



Sustainability Performance of Voided Concrete Slab Using Waste Plastic Bottles

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Abstract

The present study is aimed at investigating the cost assessment of incorporating waste plastic bottles in the manufacture of voided concrete slabs; assessing the depth ratio vis-à-vis the cost reduction of incorporating waste plastic bottles in the manufacture of voided concrete slabs; assessing the energy consumption and CO₂ emission obtained by incorporating waste plastic bottles in the manufacture of voided concrete slabs; and evaluating the impact of the depth ratio on embodied energy consumption and CO₂ emission. The study was conducted on five types of slab specimens made: (1) conventional solid slab specimens; (2) slab specimens incorporated with 5% air-filled plastic bottles; and (3) slab specimens incorporated with 10% air-filled plastic bottles. Slab specimens of size 1000×1000×150 mm thick incorporated with 0, 5, and 10% waste plastic bottles were considered for the analysis of sustainability with respect to cost, energy, and CO₂ savings. As part of the findings, it was revealed that the incorporation of waste plastic bottles into concrete slabs results in a reduction in the cost and volume of concrete. Again, using recycled plastic bottles in the slabs saved money, but for each percentage of bottles used, additional materials (plastic bottles, chicken wire, etc.) and labour were needed, which added to the cost. It was also revealed that embodied energy and CO₂ emissions decrease as the percentage of plastic bottles in the slab increases. The study has confirmed that the void slab made with plastic bottles is more sustainable than the traditional solid slab system when it comes to cost, energy use, and CO₂ emissions.

Keywords: Waste Plastic Bottles; CO₂ Emission; Concrete Slab; Sustainability; Embodied Energy.

1. Introduction

1.1. Background

The present study aims at investigating the sustainability performance of voided concrete slabs via the utilization of waste plastic bottles. This becomes imperative under the current 21st century dispensation, where there is continual advancement in scientific research and technological applications in various fields of the economy. Hence, the need to pursue more research into the architecture and construction industries. This would help bring on board efficient, sustainable, and affordable ways of erecting buildings and structures. In recent times, sustainability and affordability have been the focus of the 21st century architecture and construction industry. Thus, finding alternative ways of building in a manner that promotes environmental sustainability would, thereby, limit the amount of waste that goes into the environment as a result of construction activities. Reducing construction costs and ensuring affordable housing for all. The foregoing submissions, thus, go to buttress the need for this present study in exploring the use of alternative building materials such as waste plastic bottles in void concrete slabs and to subsequently assess the sustainability performance achieved. Thus, in order to evaluate sustainability performance in terms of cost savings, energy consumption, and CO₂ emissions.

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Implicit in the study of Sandanayake et al. [1], it is evidenced that one of the main industries that has an impact on the environment and uses a lot of resources is the construction industry. Similarly, Luo et al. [2] buttress the fact that the built structure generates considerable amounts of energy usage and carbon emissions throughout the course of its entire life cycle, beginning with the purchase of its materials and ending with its deconstruction. A major factor accounting for this, according to the researchers, is the consumption of virgin materials during construction. According to Hong et al. [3], virgin materials account for more than 15% of a building's energy consumption and carbon emissions. In addition to the latter statement, findings from Garcia et al. [4] explain that using too many virgin materials in construction increases the demand on natural resources and therefore adds to the environmental strain. For instance, Dixit et al. [5] reported that, on the global stage, the architecture and construction industry uses an estimated 40% of raw stone, sand, and gravel, 25% of virgin wood, 16% of water, and 40% of energy every year, therefore making this particular industry one of the greatest exploiters of the natural resources available to man. The authors further explained that groundwater supplies are negatively impacted by the mining process used to extract coarse aggregates. Additionally, fine aggregate extraction from riverbanks results in substantial land loss. As implied in the report of Dixit et al. [5], more land was lost as a result of the extraction of natural aggregates, from 47.14 to 112.9%.

According to Evangelista et al. [6], the usage of natural aggregates accounts for 13–20% of all CO₂ emissions produced during constructional activities, particularly, the production of concrete. Further to the above, the researchers also avowed that about one billion cubic metres of water are used by the concrete industry every year, not including wash water, or curing water. It is on the premise of their findings that Evangelista et al. [6] suggested the need to explore any replacement aggregate, either totally or partially, as it may be necessary to meet the rising demand for conventional natural aggregates. It is evident from the ongoing submissions that there is a need to substitute virgin materials with alternative building materials such as waste products since Hossain & Poon [7] confirm that replacing such virgin materials would help curb the issues of excessive waste generation and virgin material usage. This would further contribute to cost reduction and result in a decline in energy consumption and CO₂ emissions.

In recent times, empirical evidences have emphasized the utilization of waste products in the production of a myriad of construction materials, as corroborated by studies such as [8]. More so, Sandanayake et al. [9] affirm that concrete has undoubtedly, been long recognized as the primary building material that consumes the majority of natural resources and a sizable amount of energy. Again, Ali & Babu [10] assert that, in general terms, foundations, columns, beams, and slabs are the most connected components of buildings. Among these, the concrete slab is noted to be an extremely important part because, apart from supporting both life and death, it also supports other parts of the building in carrying various loads. Furthermore, a recent report by Thomas et al. [11] indicated that the slab constitutes about 90% of the building's total weight and, as such, consumes the greatest percentage of the concrete in buildings, as similarly supported by Sandanayake et al. [9]. Based on this, the slab of buildings contributes significantly to the cost of buildings, in addition to consuming much of the depleting natural resources for construction materials such as sand and stones. As environmental concerns about traditional methods of concrete provision grow, engineers are focusing on green concreting, which is defined as a method of reducing carbon dioxide (CO₂) emissions and energy consumption through the use of industrial waste products such as plastics in concrete. Hence, the need to find alternative ways of reducing cost, energy, waste, and CO₂ emissions in the production of concrete. This may bring to light, incorporating other alternative materials, such as waste plastic bottles, in the production of concrete slabs.

Over the last ten years, numerous studies have focused on lowering energy usage, carbon emissions, and the use of virgin materials in concrete as supported by Cardoso et al. [12] and Callejas et al. [13]. For instance, in the study by Cardoso et al. [12], the researchers in a quest to exploring the use of Recycled Aggregates (RA) in construction concluded that, the performance of most Recycled Aggregates is comparable to that of Natural Aggregates (NA) and could therefore, be employed in unbound pavement layers or in other applications requiring compaction. This goes to buttress the ideology of employing other waste products in concrete production. More so, in the study of Sandanayake et al. [9], the authors concluded that there was the need to intensify studies relating to the usage of waste products in construction materials such as concrete since, it results in sustainable materials that could produce environmental benefits. Nonetheless, studies such as Sandanayake et al. [9] and Sargam et al. [14] draw attention to a research gap, which could be the problem of employing waste materials in concrete due to the high costs and energy requirements involved in turning the waste materials into usable resources. Regardless of the availability of numerous studies on several aspects of employing waste products such as plastic bottles in construction materials, there is another noticeable gap. Thus, the systematic review of the existing literature still seems to be absent, particularly regarding sustainability of concrete manufactured from waste materials. Such literature reviews are imperative for the advancement of the discourse on plastic-based concrete slabs. This therefore calls for more investigating into the phenomenon of employing waste products into concrete slabs. On the premise of the ongoing submissions, makes it significant to advance this present study by way of investigating into the sustainability performance of voided concrete slabs via the utilisation of waste plastic bottles. Therefore, the results of this study offer industrial and academic parties interested in promoting sustainable concrete with important conclusions and recommendations for the future.

Another key aspect of this present study is the utilisation of waste plastic bottles in the voided concrete slabs. Plastic is a lightweight, hygienic, and resistant material that can be fabricated in a variety of ways and used in a vast array of applications. It has the highest reported production growth rate of any material. According to the Institute for Building Environment and Energy Conservation [15], global plastics production has increased to an unprecedented level. Additionally, Ndiaye et al. [16] estimates that by 2050, the world will produce around 1124 million tonnes of plastic annually if current trends in the plastics industry continue. Consequently, Hammond et al. [17] report warned that if current consumption patterns and waste management practises are not improved, by 2050 there will be an enormous increase in the 12 billion tonnes of plastic litter in landfills and the environment.

