Analytical Study and Amelioration of Plastic Pavement Material Quality

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Abstract

Solid waste increases continue to pose heavy challenges to the population living in most urban communities. The effect of these solid waste challenges is high in most urban areas of low- and middle-income countries. One type of this solid waste, which is a global concern, is plastic waste. To curb the pollution imposed by these plastics, most countries are recycling them to form usable construction materials such as pavement materials. This paper seeks to analyze and ameliorate plastic pavement qualities in order to redefine the qualities of the existing plastic pavement in Cameroon. In this research project, polyethylene terephthalate (PET) and polypropylene (PP) were used as binding materials for the production of plastic pavement. During this research, the effect of combining the two plastics mentioned above for the production of a single pavement was studied to determine the impact of their combined binding characteristics as well. The formulation of the pavement samples for evaluating the binding characteristics of polypropylene (PP) in each pavement was defined as 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, and 50%, and that of polyethylene terephthalate (PET) was defined as 10%, 15%, 20%, 25%, 30%, and 35% by weight of the total sample. The other percentage is that of sand. In the third phase, the effect of combining the two types of plastics as binding materials in a single pavement production was evaluated, and in this case, the formulations were: 10% PP plus 20% PET, 15% PP plus 15% PET, and 20% PP plus 10% PET, against 70% sand. Physical and mechanical tests carried out on both samples gave interesting results. The results showed that this quality could withstand a stress equivalent to 27.6 MPa, which is equivalent to 49 KN and can be used in less-traffic areas according to the standard (EN196/01-ASTMC). 30% PP as a binding material produced a 22.1 MPa strength that can withstand a load of 40 KN, and 25% PET produced a compressive strength of 14.1 MPa that can withstand a load of 22.4KN. The effect of the flexural strength test demonstrated that the flexural strength increases with an increase in plastic quantity in any pavement. The physical properties like density, porosity, and water absorption gave interesting values (1.953 g/cm3, 14.66%, and 3.1%, respectively) for the formulation of 25% PET, making this formulation to be considered among the best that can be adopted for pavements in water-locked areas. From the results obtained, it can be concluded that, using only 25% polyethylene terephthalate for the production of a plastic pavement, the pavements could be used in monument premises and water-locked areas. Using 30% PP, the pavement could be used in streets and yards, while using 20% PP plus 10% PET, the pavement would be used in less-traffic areas.

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1. Introduction

The role of plastics in the world today has made it an integral item in all the activities carried out in our society. Plastics are used for packaging, construction, household items, and digital equipment. Even though plastics are so useful in our society today, their useful life is very short, and the duration it takes to decay is so long. Consequently, plastics are found abandoned almost everywhere in our society today [1]. A lot of research has been done on the evaluation of the binding effect of waste plastics, especially for recycling purposes [2][3][4][5][6]. Some researchers have demonstrated that plastics have good binding characteristics if combined with sand for the production of pavements and cobbles [2][6].

Cameroon has poor road infrastructure in most rural parts, and this is attributed to the high cost of road construction materials, whereas waste materials such as plastic can be valorized or used as an alternative to asphalt for road construction. The solution to this poor road infrastructure can be partially solved by ameliorating and improving the quality of the plastic pavement. Plastic materials have good binding characteristics in composites with sand that can be applicable to road infrastructure [7][8]. Mashadi et al. used low-density polyethylene (LDPE) and mesh sand to develop a formulation of 1kg (plastics) for 5 kg (sand) and 1kg (plastics) for 7 kg (sand). The sand was inserted into the mixing machine at a temperature of 200°C for 5-10 minutes, after which the chopped plastics were inserted and mixed for 30-35 minutes. Moulding was carried out, and their results showed that the lowest damage occurred on plastic, with a sand composition of 1:5 as low as 0.113% and a compressive strength of 16.667 MPa, while the highest damage occurred on plastic, with a sand composition of 1:7 as low as 0.267% and a compressive strength of 12.963 MPa. The same formulation method was used to produce cement pavement, and the result showed that a cement and sand composition of 1:7 produced a compressive strength of 17.126 MPa, which is a clear indication that plastics can be used to replace cement in paving blocks. Dalhat et al. [9] did research on cement-less and asphalt-less concrete bound by recycled plastic. The result was compared to Portland cement concrete (PCC). All of the recycled plastic-bounded concrete (RPBC) exhibits excellent stiffness and flexural strength, approximately 5 times that of AC and 3 times that of PCC. The cracking efficiency of the RPBC is in the order of 92%, as opposed to 9% for waste (RPW) by weight of the aggregate used as the formulation for RHDPE and RPP, polymer mixed asphalt (PMAC), and AC. The RPBC demonstrates much lower thermal sensitivity and better moisture resistance than the AC. In this research, the compressive strength produced by the recycled polypropylene concrete (RPPC) was 30 MPa compared to recycled high-density polyethylene bounded (RHDPE). NK Obeng et al. [2] in Ghana carried out research on how to explore the potential of using low-density polyethylene plastic waste as a binding material for paving block production. In their research, they used concrete paving blocks composed of cement, quarry dust, and sand mixed in a ratio of 1:1:2 by weight to produce a cement pavement block that was used as a reference control for testing the compressive strength and water absorption properties of the composite paving block with less plastic content in the same mix ratio of 1:1:2 (plastics, quarry dust, and sand) and a higher plastic content with a mixed ratio of 1:0.5:2 by weight. The laboratory test of compressive strength was evaluated at 7, 14, and 21 days, and the water absorption test was done after 72 hours of soaking the samples. The study revealed that 21-day paving blocks with high plastics (HP) and low plastics (LP) had a compressive strength of 8.53 N/mm2 (0.5% water adsorption) and 7.3 N/mm2 (2.7% water absorption), respectively, higher than the reference value of 6.0 N/mm2 (4.9% water absorption) of the cement paving block.

