International Journal of Pavement Research and Technology
https://doi.org/10.1007/s42947-023-00414-8

社團法人中華鋪面工程學會
Chinese Society of Pavement Engineering

ORIGINAL RESEARCH PAPER

Study of the Performance of HDPE and PVC Plastic Aggregates in Concrete

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Received: 8 April 2022 / Revised: 4 December 2023 / Accepted: 22 December 2023

Abstract

This work aims at immobilizing High-Density PolyEthylene (HDPE) and Polyvinyl Chloride (PVC) plastic wastes in the production of concrete for construction. The partial replacement of natural aggregates with plastic aggregates in the proportions 0%, 5%, 10%, 20% and 30% was performed to obtain two groups of concretes. The comparative analysis was done with the control concrete. The experimental results showed a decrease in the workability (3.10–0 cm) and the dry density (2186–1377KN/m^3). The incorporation of HDPE aggregates in the concrete decreased the compressive strength (24.19–5.73 MPa), the splitting tensile strength (3.57–1.11 MPa), and the flexural strength (5.77–0.96 MPa). On the other hand, the incorporation of PVC aggregates in the concrete improved the flexural strength within the range of 5% and 10% of the addition (7.7 MPa for 5% and 6.25 MPa for 10% of PVC). The cubic morphology and the rough texture of PVC plastic aggregates contributed to the increase in cement paste aggregates adhesion strength. Unlike previous work where the compressive, flexural and tensile strength had decreased because of the smooth texture of the plastic aggregates, which had almost reduced the friction between the cement paste and the plastic aggregates. The decrease in mass was observed during the abrasion test from 5 to 1 g. The low Los Angeles coefficient of the plastic aggregates was responsible for this behavior. The plastic aggregate PVC can be used to reduce the weight of concrete, increase the flexural strength and abrasion of concrete.

Keywords Morphology · Texture · Plastic waste · Aggregates · Concrete

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Abbreviations

EN	European Norm
CIMENCAM	Cameroon cement
CEM	Portland cement
NF	French norm
CPJ	Compounds of Portland cement
CAMWATER	Cameroon water utilities corporation
W/C	Water–Cement ratio
HDPE	High-density polyethylene
PVC	Polyvinyl chloride
DTU	Document Technique Unifié (French building unified codes of practice)
HYSACAM	Hygiene and Health in Cameroon
STP	Plastics processing company

1 Introduction

Concrete is the most widely used and valued building material in the construction industry [1–3]. It is also one of the most used materials in the world after water [4]. Worldwide,

Published online: 02 April 2024

its use is twice that of aluminum, wood and steel combined [5]. The exploitation of natural aggregates is necessary to meet the needs of building and public works stakeholders [6]. The ever-increasing need for aggregates has led to overexploitation or even the depletion of certain natural resources [6, 7]. Aggregates are part of the constituent elements of concrete. Obtaining natural aggregates very often requires high energy consumption. In addition, the natural aggregates in concrete are very often responsible for the heavy weights of concretes. The use of aggregates from waste as a substitute for natural aggregates therefore appears to be a sustainable solution to the problems of overexploitation of quarry aggregates [6]. On the other hand, the growing problems of plastic wastes and their management are also keeping researchers busy. Their elimination has also become a big challenge for industrialized and developing countries. Several research works in the whole world are interested in the issues of waste and their treatment with respect to the environment [5]. Researchers have been busy experimenting different wastes and their use in concrete, for example foundry wastes [8], carbon fiber wastes [9], granite and glass powder wastes [10], carpet waste [11], agricultural waste [12] and plastic waste [13–16] to name just a few.

There are more and more studies interested in the making of sustainable concrete. Sarker Kunal et al. studied the strength, durability and microstructure of cow dung ash cement for sustainable development [17]. The cow dung centers possess pozzolanic properties that allow it to be used in cement as a sustainability practice, replacing some of the enormous amount of CO_2 generated globally in the production of Portland Cement (PC) [17]. Sarker Kuma et al. then noted that the increased replacement of cement by cow dung ashes gives products with better resistance to chemical attacks by HCl, NaCl and H_2SO_4, but also better resistance to water absorption and sorptivity. Thus, replacing cement with cow dung ash shows improvements in both strength and durability [17]. Beyond organic waste, such as cow dung, inert non-biodegradable inorganic waste such as plastics is increasingly used in the manufacture of sustainable concrete in construction. Based on bibliographical studies, the use of plastic waste, in particular HDPE and PVC waste in concrete, has been used either in powder form [5, 18], or in binder form [19], or in form of fiber [10] or either in the form of aggregates [18] to make the concrete light and ecological [20]. According to Li, X et al., plastic aggregates in partial replacement of coarse aggregates and fine aggregates have a greater impact on the technical properties [21]. Several previous studies have observed a deleterious effect on the mechanical properties of concrete with the addition of plastic aggregates, in particular Rayed Alyousef and Sumarsono [22–25].

Belmokaddem et al. investigated the effects of plastic aggregates types on the compressive strength and elastic modulus of concrete. PVC, HDPE, and PP aggregates were used as substitutes for natural sand and medium aggregates with volumetric replacement percentages ranging from 0 to 75%. The highest reductions in compressive strength and elastic modulus were obtained using HDPE aggregates. Good correlations between compressive strength and elastic modulus have been reported [14]. The effects of the water–cement ratio and plastic aggregates recycled from high-density polyethylene (HDPE) plastic waste on the compressive mechanical and durability properties of concrete have been study. In this study the effect of (HDPE) plastic aggregates on the reductions in slump, mechanical properties, drying shrinkage, and chloride ion penetration increased with the increase in content, size, and flaky shape of plastic aggregates [26]. Another research aimed to minimize the plastic by recycling it into construction materials was developed. For this, grinding high-density polyethylene (HDPE) was mixed with cement at different percentages to produce plastic bricks. The addition of HDPE with cement decreased the density, increased the ductility, and improved the workability which led to producing lightweight materials [27]. Sau Debasis et al. reported that through the application of superplasticizers, the workability of concrete containing recycled plastic can improve and the mechanical strengths in compression, flexural and splitting tensile on can decrease as the PE increase in concrete [28]. They also reported that replacement of up to 10% gives concrete acceptable physical and mechanical properties for structural purposes. Sau Debasis et al. show that the use of an artificial neural network (ANN) can predict the fresh and hardened properties of concrete based on plastic aggregates, but also predict the qualities of the concrete with good accuracy [28]. Another study by Sau Debasis et al. reported that the sorptivity of PE-based concrete was lowest with concrete water permeability coefficient and energy absorption increasing with the percentage of PE and PET. However, the percentage of residual mass and residual strength for any replacement decreased with increasing exposure period. They found a similar trend of Cantabro weight loss and concrete surface abrasion. Furthermore they showed that the carbonation depth increased with increasing PE and PET percentages, and the strength decreased with increasing PE and PET percentages when subjected to CO_2. They observed that below 100°C, the compressive strength of all proportions of the mixture was not affected by high temperature. [29]. Debasis Sau et al. are also interested in nine M30 quality concrete mixes containing recycled plastic waste (PE) and (PET) as volumetric replacements for natural coarse aggregates and fine aggregates. They showed a drop in strength with the increase in plastic aggregate waste in concrete as well as a reduction in density. They observed a decrease in the ultrasonic pulse velocity (UPV) as the plastic aggregates increased. They design the prediction models of slump data and mechanical resistances by artificial neural network were developed and tested by the authors. And finally they optimize the proportions of the mixture by a factorial response optimizer [30]. Moreover, in a recent study, the microstructure of PVC particles revealed a rough, rounded surface with grooves and notches that provide a tight interlock between the aggregate and matrix [31]. Researchers have worked effortlessly to reduce CO_2 emissions and mitigate the solid waste problem. In a study of Senhadji et al., scrapped PVC pipes were utilized in ordinary Portland cement based mixtures as a partial replacement for traditional aggregates, replacing natural sand and coarse aggregates in proportions of 30%, 50%, and 70% by volume. They concluded that as the replacement ratio increases, the workability of the mixture improves. A significant reduction in concrete's mechanical strength was also observed when sand was replaced with 50% and 70% PVC. Despite this loss in mechanical strength, the obtained mixtures were found to comply with the recommendations of standard for producing and using lightweight construction materials (class II structural concretes). Finally, they confirmed that using PVC to substitute sand and aggregates significantly reduced chloride ion penetration through concrete [32]. Similar results were reported by Merlo et al., where a maximum reduction of 50% and 30% was observed in compressive and flexural strengths, respectively, when replacing sand with 5% PVC. The difference in characteristics and properties between PVC and natural aggregates might be responsible for the loss in mechanical strength [33]. But the search for the right morphology and the right texture of plastic aggregates that can improve certain properties of concretes, remains still very little studied, especially in developing countries. One of the ways to eliminate this waste is to use it for the manufacture of resistant and durable materials.

