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Technical and Economic Viability of Distributed Recycling of Low-Density Polyethylene Water Sachets into Waste Composite Pavement Blocks

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Abstract: In many developing countries, plastic waste management is left to citizens. This usually results in landfilling or hazardous open-air burning, leading to emissions that are harmful to human health and the environment. An easy, profitable, and clean method of processing and transforming the waste into value is required. In this context, this study provides an open-source methodology to transform low-density polyethylene drinking water sachets, into pavement blocks by using a streamlined do-it-yourself approach that requires only modest capital. Two different materials, sand, and ashes are evaluated as additives in plastic composites and the mechanical strength of the resulting blocks are tested for different proportion mix of plastic, sand, and ash. The best composite had an elastic modulus of 169 MPa, a compressive strength of 29 MPa, and a water absorptivity of 2.2%. The composite pavers can be sold at 100% profit while employing workers at 1.5× the minimum wage. In the West African region, this technology has the potential to produce 19 million pavement tiles from 28,000 tons of plastic water sachets annually in Ghana, Nigeria, and Liberia. This can contribute to waste management in the region while generating a gross revenue of 2.85 billion XOF (4.33 million USD).

Keywords: composite; waste plastic; distributed recycling; LDPE; low density polyethylene; plastic sand composites; tensile strength; compressive strength; West Africa; economic development

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1. Introduction

Waste management remains a critical challenge in both developed [1] and developing countries [2]. Despite the effort of governments, and different organizations to curb pollution due to inappropriate waste management, the plague of waste is continuously rising, especially in West Africa [3,4]. For example, in Lomé, the capital city of Togo, the city estimated that 305,340 tons of waste were produced by approximately 1.7 million inhabitants in 2019 [5]. This represents an approximate waste generation per capita of 180 kg. Furthermore, waste production is projected to increase at a rate of 12.1% every 5 years in the region [6]. It is posited that the high population growth and the rapid and expanding urbanization on the continent are the main contributing factors [7]. Furthermore, only 20% of this waste is recovered and recycled [5].

Even though some types of waste would degrade rapidly through natural processes, plastic wastes are known two remain in the environment for more than 400 years before the end of their degradation [8–10]. Plastic pollution is largely caused by the critical lack of infrastructure to manage this rapidly expanding waste production [11]. Improperly processed plastic wastes are transported to different locations such as cities' drainage and sewer systems, rivers, lagoons, lakes and eventually much of it is deposited in the ocean [12]. Plastics stuck in the drainage systems are the cause of flooding, and air pollution by stagnant water [2]. In developing countries, this stagnation will lead to the proliferation of mosquito-borne diseases such as cholera and malaria [13]. Furthermore, when plastic wastes are left unattended on land, or when they end up in the sea, animals can get entangled or ingest the plastic debris [2,12,14–17].

In most developing countries, the task of managing waste, especially plastic waste is left to the citizens. This situation usually results in unsanitary waste disposal practices such as landfilling or hazardous open-air burning, leading to emissions that are harmful to human health [18] and the atmosphere [19] as shown in Figure 1. It is estimated that close to 1 billion tons of waste worldwide are managed in this way [12].

(**a**) (**b**)

Figure 1. Waste management practices used by citizens in Togo: (**a**) Example of litter management by local citizens with no access to organized waste disposal; (**b**) Example of burning waste plastic with organics. Note the plastic waste in the garbage bins about to be burned.

Although this form of waste treatment has negative long-term consequences for the environment and public health, finding a long-term solution remains a challenge. This method of waste management is preferred in many parts of the world in which organized waste collection is not available, as it reduces the volume and mass of the waste, and it reduces its bioactivity, meaning there is less attraction of scavenging animals to feed, breed and transmit pathogens [12]. Furthermore, participants in the informal recycling sector use open burning as a method of materials reclamation, removing combustible materials so they can access metals without having to spend time disaggregating complex piles of waste [12]. Given the complexity of the problem, as well as the perceived and actual benefits of current waste management practices, it becomes evident that traditional waste management solutions are not only extremely challenging to implement due to critical lack of infrastructure, but will also not be favored by locals who obtain more value from the waste by managing it themselves, even though they are exposed to harmful fumes during the recuperation process [20,21]. A means of distributed recycling [22,23] can provide an economic incentive for recycling while contributing to a circular economy [24,25]. In addition, there is some life cycle analysis evidence that distributed recycling [26,27] has better environmental performance than centralized recycling [28]. For distributed recycling to function in this context and be sustainable it should be done in such a way as to not harm the health of the participants.