It is recommended that paving blocks made from recycled plastic waste be used in non-traffic areas such as footpaths, pedestrian plazas, landscapes, monument premises, and waterlogged areas due to their low water absorption properties and low compressive strength. The main focus of the study is the amelioration of plastic waste pavement products in Cameroon to attain optimum engineering properties so that these pavements can be applicable for road infrastructure. This research aims to evaluate the varying effect of plastic concentration in pavements using two main types of plastics, which are polypropylene (PP) and polyethylene terephthalate (PET), and also the effect of varying the combination of these two plastics for the production of a single pavement.

2. Materials and Method

- **Waste plastics as binding elements**

The plastic materials used for this experimental study are polyethylene terephthalate (PET) and polypropylene (PP), collected from garbage areas in Yaoundé, crushed to particle sizes between 4 and 10 mm, washed, and dried for 4 days. Polyethylene terephthalate (PET) is composed mainly of water bottles, sweet drinks, and juice bottles with the same basic material properties and density of 1.38-1.39 g/cm3, a melting point of 113 °C–135 °C, and the chemical symbol (C_2H_4) n. While polypropylene plastics included leads of water bottles and household utensils such as buckets with the same basic material properties and density of 0.90-0.91 g/cm3 [10] as well as a melting temperature of 130°C–175°C and the chemical formula (C_3H_6) n, Figure 1 presents the different plastic types.

Figure 1. *Plastic types: a) polyethylene terephthalate, b) polypropylene*

- **Fine aggregate.**

The aggregate used in this experiment is coarse sand. This sand was dried properly until the moisture content was practically reduced, before being sieved into different grades. The grain size with particles between 0.125mm and 0.315mm was used in this research.

Figure 2. *Fine sand aggregate*

- **Preparation of the specimens**

Here the specimens are prepared by weighing the waste plastic materials and sand[2][3][4][5][6]. The polypropylene (PP) and sand were weighed in ratios of 1:9, 1.5:8.5, 2:8, 2.5:7.5, 3:7, 3.5:6.5, 4:6, 4.5:5.5, and 5:5 to evaluate the influence of their binding characteristics in each sample. The samples, after preparation, were allowed to set for between 2 and 7 days. The same method was applied to polyethylene terephthalate (PET) plastic waste in scale ratios of 1:9, 1.5:8.5, 2:8, 2.5:7.5, 3:7, and 3.5:6.5. The effect of combining these two plastics was also evaluated by combining the two different types of plastics in the ratios 1:2:7, 1.5:1.5:7, and 2:1:7. The crushed plastics were melted in a chamber at a temperature of about 168 °C. The melted plastics were stirred for 10 minutes, and the right proportion of sand was added to the melted plastic in the chamber. The final combination was stirred for 25 minutes before being poured into the molds

- **Laboratory testing method**

Compressive strength, flexural strength, density, porosity, and water absorption tests were done following the standards EN19601-NFP15:45-DIN1164-PREN/ISO679, EN196/01-ASTMC349-DIW1164-PREN/ISO679, and EN7721-11 [4][5].

- **Measurement of porosity and bulk density**

Porosity was measured using the Archimedes principle method, where samples are weighed in the dry state and weighed again after steeping in water for between 3 and 7 days according to the standard EN7721-11 [11]. The weighing is carried out using a precision scale. The masses of the test pieces immersed in water and the masses of the same pieces in the dry state were used to calculate the respective values of density and porosity using formulas 1 and 2, respectively.