According to Alcorn [18], plastics that find their way into nature may disturb the soil's natural structure and, in turn, the plant and microbial life there, which could have negative ecological effects. Across the international community, sustainable methods of reducing the volume of plastic waste entering the environment are envisaged. For instance, as typified in a report by Eco-cities in India program [19], two methods were highlighted as sustainable and feasible approaches, thus: (1) averting the origination of the waste by using materials in production processes and developing products that are easily recyclable is a good start and (2) recycling of waste products by re-using them for other purposes. In support for the ongoing contentions, Shiuly et al. [20] also observe the need to utilise waste plastic bottles in construction materials such as concrete slabs. This is due to the indiscriminate disposal of waste plastic bottles, which negatively affects the environment. In the study of Anon [21], UNEP revealed that, around 400 million tonnes of plastic garbage are produced annually throughout the world. Consequently, the study of NvIRONMENT [22] indicated that the COVID-19 epidemic significantly increased the production of plastic trash in items like PPE kits, disposable gloves, and sanitizer bottles. More so, about 20% of the total plastic trash produced was of the PET kind, and 29% was made up of products with a PE foundation. In the exposition of da Luz Garcia et al. [23], it is reported that, about 9% of all created plastic garbage is recycled, 12% is burned and the remaining 79% is dumped in landfills. Hence, there is the need to find alternative utilisation of such plastic waste by incorporating into the manufacture of construction materials such as concrete slabs.

Currently, Shiuly et al. [20] establish that several nations forbid the landfilling and burning of waste plastic. More so, it important to note that PE is one of the plastics that is least likely to biodegrade, leading to a mountainous build-up in the environment as indicated by da Luz Garcia et al. [23]. The leaching of various harmful contaminants, such as heavy metals and microplastics concentration in soil and water resources, results in the degradation of soil fertility and damage to the environment and public health when waste plastic is disposed of in landfills. Di-oxine and furan, among other unpleasant gases, are produced during incineration. This therefore makes waste plastic incineration inappropriate and unfriendly to the environment and therefore, emphasises on the need to find alternative use of such waste plastics in the construction industry. Subsequently, Shiuly et al. [20] explain that on the average, each person's daily activities globally, produce a yearly carbon footprint of 4.79 tonnes of CO₂ equivalents. In this light, Tayeh et al. [24] buttress the fact that 1.3% of this carbon footprint can be attributed to plastic use. This implies that PET and PE have a carbon footprint of around 6 kg CO₂ equivalent per kg according to the researchers. It is on the basis of this finding that the researchers accentuate that, recycling can be a hopeful approach in the reduction of a number of environmental issues and health risks associated with waste plastics. However, a major gap observed here has to do with drawbacks of recycling discarded plastic. Such drawbacks may include colour change, quality degradation, and higher processing costs. Therefore, handling the waste plastic requires a practical and affordable method. Hence, Shiuly et al. [20] believes that reusing plastic in the concrete industry, particularly in light weight concrete as a partial replacement of naturally derived coarse and fine aggregates, might be seen of as the most practical use for tackling the management and disposal of vast amounts of plastic waste. This supports the significance of this study by exploring the sustainability performance of voided concrete slab via the utilisation of waste plastic bottles. The influence of seismic pressures on buildings may be lessened as a result of the replacement of natural coarse and fine particles with plastic-made aggregates by lowering the fresh and dry density of concrete as opined by Akaozoglu et al., [25]. Nonetheless, Correia et al. [26] highlight other benefits of lightweight concrete in that it entails high levels of thermal and acoustic insulation and reduced manufacturing and handling costs.

Regardless, experiential findings on the replacement of either fine or coarse aggregate in concrete by 5–40% using plastic waste in the construction industry, has produced progressive and encouraging findings as evidenced in studies such as Almeshal et al. [27], Mohammad et al. [28], and Safi et al. [29]. For analysing the performance of waste plastic-based concrete as well as their durability, the researchers primarily determined physical and mechanical properties like fresh and dry density, workability, compressive strength, flexural strength, and split tensile strength [30-32]. The thermal and acoustic insulation qualities of concrete made from waste plastic were also mentioned in a relatively small number of studies [33-36]. The foregoing brings to light a peculiar research gap in that, sustainability performance of such plastic-based concrete in terms of cost assessment, depth ration, energy consumption and CO₂ emission coupled with the impact of depth ratio ration on embodied energy consumption and CO₂ emissions, has not been extensively explored therefore, resulting in the situation of insufficient repository on the subject matter of sustainability performance of plastic-based concrete slabs. In view of the above submissions, the study explores the sustainability performance of voided concrete slab using waste plastic bottles. Specifically, the objectives of this study

are:

- To investigate the cost assessment of incorporating waste plastic bottles in the manufacture of voided concrete slabs;
- To assess the depth ratio vis-à-vis cost reduction of incorporating waste plastic bottles in the manufacture of voided concrete slabs;
- To assess the energy consumption and CO₂ emission obtained by incorporating waste plastic bottles in the manufacture of voided concrete slabs;
- To evaluate the impact of depth ratio on embodied energy consumption and CO₂ emission.

Subsequent sections of this paper comprise the reviews, materials, and methodology employed to carry out the sustainability assessment of the slabs, including results discussion and conclusions drawn with respect to findings emerging from the sustainability assessment.

1.2. Significance of the Study

According to Sandanayake et al. [9], concrete has been produced all over the world from a variety of waste items. But because of things like material scarcity and high costs, the use of waste products as building materials is frequently limited. Nonetheless, empirical juxtapositions presented earlier in this paper indicate that, construction engineers are aiming at the production of green concrete slabs, thus, sustainable concrete production that are eco-friendly. This makes this present study imperative as it further explores the sustainability performance of such plastic-based concrete slabs. In addition to that, the findings of this study reveal the cost assessment of incorporating plastic waste bottles in voided concrete slabs. This would help provide additional literature to support the issues pertaining to the perceived high costs involved in the usage of recycled waste plastic bottles in the concrete production sector. More specifically, the findings of this research could help practitioners better understand current procedures, challenges, and opportunities for measuring sustainability features of green concrete thus, plastic based voided concrete. The findings of this study would then advance knowledge of current priorities and trends for the use of waste plastic bottles in the creation of durable, environmentally friendly, and reasonably priced void concrete slabs. The current study will also help different industry participants understand the elements that must be considered when creating sustainable building materials, such as the use of waste plastic bottles in voided concrete slabs.

Subsequently, the United Nations Human Settlements Programme [37] report indicate that about 1.6 billion people around the world are living in substandard or uninhabitable housing conditions. This calls for the need to take pragmatic approaches to reducing housing problems by employing local, low-cost materials and techniques as this has been an issue of major concern to the building industry, according to findings from Danso [38]. Also, the United Nations Commission for Human Settlement has, over the past few decades, tasked the building and construction industries with soliciting for Alternative Building Materials (ABM) for improving the housing stock in addition to replacing the depleting natural resource construction materials, such as sand, stone, and timber. This study provides enough evidences in the sustainability performance of voided concrete slabs via the usage of waste plastic bottles. The invention of the voided slab system has been recognised as a more sustainable system of slab provision due to its lower cost and environmental friendliness. However, the current voided technology utilises plastic waste by changing it to plastic balls before inclusion in the slabs. However, the intended idea of energy utilisation is hampered because additional energy is required to recycle the plastic into the ball properties. On the contrary, this study tends to apply the voided slab technique by utilising waste plastic bottles in their raw state. Furthermore, the plastic bottles, like the standard plastic balls used in the voided slab system, are lightweight, hollow, and recyclable after the structure is pulled down. This therefore assures that both materials can be used interchangeably in sustainable applications. So, this study used the "voided slab" method. However, instead of plastic balls in the middle of the slab, plastic bottles were used. This brings on board some form of new approach and novelty in the production process of plastic-based concrete slabs.

2. Literature Review

2.1. Voided Slab

The voided slab, also known as the Bubble Deck slab, is a reinforced concrete slab invented in the 1950s by Jorgen Bruenig. The rationale behind the invention was to make a hollow two-axis slab with the same function as a solid slab but by significantly reducing the weight of the concrete due to excessive concrete removal. According to the basic mechanics of materials principle, the concrete in the neutral axis of a slab serves no structural purpose. Getting rid of it was one of the main reasons why the Bubble Deck slab system was made. The Bubble Deck slab system reduces the overall weight of the slab to about 35, including a saving of about 40 to 50% of the load bearing capacity. As a result, the slab system is used to avoid the problem of slabs' ever-increasing self-weight. Additionally, this slab system is

reported to produce fewer carbon dioxide (CO₂) emissions, uses less concrete, and necessitates less energy to produce than traditional slabs. It is therefore a more environmentally friendly slab provisioning system because it's made with recycled plastic balls that can be recycled again after the building is torn down.

A study of the flexural behaviour of a Bubble Deck slab strengthened with FRP was conducted by Abishek and Iyappan [39]. In the study, a plastic ball of 75 mm was placed between the bottom and top reinforcement within the neutral zone of a slab specimen measuring 700×300×125 mm thick. The flexural test report indicates that the load carrying capacity, flexural strength, and deflection of the bubble deck slab reinforced with FRP were 18% greater than those of the conventional slab.

In another vein, Dheepan, et al. [40], investigated into the flexural behaviour of 600×300×100 mm Bubble Deck slab incorporated with 60 mm and 75 mm diameter plastic balls. It was reported that the flexural strength of slab incorporated with 60 mm diameter balls was higher than the slab with 75mm diameter walls.