To provide benefit for the local population while valorizing plastic waste, a decentralized waste management solution that not only manages the waste for the community, but furthermore provides economic benefits is needed. A rising solution for plastic waste management is the incorporation of plastic into building material, especially pavement tiles. Most studies that focus on this aspect of plastic waste management have proposed the use of plastic as additive to concrete bricks [29] or asphalt pavement production [30,31], usually requiring the use of sophisticated machinery. It is possible, however, to make a composite using waste plastic as the primary material with waste sand [32]. A more recent study has analyzed the use of plastic waste in pavement blocks in West Africa, but the study in Ghana focused on the use of mixed plastic to produce the pavement blocks [33]. This has the advantage of minimizing pre-processing (which can be considerable [34]) but the disadvantage that the resultant material product has notably inferior mechanical properties from those expected in pure polymers. Composites with better mechanical properties can potentially be obtained if the most commonly used plastics are sorted before pavement production. Plastic bags are a widely used in developing countries, especially in Western Africa [35,36]. In Togo, for example, drinking water sachets are made of low-density polyethylene (LDPE) and the water sachets waste are ubiquitous [37] as shown in Figure 2.

Figure 2. An example of LDPE plastic water sachet collected in Lomé, Togo, and bundled.

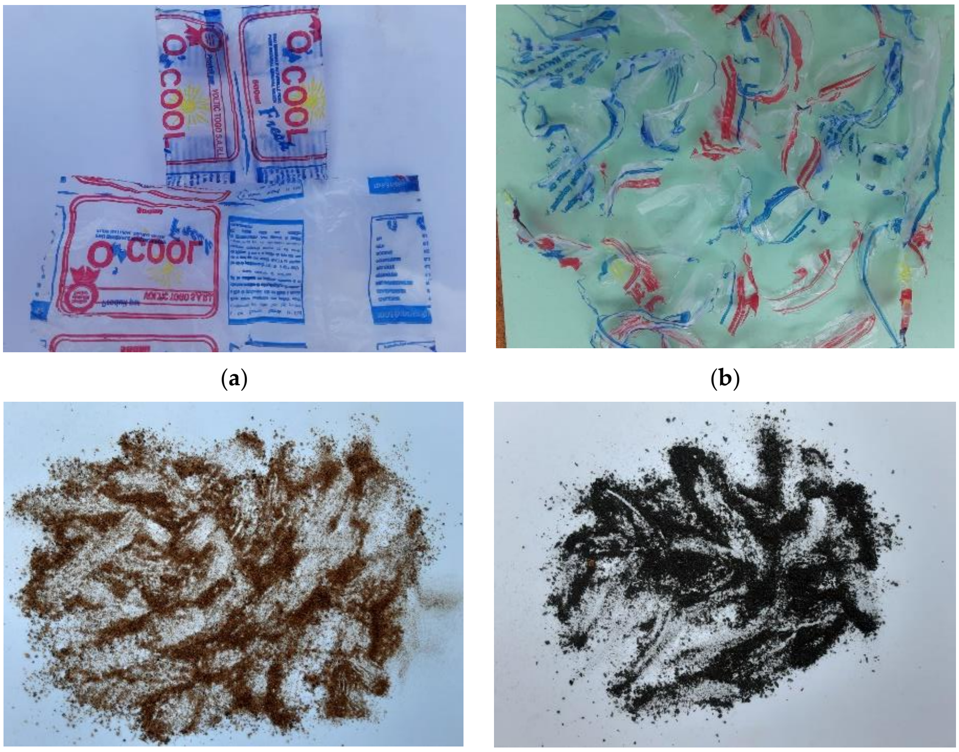
To allow populations to manage waste in a safe manner, an easy and clean method of processing and transforming the waste is required. In this context, this study aims to provide an open-source methodology to transform a specific type of plastic waste, LDPE drinking water sachets, into pavement blocks by using a streamlined do-it-yourself (DIY) approach that requires only modest capital. The methodology from the collection of the raw material to the fabrication of the pavement block is explained. Two different additives, sand, and wood charcoal ashes are evaluated as additives in the plastic and the tensile strength of the resulting blocks are tested for different proportion mix of plastic, sand, and ash. Finally, the best mix for tensile strength is compared to existing concrete pavement blocks to determine an appropriate use and the results are discussed in the context of alleviating the environmental burden of plastic waste using open-source distributed manufacturing that provides an economic benefit to the local community.

2. Materials and Methods

2.1. Raw Material Collection and Processing

Three different types of raw material were used in the fabrication process of the pavement tiles, LDPE plastic, sand, and charcoal. The specific type of plastic that was used is drinking sachet water waste plastic that is abundant because of the prominent use as a clean source of drinking water in many African countries. The drinking water sachets used in the study originated from the same manufacturer, O'COOL (see Figure 2). Using a specific type of plastic from the same manufacturer also improves the probability of the homogeneity and chemical composition consistency of the raw plastic material in the production of the pavement tiles. The plastic waste bags were collected from various sources including roadside dumps, and individual household wastes. The plastic sachet bags were shredded using scissors, washed, then left to dry to remove residual contamination from sand, water, or other waste cross-contamination. Once dry, the bags were further shredded using scissors and weighed to determine the amount of material needed.

Sand and charcoal are used as additive material to the pavement tiles mix in different proportion. Charcoal is a material that is abundant locally. The charcoal and sand were obtained locally and sifted through a 20 × 20 mesh grid with a 0.013″ (0.3 mm) diameter wire thickness. Each hole of the sieve has a square area of 0.841×0.841 mm^2. Figure 3 shows a close-up of the plastic, the sand and the charcoal used in the manufacture of the pavement tiles.