Figure 3. *Samples during porosity and bulk density testing*

$$\rho \text{kg/m}^3 = \frac{M}{V}$$

$$\text{P}(\%) = 100\text{X}\left(1 - \frac{Db}{Dt}\right)$$

Where, M is the weighed mass of the samples, V is the calculated volume of the sample from V = x h x (length, width, and thickness), D_b is the bulk density, *Dt* is the absolute density

- **Compressive strength**

Compressive strength was evaluated on polypropylene (PP) samples with the formulations 1:9, 1.5:8.5, 2:82.5:7.5.5, 3:7, 3.5:6.5, 4:6, 4.5:5.5, 5:5 that lasted between 2 days and 7 days. The standard for the evaluation was done using EN19601-NFP15:45-DIN1164 PREN/ISO679. The second evaluation was done on polyethylene terephthalate (PET) samples using the same formulation as mentioned above, but due to the fact that PET is less dense in its liquid state, PET samples with formulations from 3.5:6.5, 4:6, 4.5:5.5, and 5:5 could not be produced without air voids inside the samples, so formulations at these intervals were excluded. This method of formulation is just as L. Gungat et al. [4] who investigated the possibility of using plastic waste in block fabrication for pedestrian's paths. The plastic contents used in each mixture were 0%, 5%, 10%, 15%, 20%, 25%, and 30% by weight of the plastic-sand mixture. These tests were carried out using the CBR machine in Figure 4.

Figure 4. *A CBR Press (CONTROL T1004) with load characteristics 1000gF. Serial number 3558 belonging to the civil engineering laboratory at the University of Yaoundé 1.*

- **Three-point bending test**

The influence of PP on the three-point bending test was evaluated on samples between 2 and 7 days in accordance with the standards EN196/01-ASTMC349-DIW1164-PREN/ISO679 and EN7721-1 using the Euro press CM10N50 machine (Figure 5). For each test, three test pieces were used. The test consists of applying to the prismatic pieces of dimensions 40mmx40mmx160mm a force perpendicular to the axis of the test piece, the direction of which is along the axis of symmetry of the beam resting on two 100mm support parts. The value of the force (F) applied during the test is given by a 1/1000 precision dial gauge. The maximum ultimate stress ( ) and the modulus of elasticity (E) are deduced by the relations below, where L is the final length of the test piece, Lo is the original length of the test piece, and a is the side of the specimen.

$$\sigma = \frac{\vec{F}}{a^2} \quad (3)$$

$$\epsilon = \frac{Lo - L}{Lo} \quad (4)$$

$$E = \frac{\sigma}{\epsilon} \quad (5)$$

Figure 5. *Euro press CM10N50 machine belonging to the civil engineering laboratory at the University of Yaoundé 1.*

3. Results and Discussion

- **Compressive test**

The results obtained from polypropylene (PP) samples with formulations of 15%, 20%, 25%, 30%, 35%, 40%, 45%, and 50% after 7 days are outlined in Figure 6. The results show that the pavement with the formulation of 50%:50% (5:5) plastic to sand ratio presents the maximum compressive strength of 23.4 MPa, which can withstand a load of 40 KN. The formulations obtained from the polyethylene terephthalate (PET) samples were 15%, 20%, 25%, and 30%, and the results show that the formulation with a 25%:75% (2.5:7.5) plastic-to-sand ratio produces compressive strengths of 14.1 MPa that can withstand a load of 22.1 KN. The results are presented in Figure 6.

