, A. Houssam, A. Belaid, H. Brahim, Reinforcement of building plaster by waste plastic and glass, Procedia Struct. Integr. 17 (2019) 170–176, https://doi.org/10.1016/j.prostr.2019.08.023.
[55] B. Shanmugavalli, K. Gowtham, Reuse of Plastic Waste in Paver Blocks 6 (2017) 313–315.
[56] N. Shinde, S. Wadekar, R. Wadekar, H. Deshmukh, M. Bhute, DEVELOPMENT AND ANALYSIS OF BRICK MADE FROM WASTE PLASTIC BAGS, Int. J. Eng. Res. Adv. Technol. (2018), https://doi.org/10.7324/IJERAT.2018.3206.
[57] A. Vidales-Barriguete, E. Atanes-Sánchez, M. del Río-Merino, C. Piña-Ramírez, Analysis of the improved water-resistant properties of plaster compounds with the addition of plastic waste, Constr. Build. Mater. 230 (2020), 116956, https://doi.org/10.1016/j.conbuildmat.2019.116956.
[58] S. Acierno, C. Carotenuto, M. Pecce, Compressive and Thermal Properties of Recycled EPS Foams, Polym.-Plast. Technol. Eng. 49 (2009) 13–19, https://doi.org/10.1080/03602550903282994.
[59] P. Moghaddam Fard, M.G. Alkhansari, Innovative fire and water insulation foam using recycled plastic bags and expanded polystyrene (EPS), Constr. Build. Mater. 305 (2021), 124785, https://doi.org/10.1016/j.conbuildmat.2021.124785.
[60] M. Abouhadid, A. Mansour, R. Shafik, O. ElRawy, Thermal Performance of Plastic Bottles Walls Reused in Building Construction for Waste Reduction, IJITEE. 9 (2019) 5311–5315.
[61] S.R. Andriani, H. Isnaeni, N.R. Kusuma, E. Avandra, The Utilizations of Plastic Bottle Waste (PET) in Architecture, IOP Conf. Ser. Earth Environ. Sci. 452 (2020), 012026, https://doi.org/10.1088/1755-1315/452/1/012026.
[62] D. Ariyani, N. Warastuti, R. Arini, Ecobrick Method To Reduce Plastic Waste In Tanjung Mekar Village, Karawang Regency, Civ. Environ. Sci. 004 (2021) 022–029, https://doi.org/10.21776/ub.civense.2021.00401.3.
[63] A. Chaurasia, Reuse of Plastic Bottles as a Construction Material, IJETR. 9 (2019) 25–30.
[64] N. Datir, S.S. Kadam, Application of Plastic Bottle as a Wall Structure for Green House, IRJET. 6 (2019) 4162–4165.
[65] M.S. Haque, Sustainable use of plastic brick from waste PET plastic bottle as building block in Rohingya refugee camp: a review, Environ. Sci. Pollut. Res. 26 (2019) 36163–36183, https://doi.org/10.1007/s11356-019-06843-y.
[66] M. Jalaluddin, Use of Plastic Waste in Civil Constructions and Innovative Decorative Material (Eco- Friendly), MOJ Civ. Eng. 3 (2017), https://doi.org/10.15406/mojce.2017.03.00082.
[67] A.M.H. Mansour, S.A. Ali, Reusing waste plastic bottles as an alternative sustainable building material, Energy, Sustain. Dev. 24 (2015) 79–85, https://doi.org/10.1016/j.esd.2014.11.001.
[68] M. Oyinlola, T. Whitehead, A. Abuzeinab, A. Adefila, Y. Akinola, F. Anafi, F. Farukh, O. Jegede, K. Kandan, B. Kim, E. Mosugu, Bottle house: A case study of transdisciplinary research for tackling global challenges, Habitat Int. 79 (2018) 18–29, https://doi.org/10.1016/j.habitatint.2018.07.007.