(**a**) (**b**)

(**c**) (**d**)

Figure 3. Details of the input material used in manufacturing the pavement. (**a**) Cleaned LDPE plastic water bag waste. (**b**) Shredded LDPE plastic water bag waste. (**c**) Sifted sand. (**d**) Sifted charcoal.

2.2. Pavement Tiles Fabrication Process

Seven samples of pavement tile were manufactured by melting and molding different mixtures of LDPE plastic, sand, and charcoal. Prior to melting and mixing of the ingredients, each constituent was weighed using a digital scale to an accuracy of 0.1 g. The compositions of the tested composites are shown in Table 1.

Table 1. Mixture composition (%) of the 7 samples produced and tested, each sample weighs 1 kg.

Composite Sample Number	1	2	3	4	5	6	7
Percent LDPE Plastic (%) *	100	70	70	70	85	85	85
Percent Sand (%)	0	30	0	15	15	0	7.5
Percent Charcoal (%)	0	0	30	15	0	15	7.5

* Mixtures with greater proportions of sand and charcoal were attempted (up to 60%), but the resulting specimens did not bind well.

2.2.1. Melting and Mixing

A charcoal heated clay-lined barrel converted into an artisanal African stove (see Figure 4) was used to heat the composites. Charcoal briquettes were ignited and fired to produce a burning temperature in the range of 400 °C to 600 °C. The temperature was moderated by adjusting the forced airflow into the combustion chamber. The temperature measurements were taken periodically using an infrared thermometer with an accuracy of ±3 °C. Once the stove was within the desired temperature range, the sand and/or charcoal was mixed in a cooking pot, which was then placed on the burner. Using periodic temperature measurements, the pot skin temperature and sand/charcoal composites were heated to a temperature range of 160 °C to 170 °C. Once at steady state, plastic was slowly introduced into the pot and allowed to melt using the heat capacity of the sand. Once melting began, the temperature typically settled to around 115 °C. LDPE was slowly and continuously added until complete while being stirred. To ensure a homogenous of the mixture the material was stirred for two to five minutes after the complete addition of the plastic materials.

Figure 4. Artisanal African stove that is designed to burn wood, charcoal, or carbonized waste pellets [38].

2.2.2. Pressing and Cooling

During the mixing process described above, a 20 cm × 20 cm plate presser was brought up to a temperature range of 120 °C to 180 °C. Once mixing was completed, the mixture was transferred to the plate presser and the plastic was pressed to a thickness of 5 mm using clamps. The plate presser was then turned off and allowed to cool, at which point the pressed 20 cm × 20 cm plate was extracted.

For the fabrication of pavement tiles, the mixture would be transferred to a mold in the shape of the brick tile paver which was made from wood and lined with sheet metal.

The hot mixture was transferred into the mold and a pressing plate that is the same shape as the profile of the paver would be pressed using clamps to compress the mixture. The mixture was then allowed to cool, and the final pavement block was extracted once cooled.

2.3. Testing

2.3.1. Elastic Modulus

The objective was to create a set of six test specimens for each composite similar to ASTM D-638 Type I specimens [39]. A rough cut of the test specimens to a dimension greater than 2 mm was performed using a 5″ scroll saw and following a template profile as a guide.

Tensile testing was performed for all composite samples using a 10,000-pound load cell (Model LCF455). Elastic modulus values were measured using the crosshead extension on the Universal Testing Machine package. A crosshead speed of 5 mm/min was used.

2.3.2. Compressive Strength

To make compression samples, sample material was cut up into small pellets using cutting pliers. A 1.75 cm diameter die mold (Figure 5) was used to melt plastic pellets together to form cylindrical compression testing samples. The die was placed in the furnace (set to 200 °C) to pre-heat for 30 min. The pellets were then placed into the die and compressed manually using the die insert before heating to increase pellet packing density. The die was again filled to the top and compressed. The die was placed in a muffle furnace at 200 °C for approximately 30 min. The die was removed from the furnace and the material was compressed using the die insert. Some samples required longer (up to 1 h total) to heat. It is assumed that material inconsistencies in the LDPE material caused these inconsistencies since the furnace temperature and all other conditions remained consistent in the testing process. After the material was compressed, it was allowed to sit for approximately 5 min before being manually pushed out of the die. Samples were allowed to fully cool before compression testing. For compression testing, the same 10,000-pound load cell and testing machine used for tensile testing were utilized. A crosshead speed of 2 mm/minute was used. Results are collected for peak stress.

Figure 5. Preheated die filled with pellets.