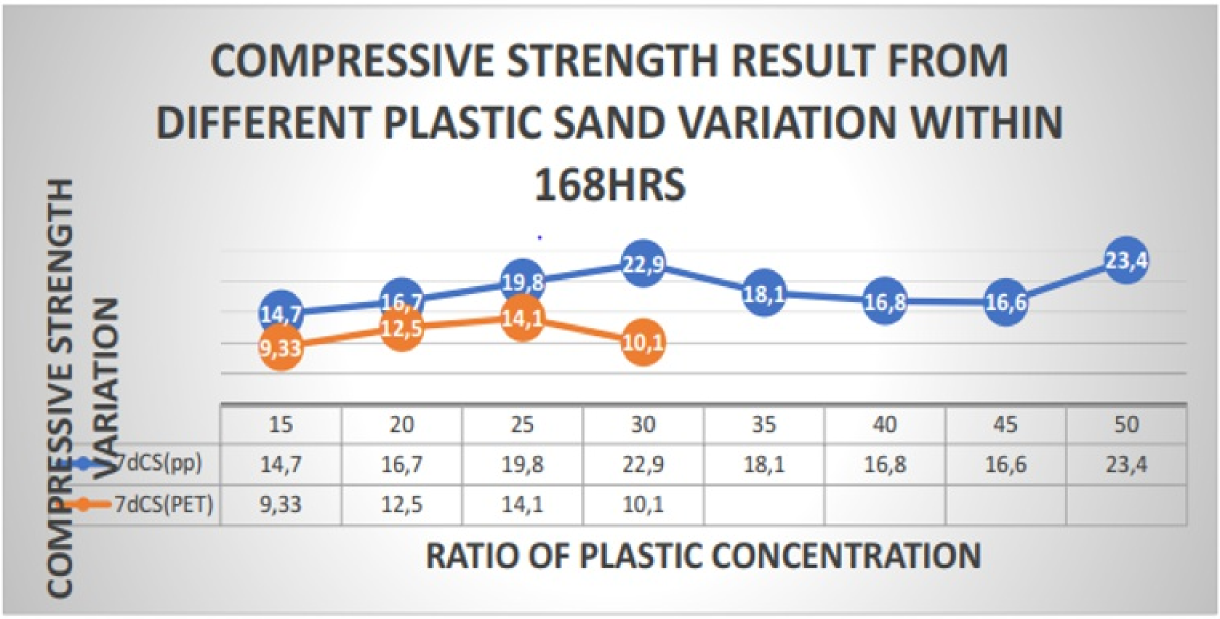

Figure 6. *Compressive test results for the two different plastics formulations after 7 days.*

The formulation obtained from the combination of polyethylene terephthalate (PET) and polypropylene (PP) is 10% PP plus 20% PET, 15% PP plus 15% PET, and 20% PP plus 10% PET of plastic to sand ratio, and the best result obtained was that of the formulation of 20% PP plus 10% PE, which means 2:1:7 of PP: PET and sand. This formulation gave a compressive strength value of 27.6 MPa, which can withstand a load of 49 kN. See figure 7.

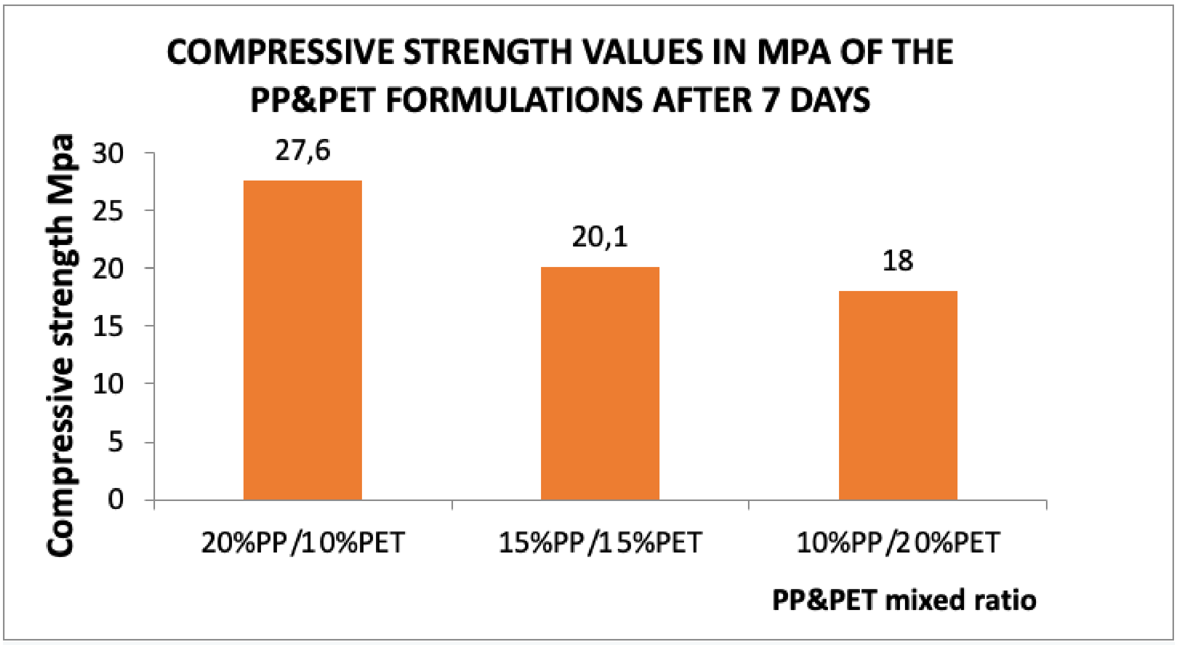

Figure 7. *Compressive test results for the formulations of the mixture of the two plastic types after 7 days*

- **Flexural test**

The results obtained from polypropylene (PP) samples with the formulations of 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, and 50% after 2 and 7 days are outlined in figure 8. The results show that the pavement with the formulation of 50%:50% (5:5) plastic to sand ratio presents the maximum flexural strength of 25 MPa after 2 days and 27.2 MPa after 7 days.