The novelty of this study lies in the partial replacement of natural aggregates by HDPE and PVC plastic aggregates of different morphologies and textures in the concrete to develop a lightweight concrete, able of resisting bending stress and abrasion for a sustainable construction. In previous works, plastic aggregates used in concrete had a smooth surface texture, which was responsible for the drops in resistance [34, 35]. In this article, two types of plastic aggregate whose morphologies were different were used, HDPE whose surface texture was smooth and with a more or less flattened shape and PVC whose surface texture was rough with a cubic shape. Less attention has been paid to the morphology and texture of aggregates from HDPE and PVC plastic wastes in the literature review. Previous work has not yet demonstrated that the surface texture as well as the shape of plastic aggregates could influence the properties of concrete. The objective of this research was to study the possibility of using two types of plastic waste (HDPE and PVC) of different morphologies and textures as substitute aggregate for natural aggregates in concrete at different percentages by weight (0%, 5%, 10%, 20%, and 30%). During the experiments, samples containing 0% HDPE and 0% PVC were treated as control samples. The grain sizes of HDPE and PVC were comparable to the grain size of natural coarse aggregate. The fresh and hardened properties of concrete have been studied using European standards. The experimental results of the physical, fresh, mechanical characterization of concrete with the addition of HDPE and PVC plastic aggregates were presented in this work. For further studies, the properties of concretes with additions of plastic aggregates of the same nature but of different texture and morphology can be studied. Similarly, the properties of concretes added with plastic aggregates of a different nature but having the same texture and the same morphology can also be studied.

2 Materials and Methods

2.1 Nature and Source of Materials

All materials used in this research were of local origin. Portland Composite Cement from (Douala-Cameroon) was used. The River sand (0/5) of a siliceous nature, gotten from Sanaga (Ebebda-Cameroon). The quarry coarse aggregate (Gneiss) crushed 6/10 was brought from Yaounde-Cameroon. For plastic waste, rigid HDPE gotten from garbage bins worn of the municipalities and PVC gotten from rigid pipes collected in landfills from PVC pipe manufacturing and recycling industries (Bafoussam-Cameroon). Drinking water came from CAMWATER-Cameroon.

2.2 Preparation and Characterization of Raw Materials

2.2.1 Cement

The cement used was a gray cement, class CEM II / B-P 42.5R produced locally according to the Cameroonian Standard NC 234: 2009 – 06. The cement used was: 42.5 grade. The technical and physical characteristics are recorded on Table 1.

The chemical composition and the specific surface of the cement were recorded on Table 2 below.

2.2.2 River Sand

The sand was previously washed with a 0.063 mm sieve, then dried in an oven for 24 h at a temperature of 105°C. Particles greater than or equal to 6.3mm were removed by sieving, before being used in the concrete. The coarse aggregate was also washed and then dried in an oven for 24 h at a temperature of 105°C. Then the particles greater than or

Table 1 Physical and technical characteristics of Cement used

Manufacturer	Type	Notation	Color	Resistance class	Standard
Cement	Compounds of Portland Cement	CEM II B-P	Gray	42.5 $N.mm^{-2}$	NC 234: 2009 – 06

equal to 14mm were eliminated by sieving. Table 3 presents the physical characteristics of the river sand, quarry coarse aggregate and plastic aggregates (HDPE and PVC). The characteristics were compared to the theoretical values in the last column of Table 3.

Before crushing the PVC pipes, the water absorption in 24 h at 23°C of the pieces of PVC pipes was 0.05% and the HDPE pieces had a water absorption of 0.06%.

2.2.3 Preparation of plastic waste

The preparation of the plastic waste begins with the collection of plastic waste, passing through sorting, washing, shredding and finally with crushing and sieving.

- HDPE type plastic

The collection and sorting of garbage bins worn at the HYSACAM landfill were done manually, only garbage bins worn made of HDPE plastic materials were sought. The garbage bins worn were then washed with clean tap water to remove dirt. The shredding of garbage bins worn was done manually with a homemade machete. They were cut into small pieces to facilitate mechanical shredding. The pieces obtained were exposed to the sun for 4 h to be dried in addition. The shredding was mechanical. The HDPE pieces were fed into knife shredding having fixed blades and movable blades. The aggregates obtained have a texture whose surface was smooth and more or less flattened in shape. In previous works, the aggregates also had a smooth texture obtained by simple blade shredding [25, 38]. The knife shredder machine used had a power of 15 Kw, a 10 mm sieve, 2 fixed blades and 3 movable blades incorporated in the shredder machine. The dimensions of grinding chamber were 200 × 250 mm with a rotation speed equal to 1470 rotations/min. The pieces of plastic were gradually introduced into the grinder. A mixture was obtained consisting mainly of coarse elements and a minority consisting of fine elements (powder) and fiber elements. After passing through a 0.315 mm sieve to eliminate very fine elements (powder), particles greater than or equal to 14mm were also eliminated by sieving. The fibers were finally eliminated by sorting. Plastic aggregates of HDPE type having a granular form were then obtained.

- PVC type plastics

The collection was done manually in the landfill of the plastics processing company (STP) in Bafoussam-Cameroon. Indeed, the scrap of rigid PVC pipes with a diameter of 160 mm and a thickness of between 3-4 mm was collected. The shredding of PVC pipes was done manually with an artisanal machete so as to obtain small pieces to facilitate mechanical grinding. The pieces of PVC plastic were gradually introduced into the crushing chamber. Grinding chamber features claw knives. The aggregates obtained after shredding have a texture whose surface was rough. Contrary to previous works, the aggregates had a smooth texture and a more or less flattened shape obtained by simple blade shredding [25, 38]. Claw knife shredding used has a power of 12 Kw, a 15 mm sieve, 2 fixed claw blades, 5 movable claw blades incorporated in the machine. The dimensions of grinding chamber were 200 × 200 mm, 200 mm rotor diameter with a rotation speed equal to 1500 rotations/min. After grinding a claw knife, the aggregates obtained consisting mainly of coarse elements and a minority of fine elements. Then the particles greater than or equal to 14 mm and less than 0.315 mm were eliminated by sieving. Plastic aggregates of PVC type having a granular form were obtained. Figure 1 presents the mode of preparation of HDPE and PVC plastic aggregates used.

2.2.4 Characterization of Plastic Aggregates

A) Morphology and texture of plastic aggregates.