2.3.3. Water Absorption Test

Water absorptivity is a good metric to evaluate the durability of concrete blocks [40,41]. To evaluate the water absorptivity of the fabricated pavement tiles the water absorption by soaking method was used [42]. The material is first dried until its weight reaches a constant value, labeled dried mass m_{dry} (g). The dried material is immersed into water and weighed at regular time intervals for 72 h or until its weight change is less than 1% during a 24 h period [40,42]. The final soaked weight is labeled m_{soaked} (g). The water absorptivity is calculated using Equation (1). A digital scale was used with accuracy of ±0.5 g. Sample dry weights were in the range of 80 to 120 g with the largest fragment of any plates.

$$\text{Water Absorption} = \frac{\mathrm{m_{soaked}} - \mathrm{m_{dry}}}{\mathrm{m_{dry}}} \times 100\ (\%) \tag{1}$$

2.4. Economic Analysis

The economic cost of recycling waste plastic using locally available equipment is evaluated and compared to existing pavement tiles on the local market in Lomé, Togo, and in some other West African countries. The cost of the process is estimated by obtaining the cost of individual materials that were used. The price is calculated in the local currency (XOF) and converted into USD using the rate of 14 September 2022 (1 USD = 658 XOF).

One of the major considerations regarding the economic analysis was determining the number of plastic sachets required per brick and estimating the number of bricks that can be made per year based on the amount of plastic waste available. The weight of a single sachet was used to determine the amount of material required to make a brick based on the mixture's density and the volume of the brick. Note that sand is much heavier than plastic, therefore a brick made with sand will weigh much more than a brick of pure LDPE for the same volume. To estimate the number of sachets 100 full (un-cut) sachets were weighed. The total weight was 200 g, with each sachet weighing 2 g.

The economic analysis was performed on the best pavement tile after completing the technical analysis. First, the volume of a pavement tile is 1887.6 $\mathrm{cm^3}$ and was calculated using a FreeCAD model of the tile [43]. LDPE (0.92 $\mathrm{g/cm^3}$) [44], sand (1.6 $\mathrm{g/cm^3}$) [45], and charcoal powder (0.23 $\mathrm{g/cm^3}$) [46] densities were, respectively, multiplied by their percent weight in the selected pavement tile to estimate the density of the paver. The density is multiplied by the volume to determine the total weight of the tile.

The raw material cost associated with the LDPE is estimated as a cost of collection because the plastic is obtained from waste material, and the type of waste where the LDPE originates from is abundant locally. For this study, it was estimated that one worker can collect 20,000 sachets (40 kg) an hour assuming the bags are all bundled in the larger bag as shown in Figure 2. This collection rate is based on the loading time from local tricycle garbage collectors in Togo. Similarly, it was assumed that users will bundle the individual plastic sachets together and that one large bag holds approximately 500 sachets (1 kg of LDPE). Hence, a worker will collect approximately 40 bundles from the community per hour. Furthermore, the cost of sand is 10,000 XOF/$\mathrm{m^3}$ (15.2 USD/$\mathrm{m^3}$), which is obtained on local markets in Togo. Using a sand density of 1600 kg/$\mathrm{m^3}$, this converts to 6.25 XOF (0.0095 USD) per kg. The charcoal powder considered in this study originates from unused residue and the cost associated with the collection is factored into the collection cost of the LDPE.

The heating in the experiments was provided by charcoal at a rate of 285 XOF (0.43 USD) per kg of charcoal [47]. A total of 701 g of charcoal is required to produce two pavers. Therefore, the fuel cost from charcoal is 99.9 XOF (0.15 USD) per paver. Additionally, the heating energy required for the fabrication process is estimated as butane equivalent as this may be preferred for mass-production of the recycled plastic pavements tiles. A tank of butane is needed to produce 200 pavement tiles. In Togo, a tank contains 12.5 kg of butane and costs approximately 6500 XOF (there has been a recent spike in the butane gas tank price in Togo due to the war in Ukraine, but prices have started to decline again [48,49]) therefore the fuel cost for butane would be 32.5 XOF (0.049 USD) per brick. Butane is three times less expensive than charcoal.

From the experimental fabrication process, a workforce of 2 people is needed to process the collected waste, and manufacture approximately 25 bricks in an hour (m), and the LDPE plastic waste collection is assumed to be handled by a single worker. As a result, the cost per brick (C_b) is estimated by adding up the energy cost, the cost of sand, and the labor cost of collection and production shown in Equation (2):

$$C_b = E_b + S_b + \left(\frac{r_{collect} + 2 \times\ r_{prod}}{m} \right) \tag{2}$$

where: E_b is the energy cost per brick, S_b is the sand cost per brick, $r_{collect}$ is the hourly wage in XOF for collecting LDPE and r_{prod} is the hourly rate for producing bricks. Note that this is the estimated production cost per brick and does not include any allowance for gross-margin, administrative costs, capital costs, and other unforeseen costs. To account for these ancillary cost, keystone pricing, which essentially assumes a 100% markup of the manufacturing cost, is used [50]. Therefore, if it is assumed that $r_{collect}$ and r_{prod} are equivalent meaning that the workers are all paid at the same rate the sale price per brick (S_b) can be expressed as:

$$S_b = 2 \times \left(E_b + S_b + \frac{3r}{m} \right) \tag{3}$$

The objective of the economic analysis is to estimate the hourly revenue generated by entrepreneurs/workers to compete with the market price of existing brick pavers/concrete tiles. A sensitivity analysis is performed by varying the sale per brick depending on the cost of similar concrete pavement tiles on the market. For each variation, the hourly wage is back-calculated using Equation (4) and compared to the minimum wage in Togo:

$$r = \left(\frac{S_b}{2} - (E_b + S_b) \right) \times \frac{m}{3} \tag{4}$$

3. Results

Waste plastic composite paving tiles were successfully produced from this low-tech method. Figure 6 shows a fabricated pavement tile using the method described above with a composite of 70% LDPE and 30% sand.