The behaviour of self-compacting reinforced concrete one-way Bubble Deck slab was studied by Yaagoob & Harba [41]. A 1200×700×60 mm plastic ball was prepared and subjected to a flexural loading test. Observations from the study indicate that the deflection at cracking load and ultimate load of the Bubble Deck slab exceeded the conventional solid slab. The use of 73mm diameter balls decreases flexural load and ultimate load compared to a slab with 60mm diameter bottles. All the bubble deck slabs exhibited fewer first crack loads than the conventional slab. In the study of Ali & Babu [10] the researchers conducted a structural study, or Bubble Deck slab, using polyethylene bubbles of a diameter of 120 mm. It was observed that a Bubble Deck slab gives greater flexural strength, stiffness and shear force capacity compared to a normal solid slab of the same properties.

In advancing on the subject matter of voided concrete slabs, Thomas, et al. [11] conducted an experiment on the flexural strength of the Bubble Deck slab. In this light, a slab of size 600×300×120 mm was incorporated with plastic balls of 60mm in diameter. Slabs of three different types, comprising of 9-number balls, 12-number balls, and 24-number balls, were prepared for the study. It was revealed from the study that the Bubble Deck configuration gives comparatively similar flexural strength performance to the solid slab. The amount of concrete required for a conventional slab was reduced by 4.7% for the 9-number slab, 7.2% for the 12-number slab, and 14.4% for the 24-number incorporated slab. Significant self-weight reduction was observed from the study. Pursuant to the findings of an experimental programme developed by Mahdi and Ismael [42] to assess the normal strength hollow core slab, it was revealed that the usage of the hollow core slab could reduce the ultimate load by 82.92 to 93.47%, while simultaneously increasing the ultimate deflection by 6.58 to 27.31%.

Consequently, an investigation into the flexural behaviour and sustainable analysis of hollow-core reinforced concrete slabs was undertaken by Mahdi and Ismael [42]. In the study, four self-compacted reinforced concrete one-way slabs with measuring 1.70 m length × 0.435 m × width × 0.125 m depth were cast and tested. Slab specimens include a control solid slab and a variety of hollow core slabs with varying numbers of longitudinal voids (two, three, and four). Using hollow-core slabs led to a 6.53, 12.37, and 17.08 % decrease in ultimate strength and an 8.72, 21.57, and 28.31% increase in ultimate deflection, respectively. Also, it can reduce the self-weight of the slabs by about 15%, 23%, and 30%, with cost-saving by about 12, 17, and 23%, and reducing the embedded energy and the CO₂ emissions by about 16.3, 24.4, and 32.5%. Additionally, it can lessen the slabs' self-weight by anywhere from 15 to 30%, save money by anywhere from 12 to 23%, and cut down on embedded energy and CO₂ emissions by anywhere from 16 to 32%.

The structural behaviour of hollow-core one-way slabs made of high-strength self-compacting concrete was investigated by Mahdi and Ismael [43]. The purpose of the research was to examine how altering the number and size of longitudinal voids affected the functionality of hollow core slabs. The experimental findings presented demonstrate that hollow-core slabs are an efficient means of reducing the self-weight of the slabs while retaining most of the structural behaviour typical of solid slabs. Furthermore, when concrete with those percentages is removed, hollow-core high-strength slabs with three longitudinal voids of diameter 50, 63, and 75 mm show cracking load reductions of 5.58, 8.37, and 13.49%, while also saving 90.06, 87.84, and 85.07% and increasing ultimate deflection by 5.4, 10.80, and 17.44%, respectively., removing 16.25, 24.375, and 32.50% of the concrete from hollow-core high-strength slabs with 2, 3, and 4 longitudinal voids of 75mm diameter, respectively, reduced the first crack load by 8.84, 13.49, and 17.21%, respectively, preserved the ultimate strength by 80.29, 85.073, and 80.613%, and increased the ultimate deflection by 7.57, 7.56, and 7.57%, respectively. Therefore, increasing the diameter of longitudinal voids rather than the number of longitudinal voids has a greater impact on reducing the ultimate load.

In a study carried out by Shetkar & Nagesh [44], the authors delivered experimental research on Bubble Deck Slab System with Elliptical Balls coupled with the characteristics of Bubble Deck slabs influenced by the ratio of bubble diameter to slab thickness as well as the efficiency and likelihood of the usage of Bubble Deck in the construction industry. In their experiment, it was observed that the applied force was provided from beneath to the topmost part of the slab, which is opposite to the direction of gravity via the utilization of hydraulic jack. The researchers discovered

that by using that level of force, it is simpler to observe the strain and deformation of rebar and concrete on the slab's top side. Until the slabs develop cracks and the failure modes manifest, it demonstrates how the hollow elliptical balls can be used to increase load bearing capacity in Bubble Deck while consuming less material, thereby allowing for a quicker building process and lower total expenses. Additionally, it has resulted in a 50% reduction in deadweight.

In the study of Amer et al. [45], it is seen that the flexural properties of two-way bubble deck slabs of reinforced concrete with plastic spherical voids were investigated by the authors. Two-dimensional flexural tests were performed utilising a specific loading frame to verify the flexural behaviour of this Bubble Deck slab, including ultimate load, deflection, concrete compressive strain, and crack pattern. Six specimens were tested in total. Four of the slabs were Bubble Deck slabs with void diameter to slab thickness ratios of 2, and two were a traditional RC slab (0.51, 0.64 and 0.80). It was demonstrated that the relationship between void diameter and slab thickness affects the crack pattern and flexural behaviour. The ultimate load capacities of Bubble Deck slabs with bubble diameter to slab thickness ratios of 0.1 and 0.64 were identical to those of solid slabs, however the ultimate capacities decreased by approximately 10% when the bubble diameter to slab thickness ratio was 0.80. Four steel beams with hinges in the upper surface supported the slab at all four edges simply in order to reduce support condition mistakes and fixed end moment during testing. In order to simulate the actual loading condition, this specimen was tested using a five-point load system with a five-loading plate and five hydraulic jacks.

Prabhu et al. [46] carried out an investigation into the durability of Bubble deck slab and their study was explained on the basis of creep and shrinkage. In this case, the researchers utilised a bubble deck element with two spherical hollows in comparison with a solid concrete block of exact dimension and of the same concrete. The researchers then measured the difference between the shrinkage strains of these two. Findings from their experimental study indicated that Bubble deck element possesses an insignificant larger marginal shrinkage strain as compared to a solid slab with same dimensions and the same concrete performances, under the same exposure to environmental conditions. The implication of their findings could suggest that the influence of carbonation shrinkage could actually be ignored in the design and manufacture of concrete structures with Bubble deck system. The latter is also due to the fact that only a small part of the concrete cross-section has exposure to this kind of shrinkage. However, as a gap to their study, even though the durability of the voided concrete slab was evaluated, the study failed to undertake a sustainability assessment of the depth ratio vis-à-vis cost reduction measures coupled with the evaluation of energy consumption and CO₂ emission.

2.2. Energy and CO₂ Emissions

The contribution of the construction industry towards embodied energy and CO₂ emissions is reported to constitute 20% of the entire energy and CO₂ emissions in the world. Out of these, construction in developed countries contributes 5–10%, whereas 10–30% is from undeveloped countries. Though figures vary from country to country, the reduction of energy and CO₂ emissions is noted to contribute effectively to the reduction of global energy consumption and CO₂ emissions. The growing importance of energy and CO₂ emissions has been recognised recently by various actors in the construction industry. However, there is still a significant and available opportunity to limit the impacts alongside the operational impact of the building for the under listed reasons.

- **Life cycle thinking:** Globally, the construction industry continues to encourage actors in the industry to carry out life cycle assessments of building solutions. For example, aside from the cost of production, operation and running of buildings, an assessment of energy and CO₂ emissions from production through to running is deemed necessary when talking about sustainability.
- **Increase in the ratio of embodied to operational energy and CO₂ emissions:** Pressure to get to zero operational carbon emissions keep putting pressure on people in the construction industry to use more thermal mass and technologies that use less or no carbon.
- **Life cycle assessment (LCA):** The growing importance of the concept of life cycle thinking in construction has led to the broad application of LCA methods in practise for decision making. The LCA method normally considers three areas of protection: human health, ecosystems, and resources. The assessment of energy and CO₂ emissions is therefore considered part of LCA as they are quantified by the LCA indicators as assessing the use of energy resources and climate change, which are linked to the three areas of protection.
- **Sustainability assessment:** There has been a shift to the adoption and standardisation of predominantly quantitative and life-cycle-oriented approaches to assessing building sustainability. The estimated value of energy and CO₂ emissions can be fed into the assessment of the life cycle use of energy and CO₂ emissions resources as part of an LCA. So, in terms of sustainability assessment, it is a full evaluation of how a building affects the environment and a full evaluation of how each building contributes to sustainable development.