The aggregate was characterized by its skeleton or its external morphology. The HDPE aggregate thus obtained after grinding and sieving has a texture whose surface was smooth, irregularly shaped, with more or less flattened aggregates and a grain size close to coarse aggregate ($d < 1$ mm and $D < 31.5$ mm) [39], where d designates the minimum grain diameter and D the maximum diameter. The color of the aggregate depends on the color of the plastic waste collected at the base. The aggregates obtained (Fig. 2) were very light and therefore less dense than natural aggregates (coarse aggregate). On the other hand, the PVC aggregate thus obtained after grinding and sieving had a texture whose surface was rough, irregular and more or less cubic in shape and a particle size close to coarse aggregate ($d < 1$ mm and $D < 31.5$ mm) [39]. Its color also depends on the color of the PVC plastic waste collected at the base. Table 4 presents the morphology and texture of the plastic aggregates used after grinding.

Table 2 Chemical composition and specific surface area of cement powder used [36]

Sample	Al_2O_3	BaO	CaO	Cr_2O_3	Fe_2O_3	K_2O	M_gO	N_iO	P_2O_5	PbO	SO_2	SiO_2	TiO_2	ZrO_2	H_2O	Total	Specific surface area $g.m^{-2}$
Cement	3.34	0.04	62.23	0.01	2.50	0.95	0.00	0.01	0.00	0.01	5.01	19.22	0.33	0.09	2.50	96.25	1.26

The aggregates obtained (Figs. 2 and 3) were light, therefore less dense than natural aggregates. However, HDPE aggregates were lighter and less dense than PVC aggregates. The texture of particles often refers to the quality of their surface. The surface of the aggregate particle was smooth and soft when it was touched, this was the case with HDPE plastic aggregates used. It was rough and had it has the texture of sandpaper as observed on the PVC plastic aggregates used. Baudouin Aissoun had also classified the texture of aggregates using the same process [40].

The aggregates were observed under an optical microscope to better appreciate their structures. Figure 4 below shows the magnification of the aggregates under an optical microscope. The magnification scale was: × 7.

b) Flattening and elongation of plastic aggregates.

A sample of 100 aggregates particles had been selected. Measurements of the geometric dimensions of each particle was determined as described by Lee [41]. The shape of the aggregates or particles was defined by the following three geometric quantities: The length L, which was the maximum distance of two tangent parallel planes at the ends of the aggregate, the thickness E, which was the minimum distance of two tangent parallel planes to the aggregate and the size G which was the dimension of the minimum square mesh of the sieve which allows the aggregate to pass. Figure 5 shows the dimensions of a particle of an aggregate.

The elongation and flattening ratios were respectively: E/G and G/L. British Standard BS limits these two ratios to 0.55 and 0.6 respectively. α was the flattening index and β the elongation index of the aggregates. The Table 5 below show the flattening and elongation characteristics of plastic aggregates and compared to natural aggregate in accordance with French standard NF P 18–561.

The particle size curves of the aggregates used are shown in Fig. 6 below:

2.3 Experimental Protocol

2.3.1 Mix Optimization

The concrete was made in accordance with the NF EN 206–1 standard, valid for concrete whose density was > 800 kg m^{-3} [43]. Coarse aggregate, Sand and Cement were mixed with water in the following proportions: 400 kg.m^{-3} of cement, 785 kg m^{-3} of Sand, 1200 kg m^{-3} of coarse aggregate and 220 kg m^{-3} of water. The coarse aggregate on sand (G/S) ratio was 1.53 and the W/C ratio was 0.55. Several dosages were carried out with the aim of gradually replacing natural coarse aggregate with plastic aggregate waste. Plastic aggregates of the HDPE and PVC type were added in the proportions: 0%, 5%, 10%, 20%, and 30% of the density of the coarse aggregate (1200 kg m^{-3}), the proportion of sand, cement, and water

Table 3 Physical characteristics of Aggregates used

Characteristics	River Sand	Quarry coarse aggregate	HDPE aggregates	PVC aggregates	Theoretical value [37]
d/D ratio	0/5	6/10	6/10	6/10	–
Fineness modulus (M_f)	2.91	3.8	3.03	3.9	$M_f > 3.2$
Coefficient of Curvature C_c	0.79	1.0	0.99	1.02	$1 < Cc < 3$
Uniformity Coefficient C_u	3.13	1.6	1.6	1.6	$C_u > 6$
Weight (Kgs)	5.762	5.629	1.608	2.473	–
Bulk density M_{Vapp} (Kg.m^{-3})	1532.45	1497.07	428.19	657.71	1500–1700
Absolute density M_{Vabs} (Kg.m^{-3})	2730	3000	–	1250	2500–2600
Water absorption coefficient C_{Abs} (%)	7.2	9.6	10.8	7	0–30
Porosity of aggregates P(%)	–	0.60	6.60	4.50	20–40
Compactness C (%)	–	99.4	93.40	95.5	-
Los Angeles Coefficient C_{LA}(%)	–	36.80	0.42	0.72	< 30
Equivalent of visual sand after washing ESV (%)	82	–	–	–	–

Fig. 1 Method of preparation of plastic waste aggregates

Fig. 2 HDPE aggregates

remaining constant. The constant quantity of water was (220 kg m^{-3}) and depended on the appropriate consistency on each dosage carried out. These operations are recorded on Table 6 below.

In addition to the reference concrete (control concrete), two families of plastic aggregate concrete were produced. The families of concretes produced have been listed as follows:

BT: control concrete or reference concrete.

BAgP-HDPE: Concrete with high-density polyethylene plastic aggregates.

BAgP-PVC: Concrete with polyvinyl chloride plastic aggregates.

Table 4 Morphology and texture of plastic aggregates

Type of plastics	Surface Texture	Morphology	Diameter	Color
HDPE	Smooth	Irregular, more or less flattened and sharpened edges	d < 1 mm and D < 31.5 mm	green or yellow
PVC	Rough	Irregular, cubic and angular	d < 1 mm and D < 31.5 mm	black or blue

The mixing was carried out mechanically using a concrete mixer for homogenization and to facilitate the mixing of the constituents of the concrete in accordance with standard XP-P 18–305 [44]. Contrary to the reference concrete, an increase in the mixing time was carried out on the plastic aggregate concretes to optimize the mixture.

2.3.2 Mixing Optimization

Table 7 below shows the optimization of concrete mixing. The appropriate water–cement ratio (W/C) ratio was sought to optimize the mixture so as to have better mechanical properties.

The W/C ratio = 0.55 was used for all dosages. The dosage of concrete as defined in Table 6 was carried out with different W/C ratios (0.45, 0.5, 0.55, 0.63, 0.7, 0.75). Several specimens were produced with these W/C values, then tested in compression, tensile by splitting and flexural, in order to determine the W/C ratio which increases the mechanical resistance the most. W/C = 0.55 corresponds to the appropriate water–cement ratio for which the mechanical strengths are maximum. Table 7 also presents the water–cement ratios according to the workability values of the concrete and according to the dosages of plastic aggregate.