Figure 6. Product of the recycled plastic pavement fabrication process (70% LDPE, 30% sand).

3.1. Tensile Tests Results

Different pavement tiles textures were obtained depending on the mixture and the weight percentage of each of the raw material, LDPE, charcoal, and sand. Multiple runs of the tensile test were performed for each composite sample and the results including error in a box plot are shown in Figure 7. According to the results, the mixture that offers the best average elastic modulus is the sample containing 70% of LDPE and 30% of sand (169 MPa). The two mixtures with the worst tensile strength are the samples with 40% LDPE 60% sand, and 70% LDPE 15% sand 15% charcoal, respectively. It should be noted that the mixture with 100% LDPE did not perform as well as with the sand composites. On the other hand, the addition of charcoal weakens the mixture regarding elastic modulus, therefore charcoal is not a good option for fabricating new composite pavement tiles with LDPE.

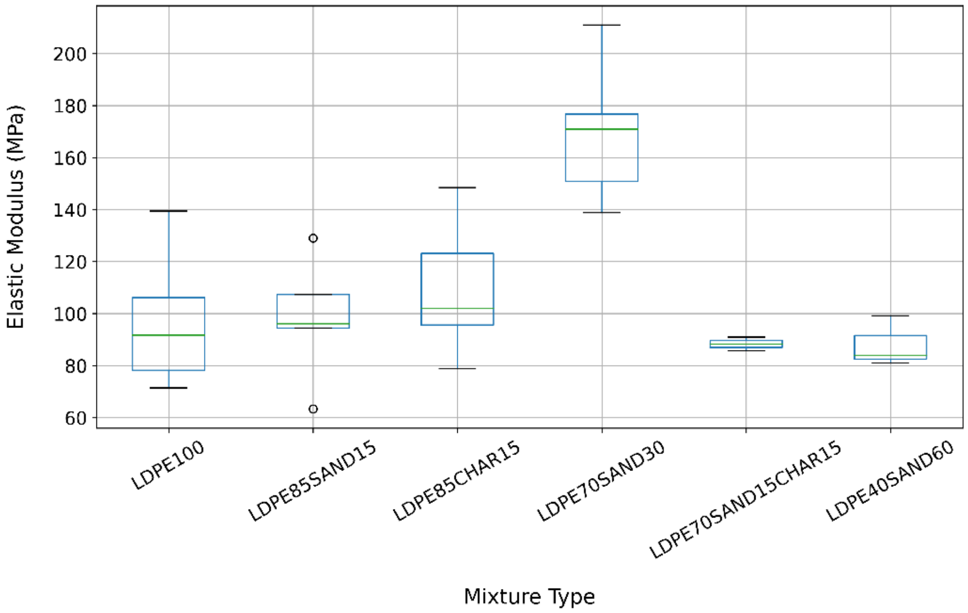


Figure 7. Elastic modulus (MPa) obtained for different mixture using tensile strength test.

3.2. Compressive Strength Test Results

The compression test was performed on the best sample (70% LDPE and 30% sand) from the tensile tests and the results are compared with pure LDPE and concrete (from existing literature [41]). As shown in Figure 8, the sample with 70% LDPE 30% sand has a higher average compressive strength compared to concrete and pure LDPE. The result show that pure LDPE plastic will break more easily under mechanical stress when compared to concrete. When LDPE is combined with sand, however, it increases the strength of the resulting composite, which can sustain more mechanical stress compared to concrete.