2.3. Assessment of Embodied Energy and CO₂ Emissions

A study on sustainability achieved by using a voided slab system was conducted by Hussein et al. [47] with the prime objective of comparing the Bubble Deck to conventional solid slabs in order to ascertain the effect of sand, gravel and cement on energy consumption and CO₂ emissions. Their study was motivated by the fact that the greatest rate of energy consumption and CO₂ emissions in concrete production results from the production of raw materials (cement, sand, gravel, and reinforcing steel). Hence, any amount of reduction in the volume of concrete production results in a reduction of the main constituent materials (cement, gravel, sand, and water), resulting in a reduction in energy consumption and CO₂ emissions. The weights of the cement, fine aggregate, and coarse aggregate used in each slab specimen were used to figure out how much energy was used and how much CO₂ was released.

2.4. Calculation of Energy Consumption and CO₂ Emission

The Calculation of amount of energy consumption and CO₂ emissions were determined from the following expression.

$$\text{Embodied Energy} = \text{Factor of embodied energy} \times \text{Quantity of material} \quad (1)$$

$$\text{CO}_2 \text{ Emission} = \text{Factor of CO}_2 \text{ emission} \times \text{Quantity of material} \quad (2)$$

Factors of embodied energy and CO₂ emissions are usually expressed in megajoules per kilogram (MJ/kg) for embodied energy and kilograms of CO₂ emission per kilogram (kgCO₂e/kg) for CO₂ emission of a product or material. The calculated values of embodied energy and carbon dioxide are clearly not precise when applied to a general category of material. This is because each material will experience a variation in material form and specific type. Additionally, available data on embodied energy and CO₂ emission factors, as per Table 1, confirm this statement. Even so, the results can be seen as good benchmarks for figuring out the performance of buildings and manufactured products over their entire life cycles [16].

Table 1. Comparison of Embodied Energy and CO₂ Emission Factors

Country	Cement		Natural sand		Aggregate		Source (s)
	Embodied energy (MJ / kg)	CO ₂ Emission (Kg /kg)	Embodied energy (MJ / kg)	CO ₂ Emission (Kg /kg)	Embodied energy (MJ / kg)	CO ₂ Emission (Kg /kg)	
Senegal	3.32	0.73	0.06	0.004	0.16	0.01	[16]
UK	4.4-4.8	0.226	0.1	-	0.1	-	[17]
New Zealand	7.8	0.994	0.1	0.007	0.1	0.0023	[18]
India	6.4	0.38	0.11	0.009	0.11	0.009	[19]

2.5. Sustainability Perspectives of Using Plastic Waste in Concrete

There are limited studies that evaluate the environmental performance of concrete and mortars made using waste plastics in the open literature. Yin et al. (2016) [48] performed a cradle-to-gate Life Cycle Assessment (LCA) on concrete walkways with four different forms of reinforcement. Traditional steel mesh, virgin PP fibre, commercial PP waste, and household PP waste were the types of reinforcement that were taken into consideration. In terms of emissions and resource consumption, recycling home and industrial PP waste outperformed virgin PP fibres and conventional steel mesh in a substantial way. Carbon emissions, equivalent oil consumption, and water usage all fell significantly when comparing industrial recycled PP fibre to steel mesh, by 93, 91, and 99%, respectively. However, compared to the technique used to produce virgin PP fibres, the washing step needed for recycling domestic PP waste increased water utilization.

Experimental research on the mechanical and physical characteristics of geopolymer concrete reinforced with Metalized Plastic Waste (MPW) fibres was conducted by Bhogayata and Arora [49]. By demonstrating the life cycle of the waste product, it was also possible to discuss the innovative mixture's environmental performance. Because of the potential for contamination from disposal and incineration, it was hypothesised that the minimal resource requirements for shredding and washing the trash for inclusion into geopolymer concrete might be a sustainable option.

The dynamic behaviour of concrete reinforced with waste PET plastic was studied by Foti and Paparella [50]. To strengthen concrete plates, long discrete PFs were hand cut from post-consumer drinking bottles and put in a grid pattern. The PET-grid reinforced plates showed improvements in ductility and impact strength, indicating possible applications in constructions subjected to shock loading.

Galvo et al. [51] used SEM analysis to determine the chemical resistance of plastic concrete using samples that had been artificially aged in a humid environment with sulphur dioxide. When it came to the harmful crystal formation of chemical phases including sulphur, plastic concretes outperformed rubber concrete. Ghernouti & Rabehi [52] demonstrated that when compared to regular concrete, concrete incorporating PBW aggregates exhibited better chemical resistance to chloride ions and sulfuric acid solutions. Moreover, Ge et al. [53] discovered that plastic mortars containing PET aggregates were extremely resistant to chemical assault because no decreases in compressive strength were noticed after 30 cycles of wetting and drying in a sulphate solution. By adding PAs, Coppola et al., [54] found that lightweight mortars had increased sulphate resistance because more macropores were present.

3. Research Methodology

The flow chart of the study methodology is presented by Figure 1.

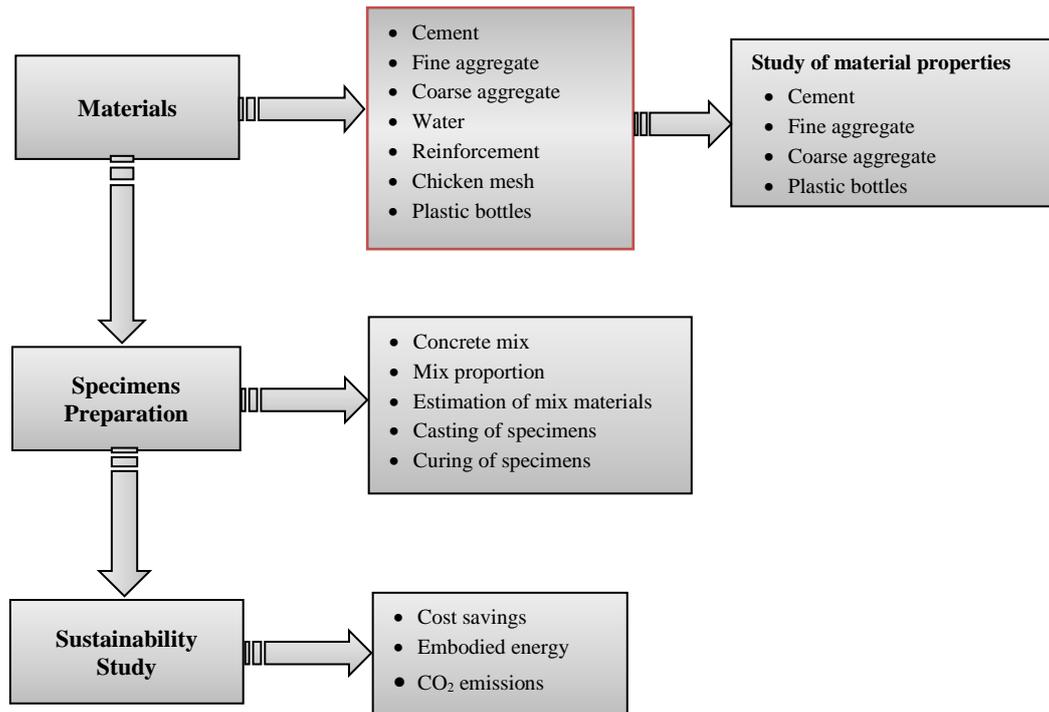


Figure 1. Methodology Flow Chart

3.1. Materials

Cement

Ordinary Portland cement of class 42.5 produced in Ghana by GHACEM (Heidelberg Cement Group) conforming to IS 8112:2013 [55] was used for the study. Tests result on the cement properties are presented on Table 2.

Table 2. Results of Test on Cement

Sl. No	Test	Experimental Values	Permissible limit as per IS 8112:2013
1.	Specific Gravity	3.11	3.10 – 3.15
2.	Normal Consistency	30.2%	25% – 33%
3.	Setting Time	-	-
	Initial	58 minutes	>30 minutes
	Final	320 minutes	<600 minutes

Fine Aggregate

The researcher used river sand that met the requirements of zone II of IS 383:2016 [56]. Tables 3 and 4 show the corresponding results upon testing of fine aggregate properties with respect to specific gravity, particle size distribution, fineness modulus, and water absorption, including bulk density. Furthermore, Figure 2 shows the grading property of the fine aggregate used.