Fig. 3 PVC aggregates

2.3.3 Preparation and Conservation of Test Specimens

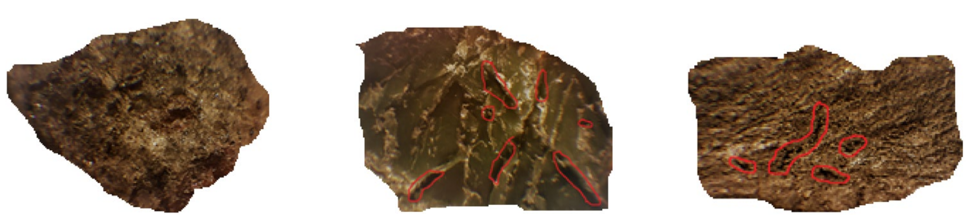
In accordance with standard NF EN 12390–1 [45], the molds and test specimens were made as follows: the PVC pipe 100 mm in diameter and 4 m long was used for this purpose. The pipe was cut in lengths of 20 cm to make standardized molds allowing to have cylindrical test specimens with a section of 78.5cm^2. These specimens were called "10/20 specimens", i.e., 10 cm in diameter and 20 cm in height. Then the wooden prismatic molds were made to have the prismatic specimens of dimension 7 × 7 x 28 cm for the bending tests only. The compaction of the concrete specimens was done manually. The Abrams cone rod used for the slump test was also used for the compaction of concrete specimens. Compaction in two layers of 10 cm each and applying 25 blows per layer was performed during the manufacture of the cylindrical specimens. All specimens must remain in the molds and be protected against impact. Vibrations should be avoided for a minimum of 16 h and a maximum of 3 days. The specimens were then kept in a room at a temperature of 20 ± 2 °C and relative humidity > 95% inside the laboratory until the time of the tests.

2.4 Laboratory Test

2.4.1 Workability of Concrete

The consistency of concrete characterizes its greater or lesser fluidity. The test that allows this consistency to be assessed was the Abrams Cone slump test (slump-test)

Fig. 4 Magnification of aggregates under an optical microscope × 7



a) Natural aggregate b) HDPE aggregate c) PVC aggregate

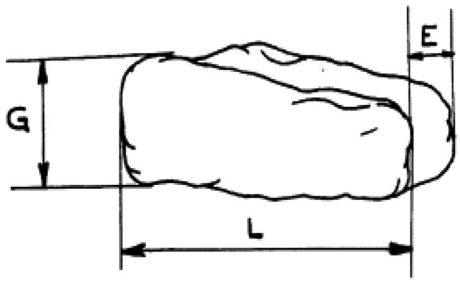


Fig. 5 Dimensions of an aggregate particle [42]

Table 5 Flattening and elongation characteristics

Aggregates	Average flattening index $\alpha = \frac{E}{G}$	Average elongation index $\beta = \frac{G}{L}$
Natural coarse aggregate	0.80	0.78
HDPE aggregates	0.34	0.74
PVC aggregates	0.70	0.81

for the workability. The workability of the three families of concrete (BT, BAgP-HDPE and BAgP-PVC) at different dosages of plastic waste (0%, 5%, 10%, 20%, 30%) was determined in accordance with standard NF P 18–451 [46].

2.4.2 Dry density of Hardened Concrete

The dry density of the hardened concrete was carried out according to the French Standard 12,390–7 [47]. After 28 days, the cylindrical specimens were removed from the mold and then put in oven for 48 h at a temperature of 65°C until the specimen was completely dehydrated. The determination of the dry density of the samples by means of the weighed mass and volume values of the samples were determined. The dry density was calculated using the following formula (Eq. 1):

$$\rho_v = \frac{M}{V} \tag{1}$$

where: ρ_v was the dry density in (kg.m^{-3}) for a sample. M was the sample dry mass in (kg) and V was the sample volume in (m^3).

2.4.3 Compressive Strength

The test was carried out in accordance with French standard 12,390–3. The specimens are loaded to failure in a compression test machine. The maximum load reached is recorded and the compressive strength calculated. The compressive strength was calculated using the following formula (Eq. 2):

$$R_c = \frac{F}{S} \tag{2}$$

Fig. 6 The particle size curves of the aggregates used

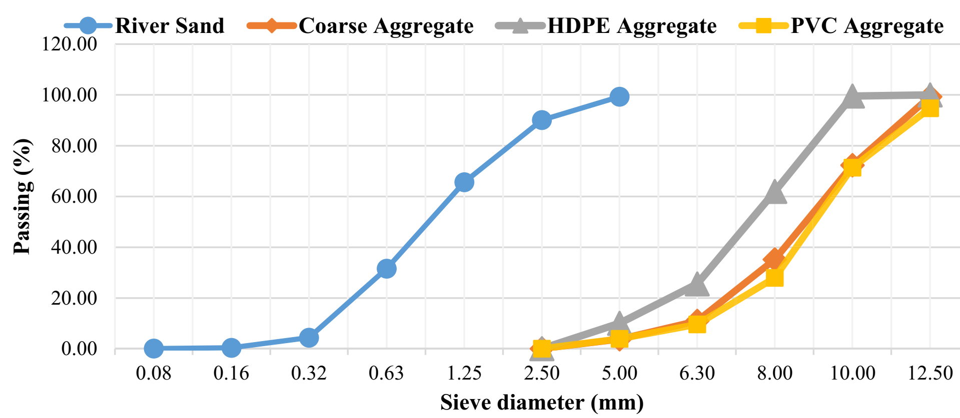


Table 6 Dosage of concrete constituents in HDPE and PVC plastic aggregates

Composition for 1m^3 of concrete	Cement (Kg m^{-3})	River sand (Kg m^{-3})	Wastes HDPE or PVC (Kg m^{-3})	Crushed coarse aggregate (Kg m^{-3})	Water (Kg m^{-3})
B.T	400	785	0	1200	220
BAgP. 5%	400	785	60	1140	220
BAgP. 10%	400	785	120	1080	220
BAgP. 20%	400	785	240	960	220
BAgP. 30%	400	785	360	840	220

Table 7 Mixing optimization of concrete

W/C	BAgP-HDPE **0%**	BAgP-PVC	BAgP-HDPE **5%**	BAgP-PVC	BAgP-HDPE **10%**	BAgP-PVC	BAgP-HDPE **20%**	BAgP-PVC	BAgP-HDPE **30%**	BAgP-PVC
0.45	7.0	7.0	4.5	6.8	1.1	5.2	0.1	3.4	0.0	0.0
0.5	15.5	15.5	10.0	15.0	2.5	11.5	0.3	7.5	0.0	0.0
0.55	31.0	31.0	20.0	30.0	5.0	23.0	0.5	15.0	0.0	0.0
0.63	49.6	49.6	32.0	48.0	8.0	36.8	0.8	24.0	0.0	0.0
0.7	70.9	70.9	45.7	68.6	11.4	52.6	1.1	34.3	0.0	0.0
0.75	94.5	94.5	61.0	91.4	15.2	70.1	1.5	45.7	0.0	0.0

Fig. 7 Cylindrical specimen after compression test

where R_c was the compressive strength in (MPa). F was the maximum load in (N). S was the section of the cylindrical specimen in (mm^2). The result obtained was the average of 3 measurements taken on 3 test specimens for the same family of concrete and at the same percentage. Figure 7 below shows the specimen after the compression test.

