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Influence of rubber aggregates from the recycled tires on the physico-mechanical and durability properties of compressed earth blocks

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Abstract

To meet sustainable development goals, global policies are strongly oriented toward valorizing alternative resources such as local materials and waste from different sectors of activity. This study aims to evaluate the influence of adding rubber aggregates from used/recycled tires (GPU) on the physico-mechanical and durability properties of compressed earth bricks (CEB). The CEB were made with an earthen matrix containing 8% cement, and 0 to 2% mass of GPU. The CEB were cured under ambient conditions (30±5°C) for 28 days. The results showed a real improvement in physical and mechanical performance and durability indicators of CEB with increasing GPU content. The apparent density changed slightly from 1697 kg/m^3 to 1733 kg/m^3. Total water absorption decreased from 21% to 19% with a slight decrease in water-accessible porosity from 35.7% to 33.1%. The capillary absorption coefficient at 10 minutes also decreased from 14 g/cm^2.min$^{1/2}$ to 10 g/cm^2.min$^{1/2}$ The increase of 29% was noted on the compressive strength in the dry state ranging from 3.5 to 4.5 MPa and of 60% on the compressive strength in the wet state ranging from 1.1 MPa to 1.7 MPa. This resulted in the improvement of the structural efficiency coefficient by 27% ranging from 2080 to 2651 Pa.m^3/kg. Abrasion resistance coefficient increased more than 50% ranging from 10.8 to 16.9 cm^2/g. By comparing the results to the normative references, the CEB containing GPU can be classified as CEB usable in load-bearing walls in a dry environment and resistant to abrasion.

Keywords: Earth brick; Rubber aggregate; Physico-mechanical property; Durability indicator; Waste recycling

1. Introduction

Over the past two decades, climate change has led to the contextualization of human evolution on psychological, technical, and financial levels. More policies and efforts are being made to promote ecological approaches and materials such as compressed earth blocks (CEB) for construction. However, the use of CEB is hampered by a certain number of sociological (Zoungrana et al., 2020) and technical barriers, one of the most notable is their low water resistance (Beckett al., 2020). To overcome this defect, the CEBs are generally stabilized with hydraulic binders (cement; lime, etc.) providing good mechanical performance and durability. However, on an environmental level, the addition of the chemical binder leads to an increase in the carbon footprint of CEB (Ganou, 2021). However, it is possible to counteract

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this negative effect of the addition of binders on the environmental impact of the CEB by adding various types of local waste. This not only contributes to reducing the carbon footprint; but also improves certain properties of the CEB. Additional attempts have already been made to reuse solid waste for CEB strengthening in waste management (Ganou, 2021; Nshimiyimana et al. 2020). The incorporation of polymeric waste in the form of fibers contributes to improving the thermal performance of CEB; although it reduces its mechanical properties in certain studies (Guettala et al., 2016; Taallah et al., 2014). Halbaoui et al (2017) obtained different results with the incorporation of rubber fibers; which increased mechanical performance. Waste can also be incorporated into the earth in the form of aggregates. This is particularly the case of the study carried out by Ganou (2021) who noted a decrease in mechanical performance; but an improvement in durability and thermal properties. Incorporation of aggregates (0 to 50%) into clay-rich soil reduced drying shrinkage and water absorption and improved the compression and abrasion resistance of CEB (Mango- Itulamja et al., 2020).

In all these cases, the dosage and size of the addition, in addition to their nature and forms, have a direct impact on the properties of the CEB. For a granular addition, the dimensions and dosage of the additions depend on the granular distribution of the raw material. The best results were obtained for the dosage of 5%; with respect to the dry mass of the earth, of biosourced aggregates of 2/4mm granular class (Ganou, 2021). On the contrary, the best results were obtained for the content of 0.2% by mass of rubber fiber with a length between 20 and 40mm (Halbaoui et al., 2017). However, the authors did not find any work dealing with the incorporation of rubber aggregates from used tires in CEB from the literature.