Table 3. Results of Test on Fine Aggregate

Sl. No.	Property	Results obtained	Permissible limit as per IS 383:2016
1.	Specific gravity	2.61	2.2 – 3.2
2.	Fineness modulus/ Grade	2.87/Zone	2.87/Zone
3.	Water absorption	1.23%	1.0% -3.0%
4.	Bulk density	1601 kg/m ³	1520 – 1680 kg/m ³

Table 4. Particle Size Distribution of Sand

Is Sieve Size	Weight Retained (Gm)	Cumulative Weight Retained (Gm)	Cumulative % Weight Retained	Cumulative % Weight Passing
10MM	0	0	0.00	100.00
4.75MM	28	28	1.87	98.13
2.36MM	57	85	5.67	94.33
1.18MM	380	465	31.00	69.00
600μ	452	917	61.13	38.87
300μ	391	1308	87.20	12.80
150μ	192	1500	100.00	0.00
Pan	0	1500	-	-
Total	1500		286.66	

$$Finesness\ Modulus = \frac{286.66}{100} = 2.87 \tag{3}$$

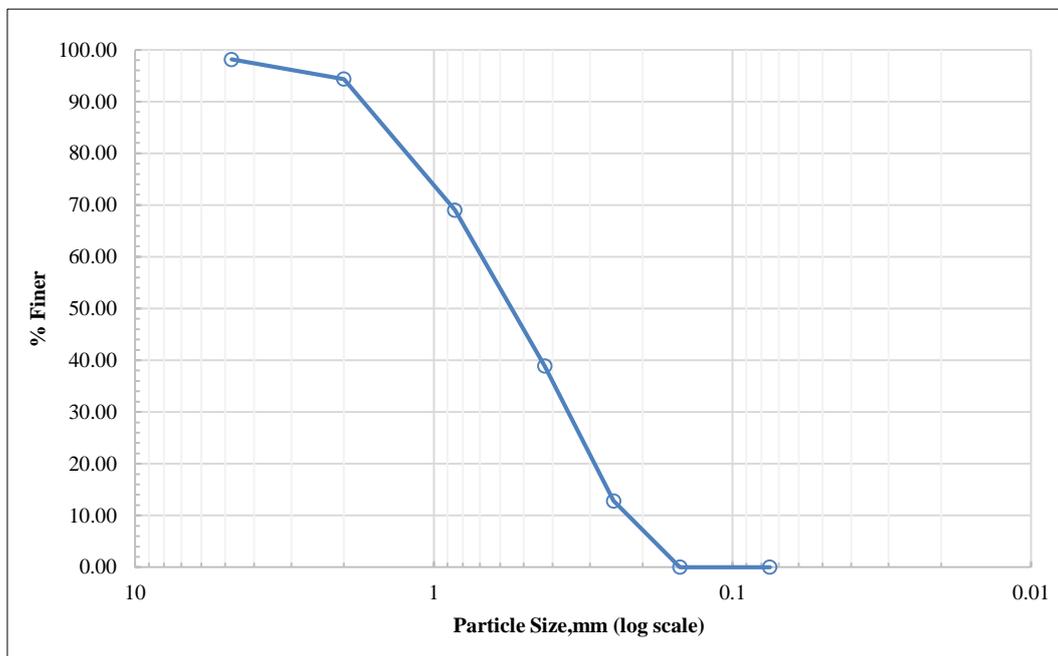


Figure 2. Graph of particle distribution of sand

Coarse Aggregate

Crushed stones constituted the coarse aggregate employed for the study. Tests for specific gravity, fineness modulus, water absorption, and bulk density were done according to IS 2386 (Part III) – 1963 [57]. Table 5 shows the respective results. Additionally, Table 6 and Figure 3 show the particle size distribution of the coarse aggregate observed from the grading test.

Table 5. Results of Test on Coarse Aggregate

Sl. No.	Property	Results obtained	Permissible limit as per IS 383:2016
1.	Specific Gravity	2.84	2.5– 3.0
2.	Fineness modulus	6.02	6.0 – 6.9
3.	Water Absorption	0.89%	< 2.0%
4.	Bulk density	1501 kg/m ³	1200 – 1750 kg/m ³

Table 6. Particle Size Distribution of Coarse Aggregate

Is Sieve Size	Weight Retained (g)	Cumulative Weight Retained (g)	Cumulative % Weight Retained	Cumulative % Weight Passing
40 mm	0	0	0	100
20 mm	0	0	0	100
16 mm	0	0	0	100
12.5 mm	22	22	1.47	98.5
10 mm	128	150	10	90
4.75 mm	1350	1500	100	0
2.36 mm			100	0
1.18 mm			100	0
600 μm			100	0
300 μm			100	0
150 μm			100	0
Pan				0
Total	1500		611.47	

$$Finesness\ Modulus = \frac{611.47}{100} = 6.11 \tag{4}$$

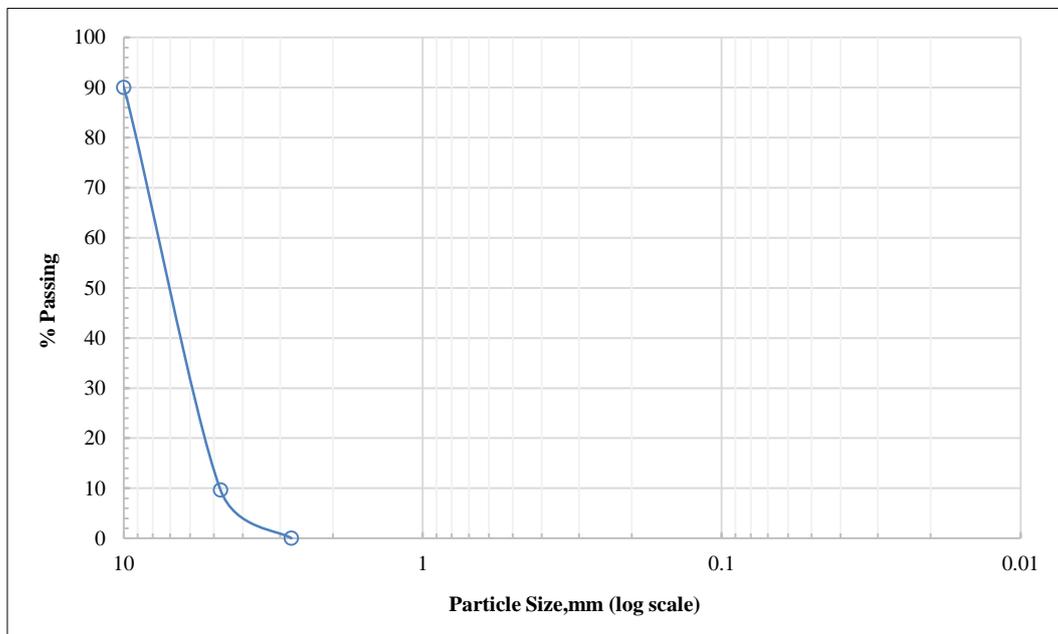


Figure 3. Graph of particle distribution of coarse aggregate

Plastic Bottle

Empty Polyethylene Terephthalate Ethylene (PET) water bottles of 500 mL capacity were collected from hotels, stores, and restaurants in and around Cape Coast Technical University for this study. The bottles were washed with mild detergent soap and water to remove packaging labels and any remaining residue. The physical characteristics of the plastic water bottles used in the study are presented in Table 7.

Table 7. Physical properties of plastic bottles used for the study

Sl. No.	Property	Value
1.	Height	215 mm
2.	Diameter (bottom)	60 mm
3.	Weight	14 g
4.	Volume	500 mL
5.	Cross-section shape	Circular

Water

Portable water produced by Ghana Water Company Limited that conforms to IS 456:2000 and IS 10500:2012) was used for the concrete mix.

Reinforcement

The slab specimens were reinforced in the compression and tensile zones using 8 mm of diameter mild steel reinforcement, which satisfied IS 432:1982 [58].

Chicken Mesh

To ensure the bottles would adhere to the concrete, they were first encased in a 20×20 mm hexagonal galvanized steel chicken mesh before being caged with the 8mm diameter mild steel reinforcement.

3.2. Concrete Mix Proportion

Material proportions for M20 nominal mix concrete were determined using Table 9 of IS 456:2000[59]. For a grade M20 concrete mix, the total quantity of dry aggregate by mass per 50kg of cement was taken as the sum of the masses of the fine and coarse aggregate, as directed by IS 456:2000 (i.e., 250kg) [59]. The required mix proportion for the concrete indicated on Table 8 was determined based on the proportion of Zone II of fine aggregate to 10mm size of coarse aggregates for a ratio of 1:112 (IS 456:2000) [59].

Table 8. Mix Proportion for M20 Concrete Mix

Concrete Grade	Materials and Quantity			
	Cement	Fine aggregate	Coarse aggregate	Water
M20	50 kg	100 kg	150 kg	30 L
Ratio	1	2	3	w/c = 0.6

3.3. Estimation of Concrete Mix Materials

The concrete recipe used for this study was adapted from Table 6 (reproduced as Table 9) of the Building Estimating Manual for West Africa by Amoa-Mensah [60]. Table 9 did not include the materials needed to make a cubic metre of concrete at the nominal 1:2:3 mix ratio, so Table 10 shows the pro rata quantities of materials needed per cubic metre of concrete at the 1:2:3 mix ratio that was used in the study.