[69] A. Raut, M.S. Patel, N.B. Jadhwar, U. Khan, S.W. Dhengare, Investigating the Application of Waste Plastic Bottle as a Construction Material: A Review, J. Adv. Res. Mech. Civ. Eng. ISSN 2208–2379 (2) (2015) 86–99, https://doi.org/10.53555/nnmce.v2i3.362.
[70] S. Safinia, A. Alkalbani, Use of Recycled Plastic Water Bottles in Concrete Blocks, Procedia Eng. 164 (2016) 214–221, https://doi.org/10.1016/j.proeng.2016.11.612.
[71] P.O. Awoyera, A. Adesina, Plastic wastes to construction products: Status, limitations and future perspective, Case Stud. Constr. Mater. 12 (2020) e00330.
[72] S. Das, B. Das, Waste plastic's green construction: introducing the process that converts 100% plastic waste into an alternative renewable various types of construction materials, Ejbps. 4 (2017) 307–319.
[73] A.E.O. Eneh, Application of recycled plastics and its composites in the built environment, Best IJMITE. 3 (2015) 9–16.
[74] B. Jethy, S. Paul, S.K. Das, A. Adesina, S.M. Mustakim, Critical review on the evolution, properties, and utilization of plasticwastes for construction applications, J. Mater. Cycles Waste Manag. 24 (2022) 435–451, https://doi.org/10.1007/s10163-022-01362-4.
[75] P. Lamba, D.P. Kaur, S. Raj, J. Sorout, Recycling/reuse of plastic waste as construction material for sustainable development: a review, Environ. Sci. Pollut. Res. (2021), https://doi.org/10.1007/s11356-021-16980-y.
[76] H.T. Mohan, K. Jayanarayanan, K.M. Mini, Recent trends in utilization of plastics waste composites as construction materials, Constr. Build. Mater. 271 (2021), 121520, https://doi.org/10.1016/j.conbuildmat.2020.121520.
[77] T.O. Ogundairo, D.O. Olukanni, I.I. Akinwumi, D.D. Adegoke, A review on plastic waste as sustainable resource in civil engineering applications, IOP Conf. Ser. Mater. Sci. Eng. 1036 (2021), 012019, https://doi.org/10.1088/1757-899X/1036/1/012019.
[78] Marine Litter Assessment in the Mediterranean -, UNEP/MAP, 2015, accessed September 2, 2022, https://wedocs.unep.org/xmlui/handle/20.500.11822/7098, 2015.
[79] State of the Environment 2019 Arab Republic of Egypt, Environment Ministry, Egypt, 2019. https://eeaa.gov.eg/portals/0/eeaaReports/SoE-2019/final%20EgyptSOE2019.pdf.
[80] Z. Allam, D. Jones, Towards a Circular Economy: A Case Study of Waste Conversion into Housing Units in Cotonou, Benin, Urban Sci. 2 (2018) 118, https://doi.org/10.3390/urbansci2040118.
[81] G.L.F. Benachio, M. do C.D. Freitas, S.F. Tavares, Circular economy in the construction industry: A systematic literature review, J. Clean. Prod. 260 (2020) 121046. doi: 10.1016/j.jclepro.2020.121046.
[82] D.M. Hervie, E.C. Winful, S.K. Tsagli, Valorization of Plastic Waste in Ghana: The Circular Approach, Int. J. Sustain. Econ. Manag. 10 (2021) 31–45, https://doi.org/10.4018/IJSEM.2021040103.
[83] M. Nodehi, V.M. Taghvaee, Applying Circular Economy to Construction Industry through Use of Waste Materials: A Review of Supplementary Cementitious Materials, Plastics, and Ceramics, Circ. Econ. Sustain. (2022), https://doi.org/10.1007/s43615-022-00149-x.
[84] J.F. Molina-Azorin, Mixed methods research: An opportunity to improve our studies and our research skills, Eur. J. Manag. Bus. Econ. 25 (2016) 37–38, https://doi.org/10.1016/j.redeen.2016.05.001.
[85] Tiseo, I., Plastic production worldwide 2020, Statista. (2022). https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/ (accessed August 8, 2022).