Therefore, this study aims to recover and reuse waste tires, constituting municipal waste in Burkina Faso, in the form of aggregates. The study aims to evaluate the effects of rubber aggregates from these secondary resources on the physical, mechanical and durability properties of CEB for applications in building construction.

2. Materials and methods

2.1. Processing and characteristics of materials

The CEB matrix was made from a red lateritic earth material, stabilized with cement and recycled tire aggregates. The earthen material was collected from Loumbila (latitude 12⁰31'9'', longitude 1⁰22'14'' and altitude 295m), at about 7 km from Ouagadougou, Burkina Faso. The physical characteristics were determined in the laboratory. The particle size analysis showed a fine class A material (NF P11-300, 1992) with 62% fraction of less than 80 microns. The Proctor tests enabled to determine the maximum dry density of 1.76 kg/m^3 at the optimal water content of 16.6%. The Atterberg limit test showed that the earth material is a silt-clay of medium to high plasticity (plasticity index of 10–25 and liquid limit of 40–65). The specific density of the earthen material is 2.9 kg/m^3. The cement used for earth stabilization is CEM II/42.5R produced by CIMAF in Burkina Faso.

The rubber aggregates used for incorporation into the matrix are obtained after the transformation of waste tires using a simple methodology implemented as part of this study (Fig 1). The aggregates have a prismatic shape with a granular class of 3.15/5 mm. The choice of this granular class is based on the study carried out by Ganou (2021). The particle size analysis of the GPUs shows a tight grain size distribution with a D_{90} of 4.3 mm. The specific density of GPUs is 0.98 kg/m^3.

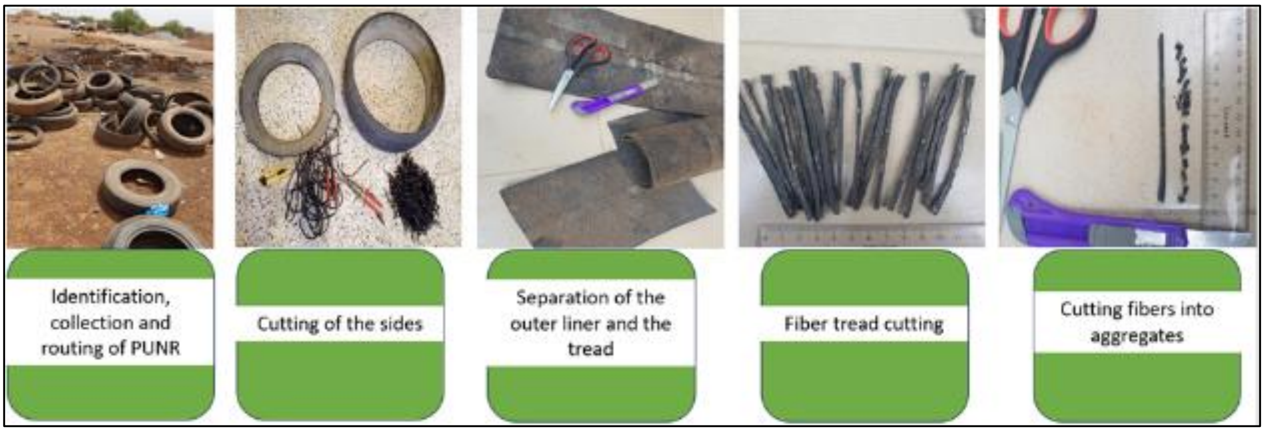

Figure 1 Synoptic diagram of the processing methodology to produce GPU from recycled tires

2.2. Production and characterization of CEB

The matrix was produced with dry earth material and 8% cement relative to the mass of the earth. The aggregates were added at a content of 0 to 2% at increments of 0.5% by weight of the matrix and mixed thoroughly. The production moisture the matrix mixture was determined conveniently with ball testing during sample processing. This content which is 23% was added to the dry mixtures of matrix and GPU. The wet mixtures were manually compressed in a mold (140x140x95 mm^3) of the Terstaram machine at a normal pressure estimated at 3.5 MPa to produce stabilized CEB. The stabilized CEBs were placed in packaging, to avoid moisture loss and minimize carbonation, during the curing at room temperature (30 ± 5°C) for 28 days. The cured CEBs were dried at 60 ± 2°C until reaching a constant mass (mass variation less than 0.1% in 24 hours) before testing their properties.