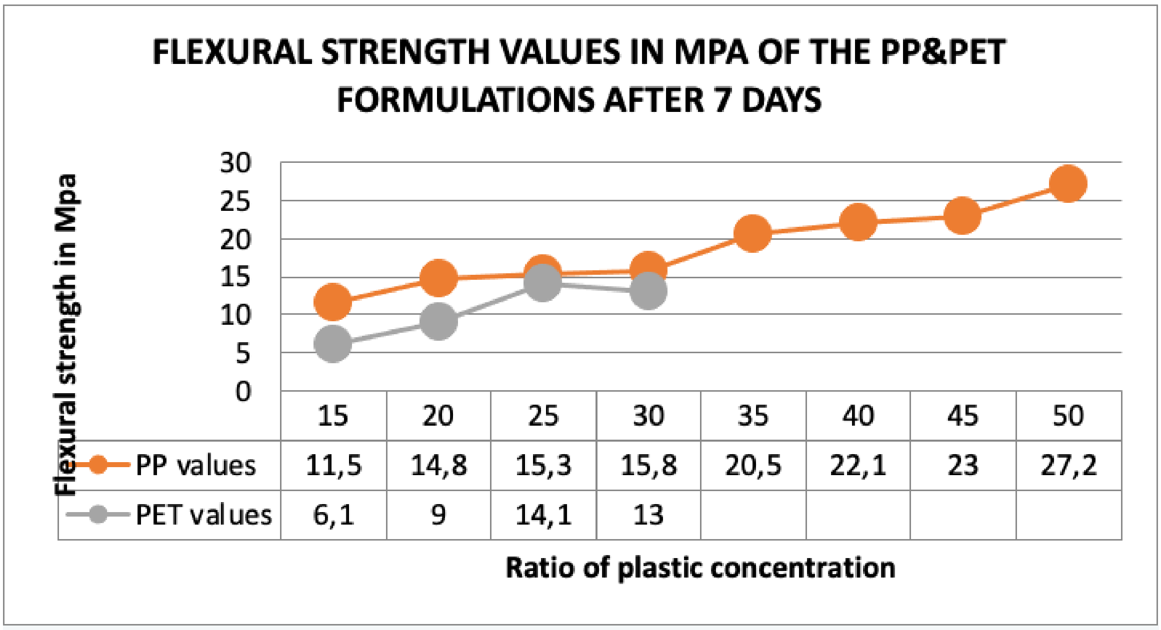

Figure 8. *Flexural test results for the formulations of PP and PET samples after 7 days*

The results obtained from polypropylene (PP) samples with formulations of 15%, 20%, 25%, and 30% after 2 and 7 days are outlined in Figure 9. The results show that the pavement with the formulation of 25%:75% (2.5:7.5) plastic to sand ratio presents the maximum flexural strength of 14.1 MPa after 7 days, and the pavement with the formulation of 30%:70% (3:7) plastic to sand ratio presents the maximum flexural strength of 12.3 MPa in 2 days. The formulation obtained from the combination of polyethylene terephthalate (PET) and polypropylene (PP) is 10% PP plus 20% PET, 15% PP plus 15% PET, and 20% PP plus 10% PET of plastic to sand ratio, and the best result obtained was that of the formulation of 20% PP plus 10% PE, which means 2:1:7 of PP: PET and sand. This formulation gave a flexural strength value of 11.9 MPa. See figure 9.