2.4.4 Tensile Strength by Splitting

The tensile strength by splitting was carried out on the different specimens (BT, BAgP-HDPE, and BAgP-PVC) at the age of 7, 14 and 28 days. The test consists of putting a cylinder of concrete along two opposite generators between the plates of a press. The test was carried out according to French standard 12,390–6 [48]. If P was the maximum compressive load producing the bursting of the cylinder by tensioning the vertical diametric plane, the tensile strength by splitting was calculated using the following formula (Eq. 3):

$$R_{tj} = 2\frac{P}{\pi DL} \tag{3}$$

where: j = age of the concrete (in days) at the time of the test. R_{tj}: was the tensile strength by splitting in (MPa) or in ($N.m^2$). P: was the maximum load in (N). L: was the length of the contact line of the specimen in (mm) and D: was the nominal diameter of the specimen in (mm). The result obtained was the average of 3 measurements taken on 3 test specimens for the same family of concrete and at the same percentage.

a) Prismatic specimen after flexural test | b) Rupture face of BT | c) Rupture face of BgP-HDPE | d) Rupture face of BgP-PVC

Fig. 8 Rupture after the flexural test

2.4.5 Flexural Strength

The flexural strength was determined on the different specimens (BT, BAgP-HDPE and BAgP-PVC) at the age of 7 and 28 days. The test consists of break up prismatic specimens of dimensions 7 × 7 × 28 (cm) subjected to a bending moment by application of a load by means of upper and lower rollers. The test was performed according to French standard 12,390–5 [49]. The maximum load recorded during the test was noted and the flexural strength was calculated. The flexural strength was given by the following formula (Eq. 4):

$$R_f = \frac{3FL}{2bh^2} \quad (4)$$

where R_f: was the flexural strength in (MPa). F: was the maximum load in (N). L: spacing between the supports in (mm). b: thickness of the specimen in (mm). h was the height of the specimen section (mm). The result obtained was the average of 3 measurements taken on 3 test specimens for the same family of concrete and at the same percentage. Figure 8 below shows the specimen after the flexural test.

2.4.6 Resistance to Wear by Abrasion at the Small Disk

The test was carried out in accordance with standard NF EN 1338 [50]. After 28 days, the abrasion test was carried out on the specimens. Two smooth faces were chosen on each cylindrical specimen and two imprints were made by a steel disk (Ø200mm ± 1mm wide 6mm ± 1mm) rotating for 60s at a speed of 3000 rotations per minute. A GRINDER MD-150 brand electric double-disk grinder (Fig. 9) with characteristics (Table 8) was used to carry out this test.

For each group of concrete, two imprints were made on three samples with the same dosage of plastic aggregates (Fig. 10).

The three cylindrical specimens were weighed then after the test of wear by abrasion with the small disk, these three specimens were weighed again. The difference in weight on each specimen determines the amount of material lost after the abrasion test. Then the average of the loss of mass was taken over the three specimens.

Fig. 9 Electric Bench Grinder

Table 8 Characteristics of Electric bench grinder

Characteristic	Value
Disk width:	6 mm
Diameter of disk:	200 mm
Power:	370 w
Cycles:	50 Hz
Rotation Speed:	3000 rotation/min

3 Results and Discussion

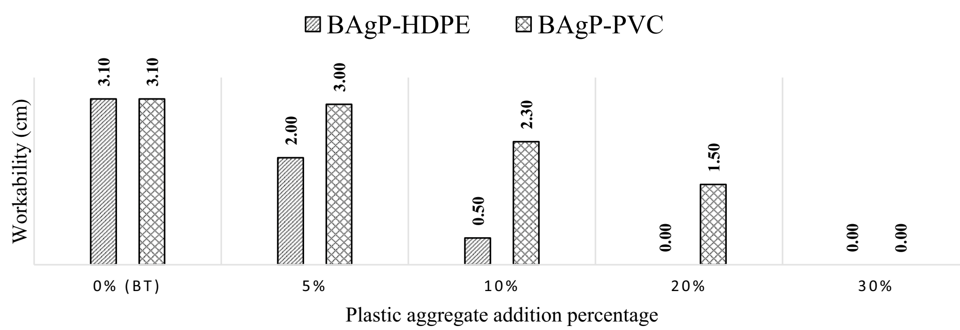
3.1 Workability of Concrete

According to Fig. 11, it was noted that the workability of plastic aggregate concrete varies according to the percentage and type of plastic waste used in the mixture. It can be seen that, when the percentage of plastic aggregates increases in the mixture, the slump decreases regardless of the type of plastic waste used. The mixture obtained has the appearance of very poor hydrated concrete.

The water absorption of each aggregate characterized on Table 3 explains this behavior of concretes with additions of plastic aggregates in the fresh state. The

Fig. 10 Wear of some specimens after abrasion tests

Fig. 11 Workability of concretes according to the percentage of addition of plastic aggregates



possibility of existence of open pores on the surface of the plastic aggregates was responsible for this behavior (Fig. 4). An increase in the water absorption of the plastic aggregates compared to the natural aggregates was observed (Table 3) despite the hydrophobic nature of the plastic aggregates. During the grinding process, the HDPE and the PVC crumpled, creating open pores on the surface and this was likely to retain water during the mixing of the concrete and this did not allow a good hydration of the cement. This poor hydration of the cement was therefore responsible for the poor workability observed. According to Table 3, the HDPE aggregates had more open pores than the other types of aggregates used, the slump is canceled from 20% of addition of HDPE aggregates in the concrete. On the other hand, the concretes with addition of PVC aggregates have a slump which becomes zero from 30% PVC. We then move to a slump of 3.1 cm for the reference concrete to a slump of 0 cm from an addition of 20% for HDPE and 30% for PVC. In all the mixtures, the concretes obtained were firm or stiff. The same observation was made by Mahmoud Abu-Saleem et al. [51–53]. However, contrary to previous observations, some studies, notably those of Choi YW, have instead found an increase in slump value ranging between 10.0 cm to 22.3 cm as a function of increasing plastic aggregates with a constant water to cement ratio equal to 53 mm [54]. In the majority of previous studies, the addition of lightweight waste affects the amount of water available in the concrete hence the workability of concrete. On the other hand, lowering slump of concrete containing plastic aggregates was due to the more or less flattened (Tables 4 and 5) and sharpened edges shapes of HDPE aggregates and the angular morphology of PVC aggregates. Latroch Noureddine has also made the same observation with other types of plastics [55].

3.2 Dry Density of Concretes

Figure 12 below represents the dry density of the cylindrical specimens. It shows that the dry density of concrete decreases as a function of the increase in percentage of plastic aggregate waste in BAgP-HDPE and BAgP-PVC. The dry density of BAgP-PVC was higher than the dry density of BAgP-HDPE. For the reference concrete (control concrete 0% BT) the dry density was 2187 kg.m^{-3}.

The reasons why the dry density of BAgP-HDPE and BAgP-PVC decrease were due to the low bulk density of HDPE and PVC plastic aggregates (Table 3). From 20% of aggregates HDPE in the concrete and 30% of aggregates PVC in the concrete, the densities were close to standard structural lightweight concrete (< 1850 kg.m^{-3}) according to ACI 318. This effect has been widely studied and observed [51, 56, 57].

3.3 Compressive Strength

For each test, the results of the mechanical compressive strength of concrete in BAgP-HDPE and BAgP-PVC plastic aggregate are the average of 3 measurements taken on 3

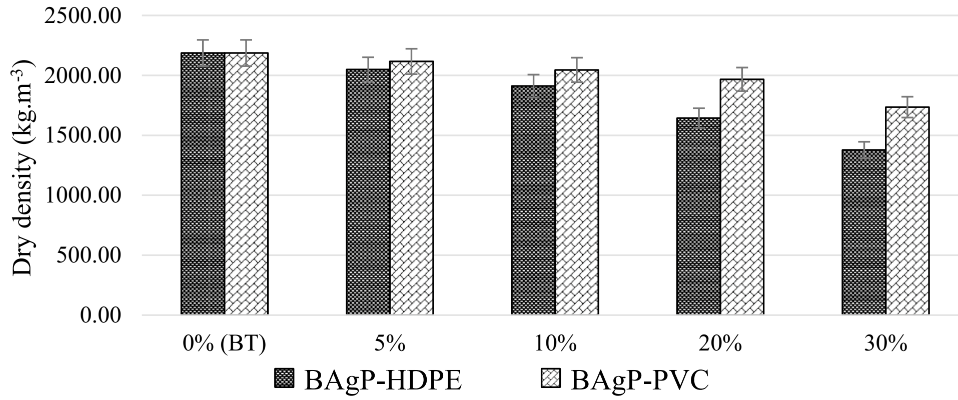


Fig. 12 Dry density of concrete

specimens at the age of 7 days, 14 days, and 28 days and are illustrated in Fig. 13.