$$\rho_b = M_d \times \rho_{w_t} / \left(M_{Sat}air - M_{SatW_t}\right) \ldots\ldots\ldots\ldots\ldots (1)$$

$$TP = 100 \times (1 - \rho_b)\rho_S \quad \ldots\ldots\ldots\ldots\ldots (2)$$

$$WA = 100 \times (M_{Sat}air - M_d)/M_d \ldots\ldots\ldots\ldots\ldots (3)$$

$$Ca_{10min} = 100 \times (M_{10min} - M_d)/1000 \times S \times \sqrt{10} \ldots\ldots\ldots\ldots\ldots (4)$$

$$Rc = 10 \times Fr/S \ldots\ldots\ldots\ldots\ldots (5)$$

$$Cab = S/(Mo - M_1) \ldots\ldots\ldots\ldots\ldots (6)$$

The physical, mechanical and durability properties of the CEBs were tested on a dry sample of mass Md (kg). The bulk density, pd (kg/m^3), was determined using equation (1) after hydraulic weighing. Msat.wt (kg) and Msat.air (kg) are the mass of the test pieces after 24 hours of water saturation weighed in water and in air, respectively; pwt (1000 kg/m^3) is the density of water. The total porosity, TP (%), was estimated from the ratio of the apparent density pb of the CEB and the equivalent specific density, ps, of the particles constituting the CEB, using equation (2). Water absorption, WA (%), after saturation, was determined using equation (3). The capillary absorption coefficient after 10 min, Ca_{10min} ($g/cm^2.min^{1/2}$), was determined using equation (4), with reference to the XP P13-901 standard (XP P13-901, 2017). M_{10min} (kg) is the mass of the sample after 10 minutes of capillary absorption through the face of CEB, S (14x14 cm^2).

Compressive strength was tested in dry and wet conditions after immersion of CEB in water for 2 hours. It was tested using a hydraulic press equipped with a force sensor with a maximum capacity of 300 kN, at a loading rate of 0.2 mm/s, with reference to standard XP P13-901 (2017). The compressive strength, Rc (MPa), was calculated in equation (5); Fr (kN) is the maximum breaking load and S (cm^2) is the applied surface. The coefficient of structural efficiency (CES) is an important physico-mechanical parameter to evaluate the contribution of the strength and density of CEB to the bearing capacity in building construction. The CES was determined as the ratio between the dry compressive strength (Rc) and the bulk density (pd) of the CEBs. Abrasion resistance is a parameter which allows to assess the loss of particle of the brick under the effect of abrasion and is determined by referring to XP P13-901 (2017) and using the equation (6).

3. Results and discussions

3.1. Apparent density, porosity and absorption

Figure 2 shows the evolution of the apparent density of CEBs containing GPU. The incorporation of 0 to 2% of GPU in the matrix of CEB stabilized with 8% of cement led to a slight increase in the apparent density from 1697 to 1733 kg/m^3 between 0 and 0.5% of GPU then a decrease to 1641 kg/m^3 between 0.5 and 2% GPU. This is due to the concomitance of three phenomena. On the one hand, there is the particle size correction due to the addition of GPU, therefore improving the densification of the CEB matrix. Then the low density of the rubber (0.98 kg/m^3) compared to the earth (2.9 kg/m^3) and cement (3.1 kg/m^3) contributes to reducing the density of the composite material and finally the lack of adhesion between the smooth surface of the rubber and the earth creates pores also reducing the density of the material.