[86] L. Lebreton, A. Andrady, Future scenarios of global plastic waste generation and disposal, Palgrave Commun. 5 (2019) 6, https://doi.org/10.1057/s41599-018-0212-7.
[87] R. Geyer, J.R. Jambeck, K.L. Law, Production, use, and fate of all plastics ever made, Sci. Adv. 3 (2017) e1700782.
[88] L. Fuhr, M. Franklin, Plastic atlas: facts and figures about the world of synthetic polymers, (2019). https://www.boell.de/sites/default/files/2020-01/Plastic%20Atlas%202019%202nd%20Edition.pdf.
[89] L.J.J. Meijer, T. van Emmerik, R. van der Ent, C. Schmidt, L. Lebreton, More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean, Sci. Adv. 7 (2022) eaaz5803, https://doi.org/10.1126/sciadv.aaz5803.
[90] J.R. Jambeck, R. Geyer, C. Wilcox, T.R. Siegler, M. Perryman, A. Andrady, R. Narayan, K.L. Law, Plastic waste inputs from land into the ocean, Science. 347 (2015) 768–771, https://doi.org/10.1126/science.1260352.
[91] W. Wit, A. Hamilton, A. Freschi, STOP THE FLOOD OF PLASTIC: How Mediterranean countries can save their sea, World Wide Fund for Nature, 2019.
[92] A.S. Ibrahim, H.M. Khaled, N.N. Mikhail, H. Baraka, H. Kamel, Cancer Incidence in Egypt: Results of the National Population-Based Cancer Registry Program, J. Cancer Epidemiol. 2014 (2014) 1–18, https://doi.org/10.1155/2014/437971.
[93] R. Verma, K.S. Vinoda, M. Papireddy, A.S. Gowda, Toxic Pollutants from Plastic Waste- A Review, Procedia, Environ. Sci. 35 (2016) 701–708.
[94] A. Salam, Environmental and health impact of solid waste disposal at Mangwaneni dumpsite in Manzini: Swaziland, J. Sustain. Dev. Afr. 12 (2010) 64–78. doi: 1520-5509.
[95] R. Srivastava, Solid Waste Management and Its Impact on the Environment:, in: K. A. Wani, L. Ariana, S.M. Zuber (Eds.), Adv. Environ. Eng. Green Technol., IGI Global, 2020: pp. 389–400. doi: 10.4018/978-1-5225-9452-9.ch019.
[96] A. Shibani, O. Mahadel, D. Hassan, A. Agha, M. Saidani, Causes of time overruns in the construction industry in Egypt, Int. Res. J. Mod. Eng. Technol. Sci. 3 (2021) 510–531.
[97] Index of construction materilas prices, Minist, Hous. Util, Urban Communities, 2022 http://admin.mhuc.gov.eg//Dynamic_Page/637945284093047276.pdf.
[98] S. Shrivastava, A. Chini, Estimating energy consumption during construction of buildings: a contractor's perspective, in: World Sustain. Build. Conf., VTT Technical Research Centre., Helsinki, Finland, 2011: pp. 18–21.
[99] 2021 Global Status Report for Buildings and Construction: Towards a Zero emission, Efficient and Resilient Buildings and Construction Sector, United Nations Environment Programme, Nairobi, 2021. https://globalabc.org/sites/default/files/2021-10/GABC_Buildings-GSR-2021_BOOK.pdf.
[100] Iron and Steel Technology Roadmap: Towards more sustainable steelmaking, International Energy Agency, 2020. https://www.iea.org/reports/iron-and-steel-technology-roadmap.
[101] M. Nodehi, V.M. Taghvaee, Applying Circular Economy to Construction Industry through Use of Waste Materials: A Review of Supplementary Cementitious Materials, Plastics, and Ceramics, Circ. Econ. Sustain. (2022), https://doi.org/10.1007/s43615-022-00149-x.
[102] Energy, Egyptian Ministry of Environment, Cairo, Egypt, n.a. https://www.eeaa.gov.eg/portals/0/eeaaReports/SoE2007Ar/10-energy.pdf.