The incorporation of plastic aggregates by substitution of natural coarse aggregate with a ratio W/C = 0.55 decreased the compressive strength of concrete when plastic aggregates increase. For reference concrete, the compressive strength at 7 days was 16.04 MPa, this resistance continues to increase at 14 days and reaches 24.19 MPa at 28 days. But these resistances will decrease as the percentage of plastic aggregates of the HDPE or PVC type increases in the mixture. This decrease of the resistance was greater with the incorporation of HDPE plastic aggregates. At 5% HDPE plastic aggregates, the strength decreases by about 47.37% compared to the reference concrete. On the other hand, at this same percentage, there was a slight decrease of 10.52% in the compressive strength with PVC plastic aggregates. But beyond 10% of PVC plastic aggregates the resistance decrease. At 28 days, the reference concrete has M20 grade, corresponding to the ordinary concrete. The maximum compressive strength is 24.19 MPa observed with the reference concrete and 22.15 MPa for the concrete type: BAgP-PVC (5%). We can conclude that the grade of the concrete is M20.

The physical characteristics of HDPE plastic aggregates may be the cause of this decrease of the strength (Tables 4 and 5). Indeed, since the texture of the surface of the HDPE aggregates is smooth, the contact was slippery with almost no friction. These results confirm the work of Albano et al. who indicated that the decrease of the resistance was due to the decrease of the adhesion force between the surface of the plastic and the cement paste [24]. On the other hand, the rough texture of the PVC plastic aggregates obtained the delay of the decrease of the resistance especially at 5% of PVC beyond this percentage, the decrease of the resistance becomes significant. In all cases, the decrease of the compressive strengths observed was also caused by the poor workability of the concretes with the addition of plastic aggregates. Other work, Kou et al. has indicated that it is the hydrophobic nature of plastic waste that inhibits the hydrating action of cement by limiting the movement of water. The presence of honeycombs on the surface of the specimens (BAgP-HDPE and from 20% of PVC in the BAgP-PVC concrete) as well as the poor workability were responsible for this behavior. The rough texture of PVC could not improve the adhesion strength with the cement paste because of the workability problem observed (Fig. 11)

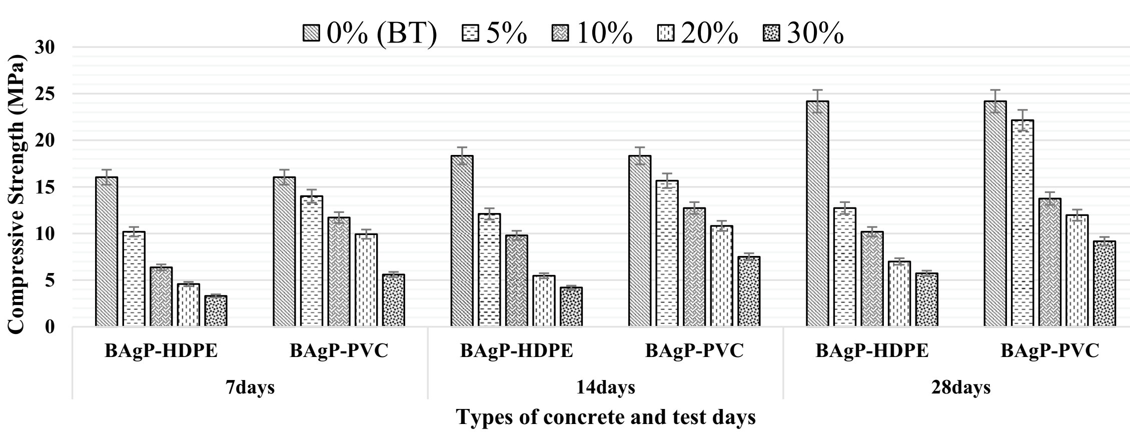


Fig. 13 Compressive strength of concrete

and the lack of chemical relationship. Between 5 and 10% of PVC, the compactness is acceptable (Fig. 8d) but does not contribute to the increase in resistance because it is dominated by a lack of chemical relationship and the reduction in workability. Kou et al. had also made the same observation concerning poor workability with PVC plastic aggregates in concrete [25].

3.4 Splitting Tensile Strength

Figure 14 shows a decrease in the tensile strength by splitting of concretes in BAgP-HDPE and BAgP-PVC plastic aggregates compared to the reference concrete (BT). At 7 days, the tensile strength by splitting of concrete was 2.42 MPa, it gradually increases as the age of the concrete increases and reaches 3.06 MPa at 14 days. But at 28 days, this resistance reaches 3.57 MPa. The incorporation of HDPE plastic aggregates by substitution for natural coarse aggregate will reduce the tensile strength by splitting of BAgP-HDPE and BAgP-PVC. At 5% HDPE the reduction in strength was approximately 12.61% of the strength of reference concrete. On the other hand, at 5% of the PVC, the resistance reduction drops by approximately 8.12%. And at 10% of HDPE and PVC, the reduction in tensile strength by splitting increases by 21.57% and 16.24% respectively. But at 30% of the plastic aggregates, the reduction in resistance exceeds 60% for HDPE against 40% for PVC.

Several reasons can explain this behavior. Indeed, the morphology and texture of HDPE plastic aggregates (Fig. 2) could be the cause of this drop in resistance. The surface texture of HDPE aggregates is smooth, which creates a sliding contact with almost no friction. However, the rupture of the specimens observed was caused by poor workability (Fig. 11), poor compactness (Fig. 8c) and lack of adhesion strength between the cement paste and the HDPE plastic aggregate. This lack of adhesive force causes the HDPE plastic aggregates to detach with the cement paste during the test (Fig. 8c). On the other hand, in PVC plastic aggregate concretes, the rupture of the specimens observed was caused by poor workability (Fig. 11), poor compactness at 20% PVC, or this rupture during the test was caused by the lack of chemical relationship between the cement paste and the plastic aggregate, which had caused the lack of adhesion strength between the cement paste and the PVC plastic aggregates as observed in the literature. The ductile nature of the HDPE and PVC plastic aggregates did not allow the plastic aggregates to burst in the specimens during the splitting traction test but rather a detachment or separation of the plastic aggregates with the cement paste (Fig. 8c and Fig. 8d). At 5% and 10% PVC, the breakage of the test pieces was more caused by the problem of workability and lack of chemical relationship. This observed reduction in tensile strength by splitting has been widely studied [25, 51, 56].