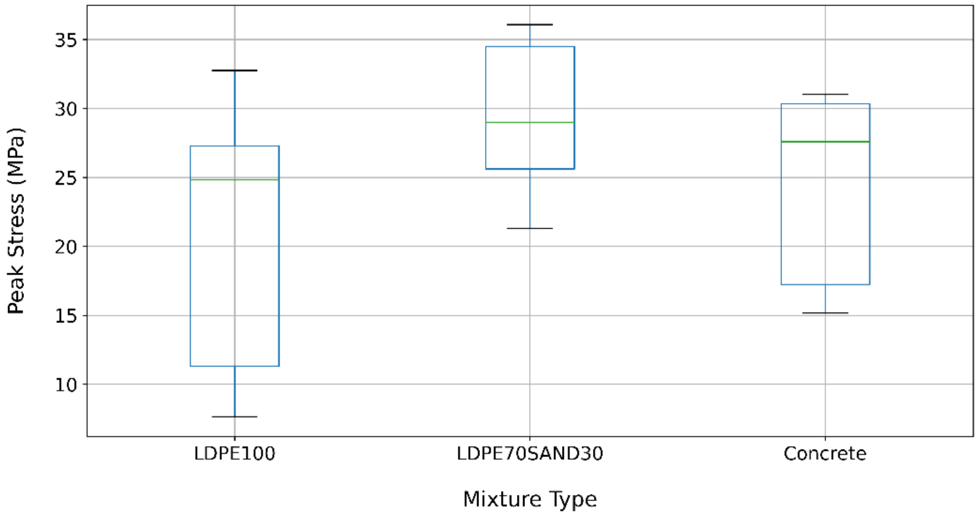


Figure 8. Compressive strength (MPa) of the best mixture obtained from tensile test (LDPE70 Sand30) compared with pure LDPE and concrete.

3.3. Water Absorptivity Test Results

Water absorptivity tests were carried out every 24 h for a period of 5 days. Typically, the wet mass stabilized by the second day with very minimal changes. After the wet weight became stable, the samples were allowed to dry and weighed again to ensure accuracy. One important note about the tests: the high LDPE samples did not absorb much water, so the majority of the "wet weight" was a result of water left on the surface. The results are shown in Table 2.

Table 2. Absorptivity (%) obtained for different mixtures using absorptivity test.

Sample Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**
LDPE Plastic (%)	100	70	70	70	85	85	85
Sand (%)	0	30	0	15	15	0	7.5
Charcoal (%)	0	0	30	15	0	15	7.5
Absorptivity (%)	6.7	2.2	15.0	10.4	6.9	7.0	6.2
Instrument Error (±%)	1.1	0.2	0.4	0.4	0.4	0.3	0.6

3.4. Economic Analysis Results

The economic analysis methodology is applied to the sample with the best parameters (70% LDPE, 30% sand). Using the proportions of LDPE and sand in the mixture, as well as their respective density, the density of a pavement tile is estimated at 1.13 g/cm^3. The equivalent weight of a tile is 2.13 kg using the volume obtained from the FreeCAD modelling [43]. This weight was validated by the physical weight of the samples. As a result, the fabrication of a pavement tile containing 70% of LDPE will require 744.8 drinking sachets, rounded to 745 to account for any waste in the process for the economic analysis. If the number of sachets collected per hour (20,000) is used as a limiting factor, 27 pavement tiles with a ratio of LDPE to sand of 70/30 can be manufactured per hour, rounded down to 25 to have a matrix mold structure (5 × 5) if the tiles are produced at scale. Using the cost of sand per weight (6.25 XOF/kg) the cost of sand is evaluated at 4 XOF/brick (0.0061 USD/brick). By replacing these values in Equation (4), the hourly wage, shown in Tables 3 and 4 for charcoal and propane, respectively, can be back-calculated as a function of the sale price per brick.

Table 3. Hourly and monthly wages per worker as a function of manufactured price per brick using charcoal as energy source.

Price per Brick (XOF)	**100**	**150**	**200**	**250**	**300**	**350**	**400**
Hourly Wage per Worker (XOF/hour)	−383	−174	34	243	451	659	868
Average Monthly Salary per Worker (XOF/month) *	−66,300	−30,189	5922	42,033	78,144	114,256	150,367

* The monthly salary is calculated by multiplying the hourly salary by the monthly averaged number of working hours in a year. The average number of working hours including holidays is 40 × 52/12 = 173.33 h.

Table 4. Hourly and monthly wages per worker as a function of manufactured price per brick using propane as heat energy source.

Price per Brick (XOF)	**100**	**150**	**200**	**250**	**300**	**350**	**400**
Hourly Wage per Worker (XOF/hour)	110	319	527	735	944	1152	1360
Average Monthly Salary per Worker (XOF/month) *	19,139	55,250	91,361	127,472	163,583	199,694	235,806

* The monthly salary is calculated by multiplying the hourly salary by the monthly averaged number of working hours in a year. The average number of working hours including holidays is 40 × 52/12 = 173.33 h.

4. Discussion

4.1. Technical Discussion of the Proposed Composite Use

The investigated parameters of the composites that were obtained in previous studies encompasses the water absorptivity and the compressive strength. In pavement block production the measured compressive strength varied between 5 and 22 MPa [30,51] depending on the type of plastic that was used in the pavement block mix. The maximum water absorption rate obtained by previous studies ranged between 0 and 2.2% [30,51]. On the other hand, other studies investigated the same two parameters for the use of plastic as additive material incorporated into bricks. The lowest and highest recorded compressive strength by the studies were 4.5 and 35.1 MPa, respectively [30,52]. The highest water absorption obtained was 37.6% when plastic was used as an additive into brick manufacturing [53].

The water absorption obtained for the best sample in this study (LDPE70 Sand30) was 2.2%. This value is in the range of water absorption values obtained by past studies. Additionally, the average compressive strength obtained in this study (29.3 MPa) is higher than compressive strength of pavement blocks from the consulted literature. This shows that using a uniform type of LDPE when waste plastic is converted into building material, yields a stronger composite compared to using a mix of plastic waste.