These results are comparable to those obtained in several studies. Nshimiyimana et al. (2020) obtained values ranging from 1602 to 1566 kg/m^3 for polymer fiber content of 0 to 1.2%. Ganou (2021) noted a gradual decrease of 2650 at 1120 kg/m^3 density with the addition of biosourced aggregates in a content of 0% to 15%. Halbaoui (2017) also obtained the values of the density decreasing almost linearly from 2900 to 2700 kg/m^3 with rubber fiber contents from 0% to 0.3%. Kiki et al. (2023) confirm the downward trend in density with the addition of straw fibers revealing values ranging from 1932 kg/m^3 to 1692 kg/m^3 for contents ranging from 0 % to 1.5%.

Figure 3 also shows the variations in total porosity and water-accessible porosity. There is an opposing trend between the total porosity which slightly increases (58.2% - 60.1%) and the water–accessible porosity which firstly decreases (35.7% -33.1%) and then slightly increases to 34.1% with GPU contents (0-2%). The increase in total porosity with the addition of rubber aggregates is explained by the lack of adhesion between the rubber and the earth matrix. The reduction in porosity accessible by water is due to the closed nature of the pores induced by the earth-rubber adhesion defect. In fact, a closed porosity appears around the rubber aggregates which does not communicate with the outside. For total porosity, the results follow the same trend observed by Kiki et al. (2023) and Nshimiyimana et al. (2020a); who also noted a slight increase in this parameter. On the other hand, the variation in porosity accessible by water which firstly decreases to an optimum is different from what is generally observed in similar studies. Indeed, in the majority of studies, the total porosity and that accessible by water follow the same trend, namely an increase with the addition of stabilizer.

This hypothesis concerning the appearance of closed porosity within the matrix is confirmed by the results of capillary absorption after 10 minutes which decreases from 14 to 10 $g/cm^2.min^{1/2}$ between 0 and 1% GPU then increases to 14 $g/cm^2.min^{1/2}$ at 2% GPU (Figure 3). This is also confirmed by the total absorption which decreases from 21 to 19% between 0 to 1% then increases to 21% with 2% GPU. Referring to the XP 13-901 (2017), CEBs are classified as weakly capillary CEB ($Cb < 20\ g/cm^2.min^{1/2}$).