3.5 Flexural Strength

Figure 15 below shows the flexural strength on the cylindrical specimens. This flexural strength is influenced by the percentage of HDPE or PVC plastic aggregates added to the concrete. At 5% and 10% of HDPE, the concretes (BAgP-HDPE) showed no variation in flexural strength at 7 days compared to the reference concrete. The value 2.89 MPa remained constant at 0%, 5% and 10% of HDPE. But beyond 10%, the concretes (BAgP-HDPE) had completely decreased to reach a value of 0.48 MPa with an addition of 30% of HDPE. However, at 28 days, the flexural strength of the concretes (BAgP-HDPE) had all increased, even if the concretes (BAgP-HDPE) had resistance values that were all lower than the reference concrete (BT). On the other hand, at 5% and 10% additions of PVC plastic aggregates, the concretes (BAgP-PVC) showed an increase in flexural strength at 7 days compared to the reference concrete. But beyond 10% of PVC, the concretes (BAgP-PVC) had completely decreased until reaching a value of 0.96 MPa

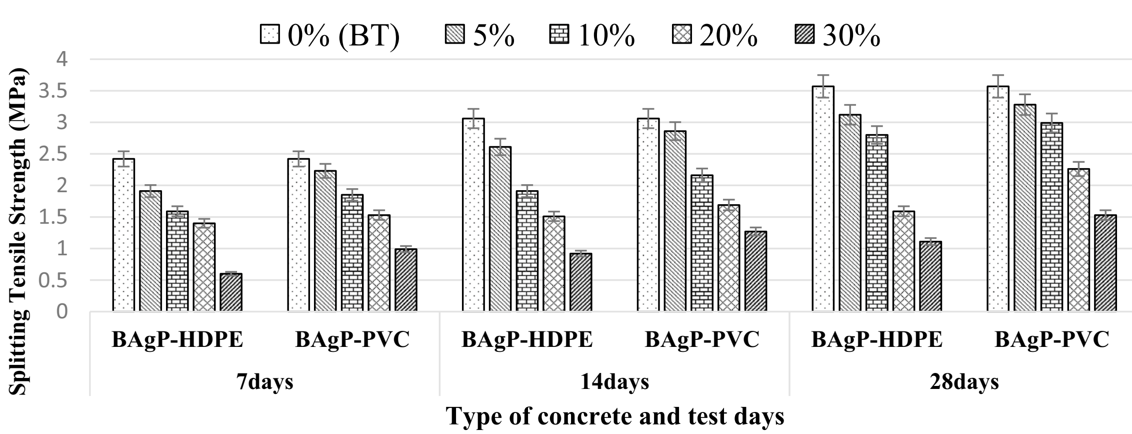


Fig. 14 Tensile strengths by splitting according to the percentage of addition of plastic aggregates

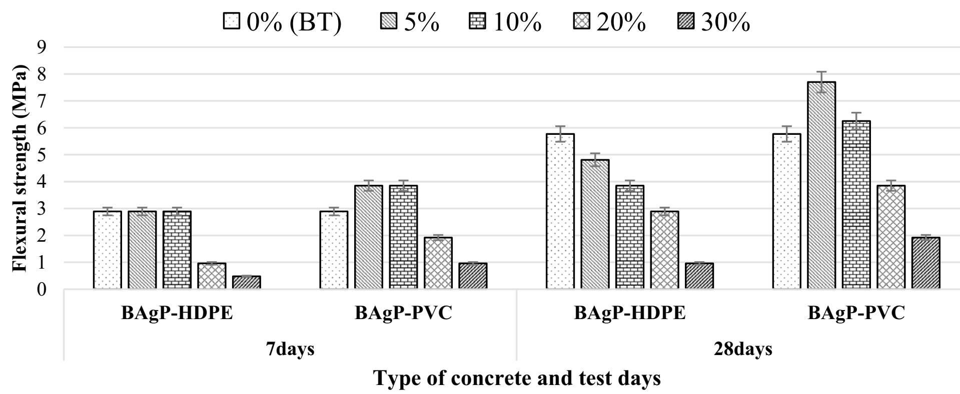


Fig. 15 Flexural strength of specimens

with an addition of 30% of PVC. At 28 days the flexural strength of the concrete had increased. However, the flexural strength with the addition of 5% and 10% of PVC remained high compared to the reference concrete. And the peak was reached with an addition of 5% of PVC. A value of 5.77 MPa was obtained for the reference concrete and 7.70 MPa for the concretes (BAgP-PVC). At 10% of PVC, the resistance decreases but maintains a value higher than that of the reference concrete. Above 10% of PVC, the flexural strength decreased considerably.

The smooth texture of the surface of the HDPE plastic aggregates (Fig. 2) negatively influenced the performance of the cement paste-HDPE plastic aggregates adhesion, which was the cause of this drop in resistance because the contact between the cement paste and the HDPE aggregates is slippery with almost no friction. On the other hand, the very low proportions of cubic particles in HDPE were at the origin of the reduction in the compactness of the granular skeleton which influenced the compactness of the concrete and caused the drop in flexural strength (Fig. 8c). These two essential parameters were major causes of the reduction in resistance observed. Despite the ductile nature of HDPE plastic aggregates, this did not have a positive influence on the flexural strength. In all dosages, failure by separation of the plastic aggregates in the concrete was observed and not failure by bursting of the plastic aggregates (Fig. 8b, c and d). The rupture of the specimens during the flexural test did not show bursting of the HDPE and PVC plastic aggregates (Fig. 8c) and (Fig. 8d) thanks to the ductile nature of the plastic aggregates. On the other hand, bursts of natural aggregates were observed in the reference concrete (Fig. 8b) after the flexural test. At 5% and 10% of PVC aggregates, the ductility of the concrete was improved. The high proportions of cubic PVC particles increased the compactness of concretes at these percentages. The rough texture of the PVC plastic aggregates (Fig. 3) improved the friction, that is to say the contact between the plastic aggregates and the cement paste. These therefore all these elements which contributed to the improvement of the flexural properties of concretes with 5% and 10% PVC. But at more than 10% PVC in the concrete, there is a problem of poor workability and reduced compactness of the concrete, which leads to a reduction in strength. The rigid PVCs used had practically the same failure modes as the rigid HDPEs used, which is why beyond 10% of plastic aggregates in the concrete, they all had the same behavior. The absence of a chemical relationship between the cement paste and the plastic aggregate observed in the literature may also be the origin of this drop in resistance observed in this study.

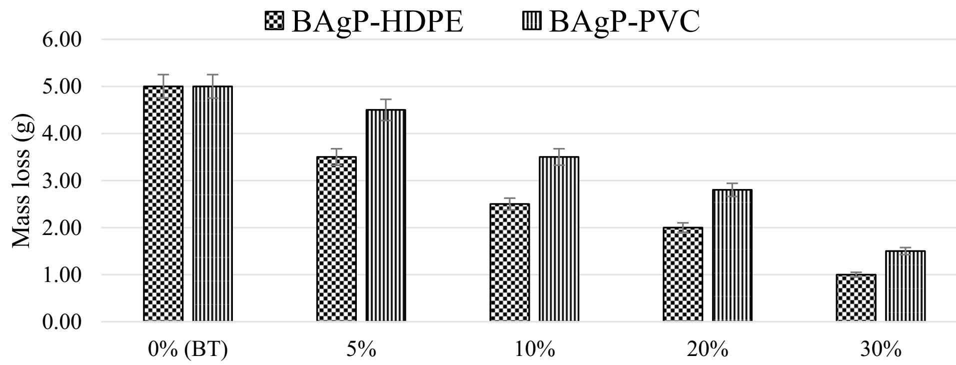
These results were contradicted by Batayneh M, et al., [58] who instead observed a drop in flexural strength, even if this drop in flexural strength was not very significant. On the other hand, Akcaozoglu and Hannawi did not find a large difference in flexural strength between plastic aggregate concretes and reference concretes [38, 59].

3.6 Resistance to Wear by Abrasion at the Small Disk

Figure 16 below represents the weight loss of the cylindrical specimens after the small disk abrasion test. The histogram in this Figure shows the mass loss as a function of the dosage and the type of plastic aggregate. It shows that the loss in mass decreases according to the increase in percentage of waste in plastic aggregates in the BAgP-HDPE and BAgP-PVC. The mass loss of BAgP-PVC was higher than in BAgP-HDPE. For the two imprints noted on the concretes, the loss of mass varies between 5 and 1 g.