Table 9. Quantities of materials/m³ of concrete (Table 6.1 of [55])

Nominal mix	Cement (1442kg/m ³)		Sand (1602kg/m ³)		Aggregate (1442kg/m ³)	
	kg	m ³	kg	m ³	kg	m ³
1:1:2	520	0.36	580	0.36	1050	0.73
1:1½:3	390	0.27	640	0.40	1150	0.80
1:2:4	300	0.21	690	0.45	1230	0.85

Table 10. Quantities of materials/m³ of concrete for the study

Nominal mix	Cement (1442kg/m ³)		Sand (1602kg/m ³)		Aggregate (1442kg/m ³)	
	kg	m ³	kg	m ³	kg	m ³
1:2:3	360	0.25	673	0.42	1203	0.82

3.4. Estimation of Materials Consumed Per Slab Specimen

The study was conducted on five (5) types of slab specimens made: (1) conventional solid slab specimen; (2) slab specimen incorporated with 5% air-filled plastic bottles; and (3) slab specimen incorporated with 10% air-filled plastic bottles. Slab specimens of size 1000×1000×150 mm thick incorporated with 0, 5, and 10% waste plastic bottles were considered for the analysis of sustainability with respect to cost, energy, and CO₂ savings. Upon calculation based on the mix ratio determined in Table 9, the resulting material quantities consumed per specimen type are presented in Table 11. Determination of values in Table 11:

- Volume of plastic bottle (from Table 7) = 500ml = 0.0005m³
- Volume of concrete slab = 1.0×1.0×0.15m = 0.15m³
- 5% volume of slab occupied by plastic bottles = 5% × 0.15m³ = 0.0075m³
- 10% volume of slab occupied by plastic bottles = 10% × 0.15m³ = 0.015m³
- Required No. of bottles for 5% bottles slab = 0.0075m³/0.0005m³ = 15No. bottles
- Required No. of bottles for 10% bottles slab = 0.015m³/0.0005m³ = 30No. bottles
- Volume of concrete consumed by slab type = volume conventional solid slab – volume of concrete occupied by % plastic bottles
- For 5% Bottles, concrete consumed = 0.15 – 0.0075 = 0.1425m³
- For 10% Bottles, concrete consumed = 0.15 – 0.015 = 0.135m³

Quantities of concrete materials such as cement, fine aggregate, coarse aggregate, and water were determined by multiplying the volume of concrete consumed by the respective mass of material obtained from Table 10. In all, a total of 15 No. and 30 No. of 500mL waste plastic water bottles were consumed, considering 5% and 10% incorporated, respectively.

Table 11. Breakdown of materials consumption per slab specimen

% Bottle	Type of specimen	Size of Specimen (mm)	No. of Bottles consumed	Volume of concrete consumed (m ³)	Quantities of concrete material used for the study			
					Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Water (L)
0%	Conventional slab	1000×1000×150	0	0.15	54.00	100.95	180.45	32.4
5%	Air-filled plastic bottles slab	1000×1000×150	15	0.1425	51.30	95.90	171.43	30.8
10%	Air-filled plastic bottles slab	1000×1000×150	30	0.135	48.60	90.86	162.41	29.2

3.5. Cost Assessment Study

The objective is to determine the percentage cost reduction or increment of incorporating waste plastic bottles in concrete slab. The under listed steps were followed in carrying out the cost assessment:

Step 1: Determination of market price of grade M20 concrete:

Selected construction agencies operating in Cape Coast (the study area) were contacted for the prices of grade M20 (1:2:3-10mm aggregate). Rates in Ghana Cedis (Gh¢) received are presented in Table 12. The calculated average rate was used for the cost assessment study.

Table 12. Rate of Grade M20 Concrete from selected Agencies in Ghana as of April 2022

Agency	Rate (Gh¢/m ³)
Architectural and Engineering Services Ltd	1,200.00
Public Works Department	1,144.52
Procurement and Project Management Consultancy	1,150.00
Works Department (Cape Coast Metropolitan Assembly)	950.00
Average	1,111.13

Step 2: Volume concrete consumed:

The volume of concrete consumed per type of slab specimen from Table 11 were considered.

Step 3: Determination of cost per Specimen:

The cost per each type of slabs specimen was obtained by multiplying the volume of concrete described in step 2 by the average rate of M20 concrete obtained from Table 12.

Step 4: Determination of cost of concrete saved:

The cost of savings made on concrete per type of slab was calculated by subtracting the cost of specimen from the cost of conventional solid slabs (control slabs specimen without bottles).

Step 5: Determination of additional cost for plastic bottles inclusion in slab specimen:

The incorporation of the plastic bottles in the slabs specimen resulted in additional cost detailed in Table 13. Details of corresponding values in Table 13 are indicated in Appendix I of this paper.

Table 13. Details of additional cost for bottles inclusion in slab

S/N	Description	Air-filled bottles (Gh¢)	
		5% bottles inclusion	10% bottles inclusion
1.	Waste plastic bottles	0.03	0.06
2.	Chicken mesh	1.86	1.86
3.	Binding wire	0.12	0.24
	Labour		
4.	Encasing of bottles with mesh	0.50	0.83
Total per Specimen for 750×300×150 mm		2.51	2.99
Total per specimens for 1000×1000×150 mm (Pro rata)		11.16	13.29

Step 6: Determination of Overall cost of specimens

The overall cost incurred for each slabs type was determined from the following expressions:

Overall cost of specimen = Cost of specimen (from step 3) – Cost of concretes saved (from step 4) + Additional cost of incorporating plastic bottles (from step 5)

Step 7: Determination of % cost reduction or increment

The difference between the final cost of conventional solid slab specimens and the final cost of specimens per each percentage bottle inclusion is expressed as a percentage cost reduction or increment as follows:

% Cost (reduction or increment) = (Final cost of conventional slabs specimen - Final cost of specimen per percentage bottles including)/(Final cost of conventional slabs specimen)×100

The corresponding remark on the result:

- Negative percentage = increase in the final cost of slabs provision;
- Positive percentage = cost savings on slabs provision.

3.6. Assessment of Energy Consumption and CO₂ Emissions

The calculation of the amount of energy consumption and CO₂ emissions was based on Hussein et al. (2020) [48] methods provided under section 2.2.2 under literature. The factors for embodied energy and CO₂ emissions were obtained from Table 1, sourced from Ndiaye et al. (2005) [5]'s study on evaluation of the embodied energy in building materials and related CO₂ emissions in Senegal. The adoption of Ndiaye et al. (2005) [5] factors from other sources is because of Senegal's being a developing country just like Ghana (where the study experiment was conducted) and, as such, both countries belong to the same continent (West Africa).

4. Results and Discussion**4.1. Cost Assessment Study**

Table 14 and Figure 4 show the analysis of the cost study on slab specimens incorporated with waste plastic bottles versus conventional solid slab. The air-filled bottle slabs resulted in a higher cost reduction than the conventional because the slab that is Gh¢161.17 for 5% bottle slab and Gh¢142.62 for 10% bottle incorporated slab, as against the

control conventional of Gh¢166.67. Overall, the inclusion of plastic bottles in slab results in a cost reduction varying proportionally to the percentage of bottles included. This confirms the remarks from the review study that the voided slab system reduces the volume of concrete occupying the neutral axis of the slab, thereby reducing the cost. Alternatively, choosing either 5% or 10% bottle incorporation in slab resulted in significant percentage cost differences. For air-filled bottle consideration, a percentage cost reduction difference of 264% was achieved between the choices of 10% over the 5% bottle inclusion. It can therefore be concluded that though the incorporation of waste plastic bottles into concrete slab insulation is a cost reduction, the cost of reduction varies with respect to the percentage of bottles incorporated into the slab and the type of material used to fill the bottles before they are incorporated into the slab. The study has proven that the inclusion of the 10% bottles in slabs that are air-filled seemed more economical in terms of cost reduction.