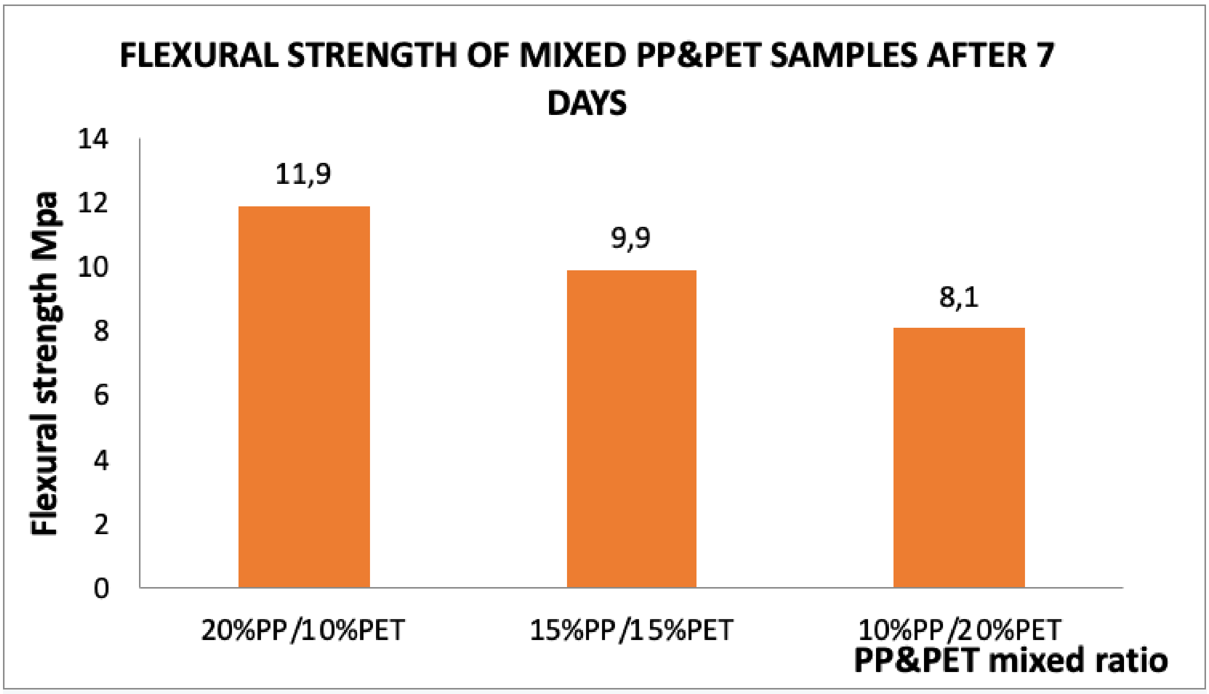

Figure 9. *Flexural test results for the formulations of the mixture of the two plastic types after 7 days*

- **Results of physical tests**

In this work, physical tests were done only for samples that presented good mechanical strength values during the mechanical tests.

- **Density test results**

The histogram in Figure 10 presents values of the density of the PP samples and PET formulations in g/cm3.

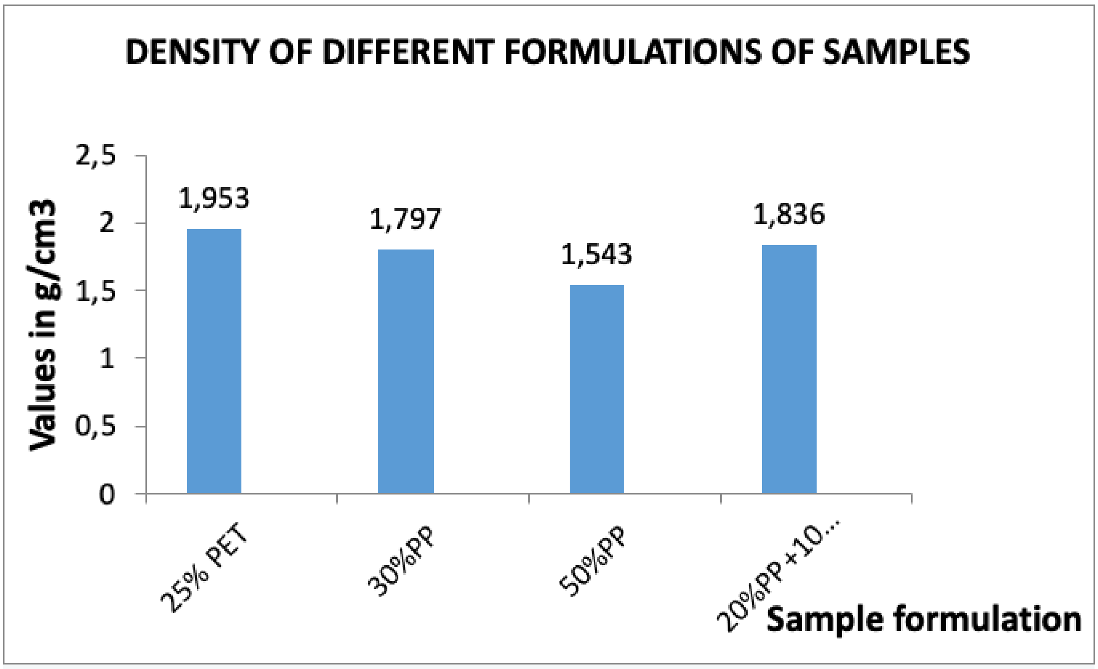

Figure 10. *Density values of the best samples for both formulations after 7 days*

- **Porosity and Water absorption test results**

The histogram in Figure 11 presents the values of porosity and water absorption of the PP and PET sample formulations.