[103] Enery in the metallurgical industries, Egypt. Chamb. Metall. Ind. (n.a). https://www.cmiegypt.org/Studies_and_statistics/193/Default.aspx. (accessed May 3, 2022).
[104] EGYPT'S FIRST BIENNIAL UPDATE REPORT to the UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, Ministry of Environment, Egyptian Environmental Affairs Agency, Cairo, Egypt, 2018. https://unfccc.int/sites/default/files/resource/BUR%20Egypt%20EN.pdf.
[105] Africa's First Plastic Bottle House Rises in Nigeria, Inhabitat - Green Des, Innov. Archit. Green Build. Green Des. Innov, Better World, 2011 https://inhabitat.com/africas-first-plastic-bottle-house-rises-in-nigeria/ (accessed December 11, 2022.
[106] N. Valencia, This House was Built in 5 Days Using Recycled Plastic Bricks, ArchDaily. (2017). https://www.archdaily.com/869926/this-house-was-built-in-5-days-using-recycled-plastic-bricks (accessed August 19, 2022).

[107] C. Plastics, Unbottled potential: Nova Scotia beach house made from 620,000 recycled PET bottles, Can, Plast, 2020 https://www.canplastics.com/features/unbottled-potential-nova-scotia-beach-house-made-from-620000-recycled-pet-bottles/ (accessed September 3, 2022.
[108] OTHALO AS - The Future of Housing, (n.d.). https://othalo.com/ (accessed August 22, 2022).
[109] UN-Habitat aims to use plastic waste to support housing for all, UN-Habitat. (2020). https://unhabitat.org/un-habitat-aims-to-use-plastic-waste-to-support-housing-for-all (accessed August 22, 2022).
[110] L. Yao, Z. Leng, J. Lan, R. Chen, J. Jiang, Environmental and economic assessment of collective recycling waste plastic and reclaimed asphalt pavement into pavement construction: A case study in Hong Kong, J. Clean. Prod. 336 (2022), 130405, https://doi.org/10.1016/j.jclepro.2022.130405.
[111] L. Grozdanic, Colorful People's Pavilion in Eindhoven is made from 100% borrowed materials, Inhabitat - Green Des. Innov. Archit. Green Build. Green Des. Innov, Better World, 2017 https://inhabitat.com/colorful-peoples-pavilion-in-eindhoven-is-made-from-100-borrowed-materials/ (accessed August 19, 2022.
[112] R. Vasudevan, A. Ramalinga Chandra Sekar, B. Sundarakannan, R. Velkennedy, A technique to dispose waste plastics in an ecofriendly way – Application in construction of flexible pavements, Constr. Build. Mater. 28 (2012) 311–320. doi: 10.1016/j.conbuildmat.2011.08.031.
[113] V. Vasudevan, TEC, Madurai, and CRRI, Guidelines for the use of Plastic Waste in Rural Roads Construction, Ministry of Rural Development., National Rural Roads Development, Agency Ministry of Rural Development., New Delhi, 2019.
[114] Macguire, E, World's longest recycled bridge spans Scottish river, CNN. (2011). https://www.cnn.com/2011/12/06/world/recyclable-bridge/index.html (accessed September 4, 2022).
[115] E.R.P. Gerard VAN, Malcolm MCKAY, Recent Australian Developments in Fibre Composite Railway Sleepers, Electron. J. Struct. Eng. 13 (2013) 62–66, https://doi.org/10.56748/ejse.131611.
[116] D. Kumar Bagal, S. Kumar Singh, B. Naik, A. Barua, S. Jeet, B. Parida, A. Kumar Pattanaik, Recent Developments and Future Prospects of Manufacturing of Broad Gauge Railway Sleepers Using Waste Materials in India, IOP Conf, Ser. Mater. Sci. Eng. 970 (2020), 012002, https://doi.org/10.1088/1757-899X/970/1/012002.
[117] S. Nair, Network Rail introduces composite railway sleepers at Sherrington Viaduct, Railw, Technol, 2021 https://www.railway-technology.com/news/network-rail-sherrington-viaduct/ (accessed March 8, 2023.