Table 14. Observations on Cost Assessment

%Bottle	Type of specimen	Volume of concrete consumed (m ³)	Average of rate of concrete (Gh¢)	Cost of concrete (Gh¢)	Cost of savings on concrete (Gh¢)	Additional cost due bottles inclusion (Gh¢)	Overall Cost of specimens (Gh¢)	% Cost Reduction
A	B	C(Refer Table 10)	D (Refer to Table 11)	E = C × D	F = 166.67 - E	G (Refer to Table 12)	H = G-F+E	I=[(166.67-H)/166.67]
0%	Conventional slab (No bottles)	0.150	1,111.13	166.67	-	-	166.67	0.0%
5%	Air-filled plastic bottles slab	0.1425	1,111.13	158.34	8.33	11.16	161.17	3.3%
10%	Air-filled plastic bottles slab	0.135	1,111.13	150.00	16.67	13.29	146.62	12.0%

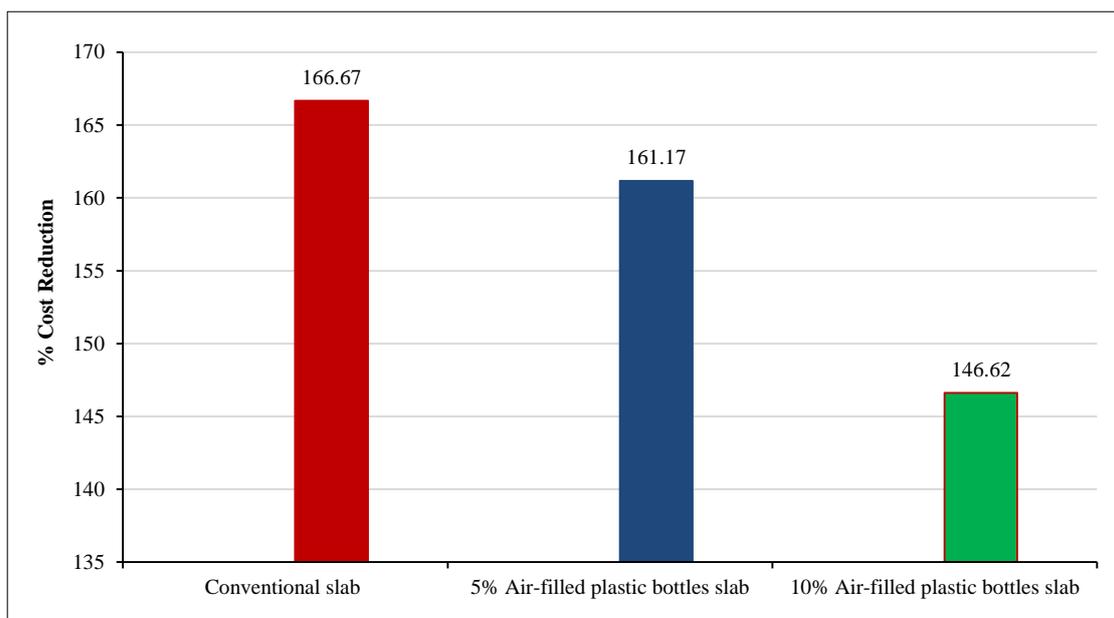


Figure 4. Summary of overall cost of slab specimens

4.2. Depth Ratio vs Cost Reduction

The thickness of the slab (150 mm) was further analysed with the bottle diameter (60 mm) to make projections for subsequent cost reduction with respect to other standardised lower slab thicknesses, considering a minimum of 20 mm cover thickness to the embedded reinforcement. As presented in Table 15, slab thicknesses of 100 mm and 125 mm were considered since their adoption would not compromise the cover thickness. It can be deduced from Table 10 that, for 150 mm thick, the bottle diameter occupies 40% with a corresponding cost reduction of 3.3% and 12% for 5% and 10% plastic inclusions. However, the cost reduction increased to 4% and 14.4% (125 mm thick slab) and 5% and 18% for slabs of 100 mm, all based on the same bottle diameter. Furthermore, it can be deduced from the entire cost analysis that the use of 60 mm diameter bottles in the 150mm thick slab is not economically viable because the bottles do not fully occupy the non-usable portion of the slab as per the principle of the Bubble Deck slab invention. Additionally, the selection of 100 mm or 125 mm thick increases the depth ratios as per Table 10 and subsequently reduces the volume of concrete required, thereby reducing the overall cost of the slab according to the respective percentage of bottles included.

Table 15. Observations on Depth Ratio vs. Cost Reduction

Thickness of slab (mm)	Depth ratio (Slab thick / bottles dia.)	Cost reduction (%)	% Plastic bottles in slab
150	60 / 150 = 0.40	3.3	5%
		12.0	10%
125	60 / 125 = 0.48	4.0	5%
		14.4	10%
100	60 / 100 = 0.60	5.0	5%
		18.0	10%

4.3. Assessment of Energy Consumption and CO₂ Emissions

Further sustainability studies with respect to embodied energy and CO₂ emissions achieved from voided slab incorporated with waste plastic bottles were conducted. Figures 5 and 6 show the summary of the observations on sustainability achievement obtained from Tables 16 and 17. From the observations referring to the Tables 16 and 17, and Figures 5 and 6, it can be observed that the embodied energy achieved by incorporating the 5% and 10% bottles in slabs amounted to 27.429 MJ/kg and 25.989 MJ/kg for coarse aggregate, 5.754 MJ/kg and 5.452 MJ/kg for fine aggregate, and 170.32 MJ/kg and 161.35 MJ/kg for cement. On the contrary, the conventional slab resulted in an embodied energy of 28.872 MJ/kg for coarse aggregate, 6.057 MJ/kg for fine aggregate, and 179.28 MJ/kg for cement. The CO₂ emissions achievement followed the same pattern, with 1.714 kg/kg and 1.624 kg/kg, 0.384 kg/kg and 0.363 kg, 37.45 kg/kg and 35.48 kg/kg, respectively for coarse aggregate, fine aggregate, and cement. On the contrary, the CO₂ emissions achieved from the conventional solid slab amounted to 1.805 kg/kg (coarse aggregate), 0.404 kg/kg (fine aggregate) and 39.42 kg/kg (cement). In the nutshell, the amount of embodied energy and CO₂ emissions achieved reduces as the percentage of bottles included increases. This finding confirms the study by Mahdi and Ismael (2021) [3] that voided slab creates voids within the central portion of the slab where it is of no structural function, thereby reducing the volume of concrete and concrete materials, and subsequently reducing its corresponding embodied energy and CO₂ emissions.

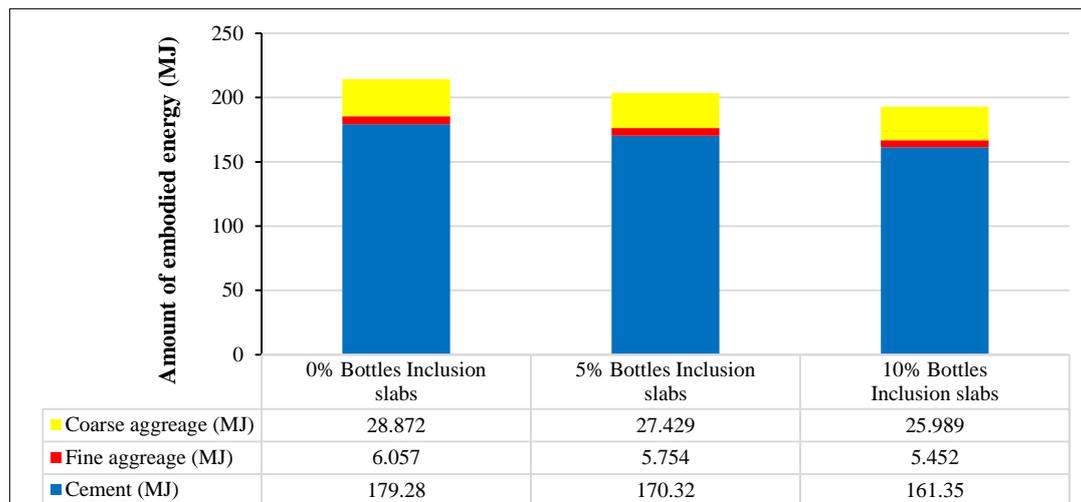


Figure 5. Summary of Embodied Energy consumed

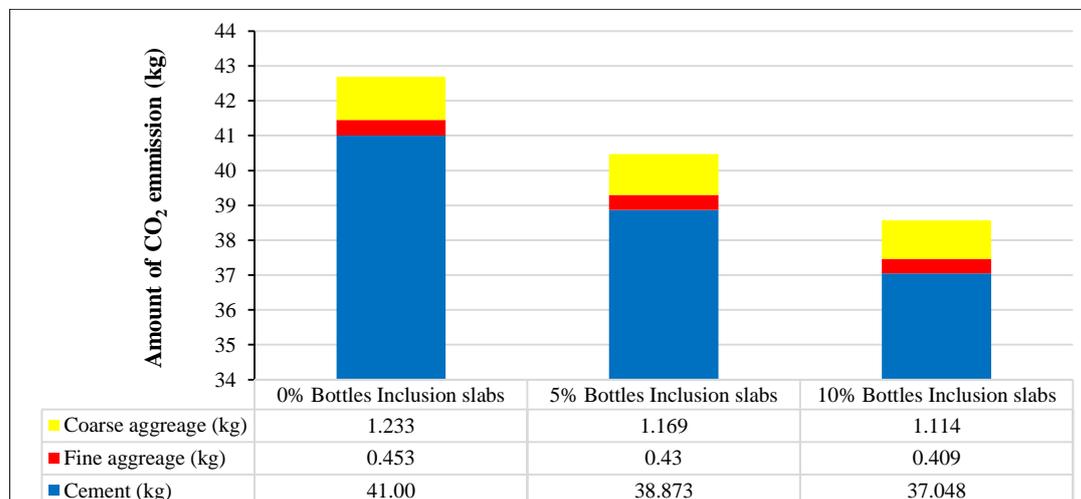


Figure 6. Summary of Embodied Energy consumed

Table 16. Comparison of Embodied Energy achieved by incorporating plastic bottles in concrete slab