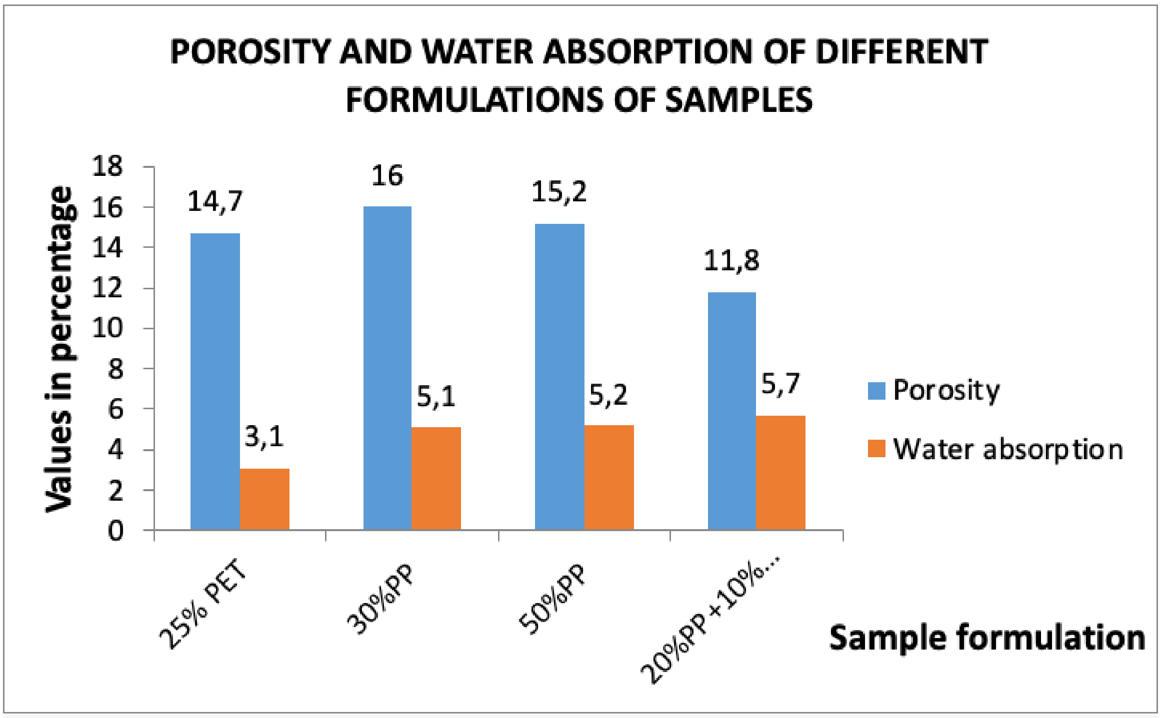

Figure 11. *Porosity and Water absorption values of the best samples for both formulations after 7 days*

From the results obtained from the physical tests, we notice that the formulation of PET and sand with a ratio of 25% to 75% presents the best. The reason is that a good pavement needs to have fewer pores to prevent water from coming out of the yard, especially when used in swampy areas. This particular formulation also presents interesting mechanical properties.

4. Comparison between values obtained from samples and values obtained from pavements produced in Cameroon

When compared to results obtained from existing pavements in Cameroon, we notice that pavements obtained from our formulations gave better values than those of the existing pavements in Cameroon. Figure 12 presents those results. From this conclusion, we can recommend pavements made using the formulations in this work to pavement producers in Cameroon.