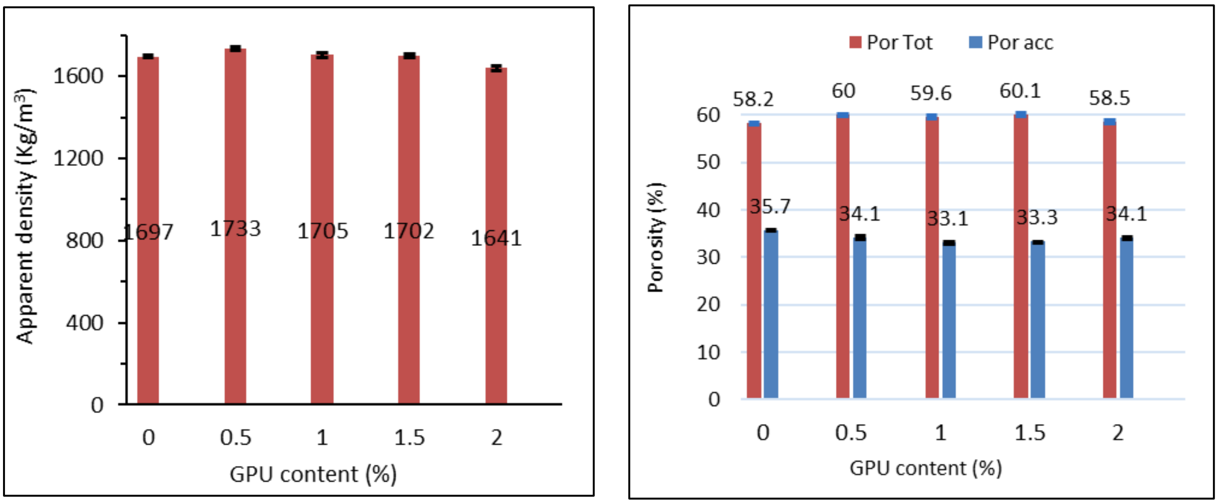

Figure 2 Density and porosity as a function of GPU content

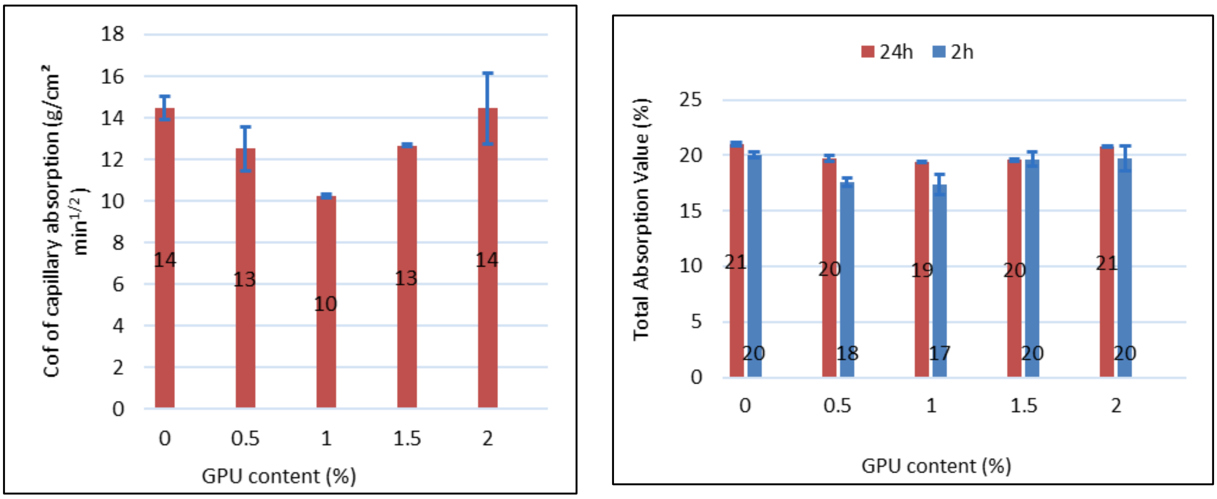

Figure 3 Capillary and total absorption as a function of GPU content

3.2. Compressive strength

Figure 4 presents the evolution of the dry and wet compressive strength of the samples. There is an increase in the resistance in dry state and in wet state with the incorporation of GPU up to an optimum; then a decrease. For dry compressive strength, the values increase by 29% (3.5 to 4.5 MPa); between 0 and 1% GPU then decrease to 3.9 MPa with 2% GPU. For wet compressive strength, the values increase by 59% (1.1 to 1.7 MPa) between 0 to 1% GPU and decrease to 1.5 MPa with 2% GPU. The increase in dry and wet strength is due to the positive influence of the rubber grains on the granularity of the material. In fact, the earth contains a large proportion of fines (62%), the GPU, having a high grain size (D_{90} of 4.6 mm), corrects the grain size by increasing the content of large grains.

These results are comparable to those obtained by Ganou (2021) who noted an increase of 5.5 to 6.5 MPa; i.e. of 18% [(6.5-5.5)x100/5.5] between 0 to 5% of aggregates then a reduction to 3.5 MPa with 15% of aggregates. Halbaoui (2017) also observed the same behavior; but with a greater amplitude of evolution between the control bricks and the bricks at the optimal rubber fiber content (7.4 to 10.6 MPa for 0 to 0.2% fiber) i.e. increase of 43% and finally a decrease to 8.5 MPa with 0.3% fiber. Nevertheless, they are different from those obtained by Nshimiyimana et al. (2019) who observed the decrease of dry compressive strength with increasing polymer fiber content from 4.9 to 3.2 MPa between 0 to 1.2% fiber. The same goes for Kiki et al. (2023) who revealed a reduction in dry and wet compressive strength 5.1 MPa to 1.76 MPa; i.e. 65.4% [(5.1-1.76)x100/5.1] for dry compression and 3 MPa to 0.56 MPa; i.e. 81% [(3-0.56) x100/3] for wet compression. These values decrease for contents ranging from 0 to 1.5% of quackgrass fiber. The same trend was observed with an increase from 0 to 4% of sawdust which caused a drastic reduction in dry resistance (4.5MPa to 1.1MPa) i.e. a decrease of 77% (Avamasse, 2011). According to the XP P13-901 standard, all CEB containing GPU resist compression well (Rc≥4 MPa) and can be classified as CEB 40.