% Bottle	Type of specimen	Cement (MJ/kg)	Fine aggregate (MJ/kg)	Coarse aggregate (MJ/kg)
0%	Conventional slab	179.28	6.057	28.872
5%	Air-filled plastic bottles slab	170.32	5.754	27.429
10%	Air-filled plastic bottles slab	161.35	5.452	25.989

Table 17. Comparison of CO₂ Emission achieved by incorporation of plastic bottles in concrete slab

% Bottle	Type of specimen	Cement (kg/kg)	Fine aggregate (kg/kg)	Coarse aggregate (kg/kg)
0%	Conventional slab	39.42	0.404	1.805
5%	Air-filled plastic bottles slab	37.45	0.384	1.714
10%	Air-filled plastic bottles slab	35.48	0.363	1.624

4.4. Impact of depth ratio on Embodied Energy Consumption and CO₂ Emissions

Tables 18 and 19, extracted from Tables 15 and 16, show the embodied energy and CO₂ emissions achieved from air-filled plastic slabs with respect to varying slab thickness. The objective here is to examine the impact of varying slab thickness on the attainment of embodied energy and CO₂ emissions with respect to the 60 mm diameter plastic bottles included in slabs. The initial 150 mm slab thickness was reduced to standardised slab sizes of 125 mm and 100mm, respectively. This resulted in a depth ratio of 0.48 and 0.67 from the calculation of slab thickness divided by the diameter of the bottle. These ratios also tell us that the percentage of the slab occupied by the plastic bottles is within the neutral axis as per Bubble Deck slab ideology. Referring to the study on Bubble Deck slab by Dheepan et al. (2017) [10], for a depth ratio of 0.67 and its corresponding performance achievement, an air-filled bottle slab with a depth ratio of 0.40 is not environmentally sustainable, though some level of sustainability with respect to embodied energy and CO₂ emissions was achieved as per Tables 16 and 17. However, if the slab thickness is reduced to 125 mm and 100 mm, the corresponding depth ratio of 0.48 and 0.67, the resulting embodied energy and CO₂ emissions as per Tables 12 and 13 look appreciable. For a slab thickness of 125 mm, the embodied energy and CO₂ emissions decrease by an additional 20% when compared to a slab of 150 mm. By the same comparison, a slab of 100 mm in thickness will exhibit a 33% further reduction for both 5% and 10% plastic bottle inclusions.

Table 18. Depth Ratio vs. Embodied Energy Consumption of Air-filled Bottle Slabs

Thickness of slab (mm)	Depth ratio		Cement (MJ/kg)	Fine aggregate (MJ/kg)	Coarse aggregate (MJ/kg)	Reduction per slab thickness	% Plastic bottles in slab
	D/H (Slab thick / bottles dia.)	Reduction factor					
150	60/150 = 0.40	0.40/0.4 = 0	37.45	0.384	1.714	0.00	0%
			35.48	0.363	1.624		
125	60/125 = 0.48	0.40/0.48 = 0.83	31.08	0.319	1.423	0.20	5%
			29.45	0.301	1.348		10%
100	60/100 = 0.60	0.40/0.60 = 0.67	25.09	0.257	1.148	0.33	5%
			23.77	0.243	1.088		10%

Table 19. Depth Ratio vs. CO₂ Consumption of Air-filled Bottle Slabs

Thickness of slab (mm)	Depth ratio		Cement (MJ/kg)	Fine aggregate (MJ/kg)	Coarse aggregate (MJ/kg)	Reduction per slab thickness	% Plastic bottles in slab
	D/H (Slab thick / bottles dia.)	Reduction factor					
150	60 / 150 = 0.40	0.40/0.4 = 0	170.32	5.754	27.429	0.00	5%
			161.35	5.452	25.989		10%
125	60 / 125 = 0.48	0.40/0.48 = 0.83	141.37	4.776	22.766	0.20	5%
			133.92	4.525	21.571		10%
100	60 / 100 = 0.60	0.40/0.60 = 0.67	114.11	3.855	18.377	0.33	5%
			108.10	3.653	17.413		10%

5. Conclusions

From the observations of the sustainability assessment of the slabs with used plastic bottles compared to the traditional solid slab system, the following can be said:

- The incorporation of waste plastic bottles into concrete slabs results in a reduction in the cost and volume of concrete, hence reducing the consumption of the depleting natural resources of concrete materials such as sand and stone. If 5% or 10% of used plastic bottles are mixed into a concrete slab, the overall cost will go down by about 6% and 13%, respectively.
- Also, using recycled plastic bottles in the slabs saved money, but for each percentage of bottles used, additional materials (plastic bottles, chicken wire, etc.) and labour were needed, which added to the cost. The study, upon analysis, with respect to reducing the slab thickness from 150mm to 125mm and 100mm, resulted in a significant cost reduction. For 125mm thick slabs, 4% and 14.4% cost reductions were observed for 5% and 10% plastic bottles. Whereas the 100mm thick slab resulted in 5% and 18% cost reductions for the 5% and 10% air-filled bottles incorporated.
- Observations from the study have shown that embodied energy and CO₂ emissions reduce as the percentage of plastic bottles in the slab increases. This is because putting plastic bottles in the slab tends to leave holes or voids, which means less concrete is needed to make the slab. Furthermore, the reduction of the slab thickness to 125 mm and 100 mm further increased the reduction in embodied energy and CO₂ emissions by 20% and 33%, respectively.
- The volume of concrete reduces as the percentage of bottles included increases. Thus, subsequently, the embodied energy and CO₂ emissions reduce as the percentage of bottles included in the slab increases.
- The study has proven that slabs incorporated with plastic bottles are more environmentally friendly when compared to conventional solid slabs.

The study has indeed confirmed that the voided slab incorporated with plastic bottles in terms of cost, embodied energy, and CO₂ emissions is more sustainable when compared to the conventional solid slab system. However, its adoption and application cannot be solely based on these results while compromising structural integrity in terms of load and deflection behaviour, etc. Due to this, further studies regarding structural and durability performance are envisaged.

6. Declarations

6.1. Author Contributions

Conceptualization, D.K.D.; methodology, D.K.D.; software, D.K.D.; validation, A.K.K.; formal analysis, D.K.D.; investigation, D.K.D.; resources, D.K.D.; data curation, D.K.D.; writing—original draft preparation, D.K.D.; writing—review and editing, D.K.D.; visualization, D.K.D.; supervision, A.K.K. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

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6.4. Acknowledgements

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

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Appendix I. Determination of Additional Cost due to Bottles Replacement

A.1. Cost of Plastic Bottles Acquisition

- Cost of plastic bottles (1000 bottles)–Free
- Transportation = $\frac{Ghc10.00}{1000bottles} = Ghc\ 0.01/bottle$
- For 5% bottles inclusion = 3bottles \times Ghc0.01 = Ghc 0.03
- For 10% bottles inclusion = 6bottles \times Ghc0.01 = Ghc 0.06

A.2. Cost of Chicken Mesh

- Market price of 1m \times 25m = Ghc 100.00
- Cal of total area chicken specimen required per specimen
 - Area A = 0.25m \times 0.06m \times 2 = 0.03m²
 - Area B = 0.7m \times 0.06m \times 2 = 0.084m²
 - Area C = 0.7m \times 0.25m \times 2 = 0.35m²
 - Total Area = 0.03m² + 0.084m² + 0.35m² = 0.464m²

There of chicken mesh consumed per specimen: = $\frac{Ghc100 \times 0.464m^2}{1m \times 25m} = Ghc\ 1.86$

A.3. Cost of Binding Wire

- The cost of binding wire of 385m length is Ghc100.00
- Cutting length for tying at bottom is 200mm and 100mm at the lid, hence total length is 300
- Cost of tying per bottle = $\frac{Ghc50 \times 0.3\ m}{385\ m} = Ghc\ 0.04$
- For 5% bottles inclusion = 3bottles \times Ghc0.04 = Ghc 0.12
- For 10% bottles inclusion = 6bottles \times Ghc0.04 = Ghc 0.24

A.4. Cost of Encasing Plastic Bottles with Chicken Mesh

- Work includes:
 - Setting out of bottles on mesh
 - Tying of bottles to mesh with binding wire
 - Cutting and moulding of mesh around bottles
- For 5% bottles inclusion, it cost Ghc5.00 to complete 10No specimens per hour
- Therefore, cost per 1No specimen = Ghc5/(10No specimens)=Ghc0.50
- For 10% bottles inclusion, it costGhc5.00 to complete 6No specimens per hour