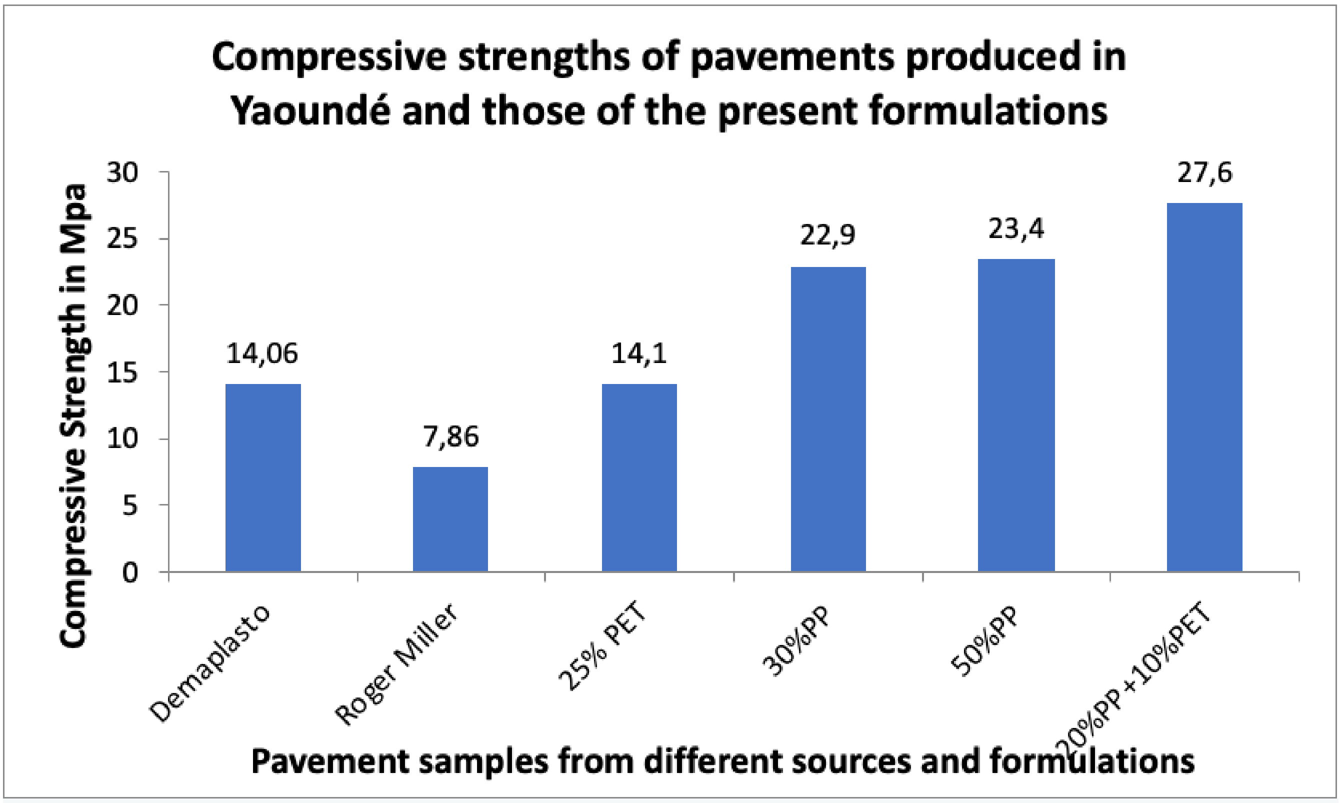

Figure 12. *Histogram presenting comparative results of the compressive strengths of pavements produced in Yaoundé and those of the present formulations*

5. Conclusion

Absolutely at the end of this work, the following conclusions can be drawn:

- Using the polyethylene terephthalate (PET) formulation of a 2.5:7.5 ratio of plastics to sand, we had a compressive strength of 14.1 MPa after 7 days, which can withstand a load of 22.1 kN. We can thus deduce that, using only 25% polyethylene terephthalate as a binding material for the production of plastic pavement, these qualities of pavements will be applicable in monument premises and water lock areas.
- Using the polypropylene (PP) formulation of a 5:5 ratio of plastic to sand, we had a compressive strength of 23.4 MPa, which can withstand a load of 40 kN. So, pavements with these qualities can be applicable in streets and yards in urban communities.
- Using the combination of polypropylene (PP) and polyethylene terephthalate (PET) with a formulation of 2:1:7, respectively, for PP, PET, and sand, we had a compressive strength of 27.6 MPa after 7 days. This result shows that the samples of this formulation can withstand a load of 49 kN. So, these types of pavements can be applicable in less-traffic areas.
- The physical test results presented the PET-sand formulation of 25%: 75% as being the best. It has good porosity, water absorption, and density values of 14.66%, 3.1%, and 1.953g/cm^3, respectively.
- The results obtained from these formulations were compared with those of the existing pavement in Cameroon (obtained without a precise mix formulation of the different plastic types), and compressive strengths were greater than

that of the existing pavements produced in the country.

Conflict of Interest

The authors declare that they have no conflict of interest.

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