One of the reasons that may be at the origin of this loss of mass was the low wear resistance of the cement paste. The reason why the mass loss was less for the BAgP-HDPE and BAgP-PVC concretes as compared to the reference concrete was that the natural aggregate used (gneiss) has a Los Angeles coefficient higher than the Los Angeles coefficient

Fig. 16 Mass loss after abrasion test



of HDPE and PVC plastic aggregates (Table 3). This means that during the abrasion test, the natural aggregate (coarse aggregate) in contact with the small abrasive disk wears out faster than the plastic aggregates, thus causing a loss of mass in BAgP-HDPE and BAgP- PVC. The decrease in mass loss observed for BAgP-HDPE and BAgP-PVC was therefore due to the resistance to wear by friction of these concretes as compared to the reference concrete. The More the Los Angeles coefficient of the aggregates was weak, the more the mass loss after wear by friction (abrasion) of the concretes was weak. Mahmoud Abu-Saleem et al. observed the same behavior with other types of plastic aggregates [52]. On the other hand, this result was contradicted by Barnes et al. [60] who instead observed a vulnerability of the plastic grains during the abrasion test on concrete.

3.7 Flow Chart

Figure 17 below shows the chart of this research work.

4 Conclusion

At the end of this study, the plastic aggregates were characterized. The morphology and the texture of the plastic aggregates obtained after grinding were presented. Two groups of concrete (BAgP-HDPE and BAgP-PVC) were studied and compared to the reference concrete. The results showed that:

1. The workability decreases when the plastic aggregates increase in the mixture, the open pores on surface of plastic aggregates was responsible for this behavior;
2. The dry density of BAgP-HDPE and BAgP-PVC decreased when the plastic aggregates increased in the mixture due to the low density of the plastic aggregates used;
3. The compressive strength of BAgP-HDPE decreased when the plastic aggregates increased due to the smooth texture of the aggregates. On the other hand, the BAgP-PVC had a slight decrease due to the angular morphology of the PVC plastic aggregates. The same observation was made for the splitting tensile strength;
4. The flexural strength of BAgP-PVC improved at 5% and 10% addition due to the rough texture of PVC plastic aggregates. On the other hand, the resistance of BAgP-HDPE fell earlier because of the morphology and texture of the HDPE aggregates;
5. Abrasion resistance also showed great improvement in both concrete groups (BAgP-HDPE and BAgP-PVC). This was due to the resistance of plastic aggregates to fragmentation.

A proportion of 5% of PVC plastic aggregates can be recommended in the concrete, because at this proportion the concrete is light compared to the reference concrete. Moreover, at this proportion, a considerable improvement in the flexural strength is observed compared to the reference concrete and the HDPE plastic aggregate concrete. An improvement of abrasion was also observed compared to the reference concrete. In view of these good properties, a recommendation for the use of this new material (BAgP-PVC) at 5% and 10% plastic aggregates for outdoor paving and flat roofs of constructions is possible. Detailed investigation like SEM, carbonation, permeability, sulfate and/or chloride attack on aggregates and concrete can be also recommended for further studies to better understand this concept.

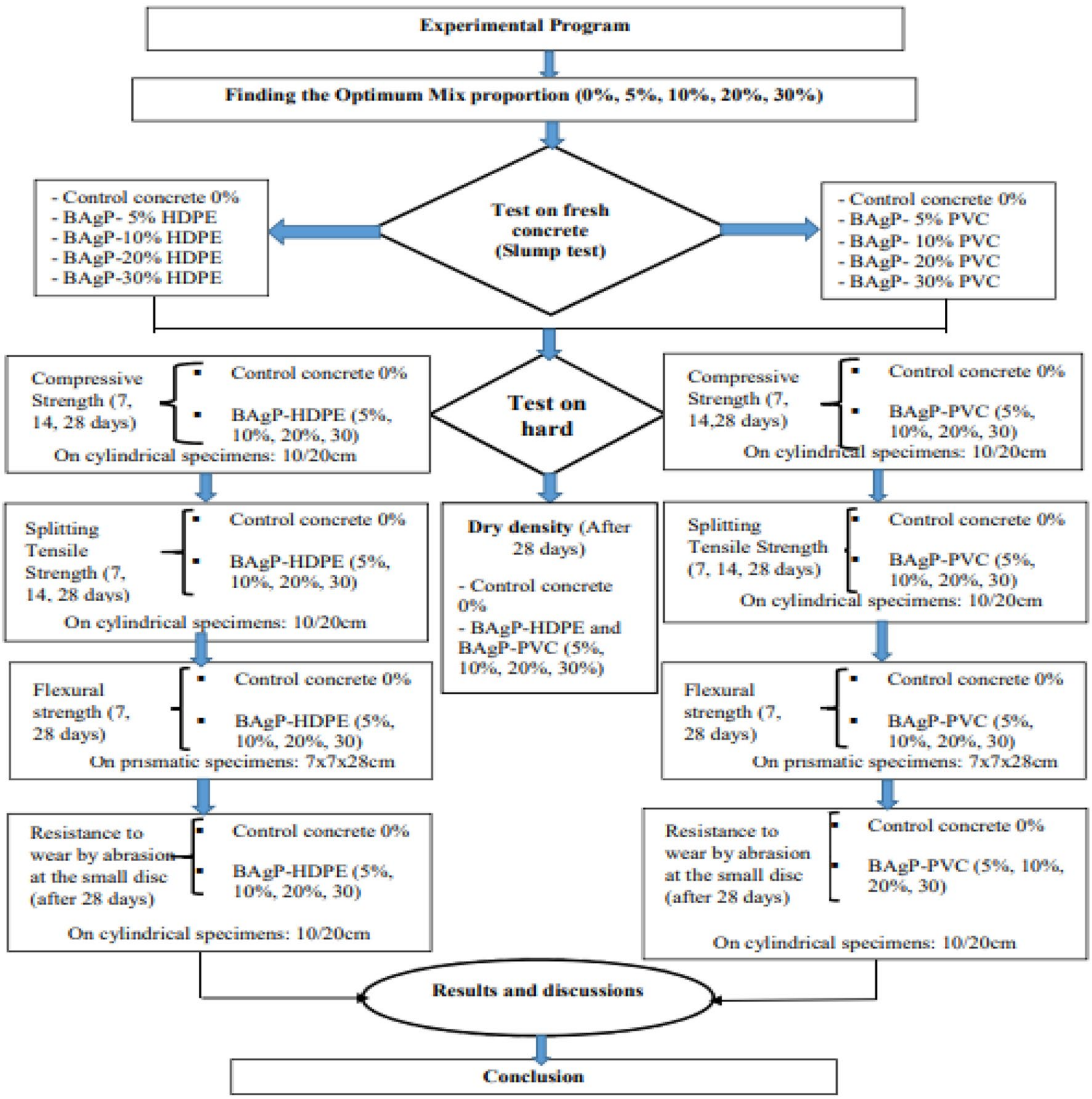


Fig. 17 Chart of the research work

Acknowledgements The authors gratefully acknowledge the support of the mechanical laboratory of HTTTC (high technical teacher training college) of University of Douala, the local materials promotion authority (MIPROMALO), the laboratory of National High School Polytechnic of University of Yaoundé 1 (ENSP), the laboratory of National Advanced School of Public Works of University of Yaoundé 1 and the laboratory of Higher Technical Teacher Training College, Omar Bongo University in Libreville.

Author Contributions KN Arnaud initiated the project and project administration, investigation and writing-original draft; MM Arnold and DD Aubain: Supervision, formal analysis, validation, writing review and editing, Revise the manuscript; YE and NB: Methodology, Data curation, Visualization, writing review and editing; CHB: read and approved the final manuscript.

Funding No funds, grants, or other support was received.

Data availability The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

Declarations

Conflict of interest The authors declare that they have no known competing interests.

Ethical Statement Not applicable.

Consent Statement Not applicable.

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