The flexural strength obtained in this study is higher than that of concrete while the compressive strength is similar to regular concrete [54,55]. As a result, the proposed composite of 70% LDPE waste plastic and 30% sand could be used for multiple applications that requires concrete block. For example, the pavement blocks that were manufactured in this study can replace pavement blocks used in backyards, walkways, and gardens. The composite also shows promise to be used as building material, but further research is required to ensure structural stability, thermal stability, and UV stability, especially because regular concrete has a higher density compared to LDPE-sand mixture.

4.2. Economic Implications

To analyze the economic feasibility of the proposed pavement tile, the results in Tables 3 and 4 are compared with the local sale price of concrete pavement tiles and the minimum wage in Togo. Because pavement tile prices are not regulated in Togo, there is a wide variation on prices on the market. The local Togo market provided an average cost of the I-style brick pavers that are the subject of this study of 5000 XOF (7.60 USD) per m^2. This is equivalent to 150 XOF (0.23 USD) per brick (with approximately 33 installed bricks per m^2). In addition, the documented cost of tiles was obtained from vendors in Ghana, a neighboring country to Togo with similar prices. Based on the data obtained from the vendors, the lowest price was 72 XOF (0.11 USD) while the highest price was 715 XOF (1.09 USD) [56]. Thus, the average price of pavers in Togo is roughly double the lowest cost in the market in Ghana and less than half of the highest costs found in Ghana. According to the results in Table 3, if charcoal is used as a heat source and the tiles are sold at the average price of 150 XOF, then the fabrication of the tiles is not profitable. It only becomes profitable when the tiles are sold a 250 XOF (0.38 USD) that is in the range of prices for tiles in Togo, but more expensive than the average price. For this approach to be viable customers might prefer the product over standard pavers because of color, texture or the recycled green/sustainable attributes.

On the other hand, Table 4 shows that if the 70% LDPE 30% sand mixture recycled pavement tile proposed in this study is sold at a price of 150 XOF, it is possible to pay the workers a monthly wage of 52,360 XOF (79.57 USD). The minimum wage in Togo for unskilled labor being 35,000 XOF (53.19 USD) per month [57], a team of 3 entrepreneurs equally sharing the costs and profits could make roughly 1.5 times the minimum monthly wage if selling at market prices (150 XOF per brick). Because the ancillary costs are factored in the sale cost of the brick, selling the bricks at a similar cost as the market price for concrete tiles will guarantee a 100% profit margin that can be reinvested into the company. This indicates that recycling LDPE water sachets into pavement tiles at scale using sand is economically feasible. This economic feasibility enables a distributed recycling enterprise that can contribute to the waste management and improve the quality of life for the community.

In Lomé, water sachets are one of the main sources of drinkable water for the local population. They are therefore relied on heavily and consumed significantly. Although there exists no official analysis of the use of water sachets in the Lomé region it is possible to estimate the amount of waste sachets that are produced annually to estimate the amount of plastic paver production that could theoretically be sustained. The population of Lomé is approximately 1.93 million in 2022 [58]. Although exact numbers from Togo are not known, Ghana, Togo's neighboring country to the West estimates that approximately 43% of urban homes rely on the 500 mL water sachets that are the focus of this study [59]. Using this as a guide, approximately 770,000 (40%) people in Lomé use these sachets as their primary drinking source. As a conservative estimate it is assumed that each user only consumes one sachet a day (note this is likely very conservative as most people likely consume at least 2 or 3 sachets a day). Using this assumption, over 770,000 water sachets are consumed a day. That is enough to support the production of 1050 pavers a day, assuming a single brick with 70% LDPE 30% sand contains 745 sachets. With these conservative estimates, over 380,000 pavers could be produced per year and reduce plastic waste pollution by an estimate of 140 tonnes per year and pave approximately 11,500 m^2 in Lomé alone. At a production rate of 1050 pavers a day, recycling plastic waste in Lomé will generate at least 15 employments with wages greater than 1.5 times the minimum wage in Togo. Furthermore, the recycling of LDPE water sachets into pavement tiles in Lomé will generate a gross average monthly revenue of 3.4 million XOF (5167.17 USD).

The plastic waste management challenge is plaguing other countries in West Africa and across the world. The combined consumption of water sachets in Ghana, Nigeria, and Liberia was estimated to 28,000 tonnes a year [36]. This number represents 14 billion individual water sachets that could be used to produce 19 million recycled pavement tiles and prevent the plastic waste to end up in the ocean. In these three countries combined, recycling LDPE waste into pavement tiles will create more than 365 jobs and generate a gross annual revenue of 2.85 billion XOF (4.33 million USD). The result of the present study can be replicated in other countries as the material used in the fabrication process are locally available.

4.3. Limitations and Future Work

The procedure used in this study is slow as every step is implemented manually. For the proposed recycled pavement tile to be scalable at an industrial level, the production process requires refinement and automation. Additionally, the energy source used in the study is wood charcoal burned in an artisanal stove. Open-air combustion of charcoal for heat generation makes it is difficult to regulate the temperature and economically more expensive. Future studies need to investigate the automation of the production system and analyze the use of other heating energy sources such as concentrated solar or solar photovoltaic-powered heat pumps.

The fabricated tiles in this study are dependent on specific parameters such as the temperature, the pressure, the size of the particles. In the current experimental study, those parameters were fixed. Even though the pavement tiles obtained using the fixed parameters have proven to be useable as concrete pavement tiles replacement, they can be refined. In future studies, the parameters could be controlled and varied to analyze their impact on the quality of the final product. In addition to using another method for a better temperature control, using a pressure-controlled recipient for melting the mixture and manufacturing tiles under different pressure levels could be beneficial in improving the efficiency of production for the pavement tiles.

The results of the study showed that the 70LDPE 30 s and mixture has the properties to be safely used as garden, walkways, and backyard pavement. The properties obtained for the material have also indicated they could be used in advanced applications such as streets and buildings, however, more tests are warranted for the proposed mixture to be used for these applications. Streets and buildings are strategic and sensitive structures, therefore future studies are required to perform advance tests on the proposed mixture, complete bricks, and lifetime degradation studies. Recent work on another waste plastic sand composite appears promising for paving streets [32], and the following laboratory tests could be performed on the composite in this study that included: Hamburg wheel tracking device (HWTD) for high-temperature properties, disc-shaped compact tension (DCT) test for low-temperature performance, tensile strength ratio (TSR) to determine the moisture susceptibility and the dynamic modulus to assess the deformation characterize under various loads and frequencies, a water permeability test, and the Cantabro loss test to measure mass loss of aggregate. Some of the additional tests that can be performed before road tests, also include rebound hammer testing, penetration resistance tests or drilled core compression tests [60]. For the composite to be used in building, future studies must analyze the thermal conductivity to find the heat retention and the insulation properties of the material as well as its fire resistance and off-axis loading.

The proposed pavement tiles have the potential to improve waste management, especially regarding water sachets. For a newly proposed technology to be considered environmentally beneficial, however, a life cycle analysis (LCA) is needed. The most pressing topic for future studies is the assessment of the life cycle of the fabrication process from cradle to grave. The LCA needs to encompass the collection of the waste plastic and the sand to the disposal or recycling of the pavement tiles. For this, a practical aging test is needed to determine the lifetime of the proposed pavement tile to determine its resistance to weathering and UV degradation. Of particular concern is the potential for the composite in some applications to cause microplastics, which could have a major environmentally detrimental effect [61]. The LCA also needs to account for the positive impacts of removing the plastic from the environment as well as address the challenges with using sand in the pavement tiles production at a larger scale. Furthermore, a chemical analysis of the fumes produced during the process can be performed to ensure the safety of the workers that will be handling the melting of the plastic.

The plastic waste used in this study contains only LDPE and the results have shown that the tiles obtained using only LDPE have a higher quality than tiles fabricated from a mixture of plastic waste. Therefore, future studies could look at the use of other type of plastic waste such as high-density polyethylene (HDPE) or polyethylene terephthalate (PET) for the manufacture of pavement tiles. Additionally, the color of the tiles obtained in this study are black. Future studies could focus on the use of color additives to customize the plastic to the end users' preferences.

5. Conclusions

The technical and economic viability of recycling LDPE water sachets in Togo is analyzed in this study. The LDPE water sachets waste were combined with sand and charcoal in different proportions to form new composites that were molded into pavement tiles. A battery of tests was conducted to determine the tensile and compressive strength of all mixtures and the water absorptivity of the best sample. The results show that charcoal binders weakened mechanical properties while sand improved the properties of the composites. The best mixture obtained was composed of 70% LDPE and 30% sand composite and had an elastic modulus of 169 MPa, a compressive strength of 29 MPa (similar to concrete), and a water absorptivity of 2.2%. Thus, this composite had better properties than previous published mixed plastic pavers. Therefore, the proposed composite can be used for garden, backyards, and pavement tiles. With additional testing in future studies, the composite can be considered for advanced applications such as streets pavement and building material.

The economic analysis covered the collection expenses, manufacture cost, labor costs, and administrative costs. The analysis revealed that if the pavement tiles are manufactured by a group of three entrepreneurs and sold at current prices of pavement tiles in Togo, they can earn at least 1.5 times the minimum wage with 100% profit margin that can be reinvested in the company. In addition, the production of pavement tiles using the method and mixture proposed here can prevent the daily dumping of 770,000 water sachets in water bodies and sewers in Lomé, the capital of Togo. In the West African region, this technology can improve the management of 14 billion individual water sachets and can produce 19 million pavement tiles annually in Ghana, Nigeria, and Liberia. This can contribute to waste management in the region as the technology will prevent the disposal of 28,000 tonnes of plastic water sachets in the environment and generate a gross revenue of 2.85 billion XOF (4.33 million USD). Future studies are needed to determine the life cycle environmental and economic impacts of the tiles manufacture process as well as the abrasion and potential for generating microplastics and their impact on the environment.

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