The structural efficiency coefficient (CES) was evaluated as the ratio between the dry compressive strength and the bulk density of the CEB (Figure 4). For structural applications, the goal would be to maximize strength and minimize the weight (density) of materials to increase CES and improve load-bearing capacity. It is noticed that the addition of GPUs significantly improves the CES of CEB. The CES of stabilized CEBs increased by 27% (2080 to 2651 Pa.m^3/kg) with 0 to 1% of GPU; then decreased to 2407 Pa.m^3/kg with 2% GPU.

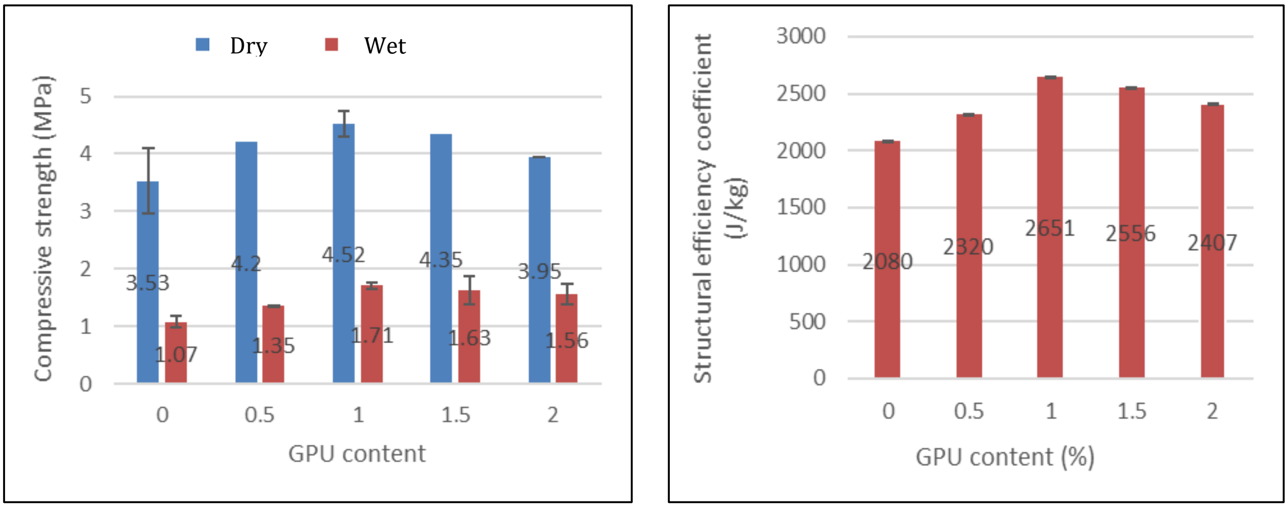

Figure 4 Compressive strength (in dry and wet state) and structural efficiency coefficient

The increase is due to the low density of the GPU which decreases the overall density of the brick while increasing its resistance through the granular correction to the earthen particles. These results are comparable to those of Ganou (2021) who noted an increase in the CES from 2075 to 4545 Pa.m^3/kg between 0 to 10% of CNCS and to 3125 Pa.m^3/kg with 15% of CNCS. However, these results are different from the results obtained by Nshimiyimana et al (2020) who noted a progressive decrease in CES (3040 to 1788 Pa.m^3/kg) with the addition of polymeric fibers (0 to 1.2%). The CES also decreases from 2500 to 2200 Pa.m3 /kg for plant fibers and from 2500 to 1800 Pa.m^3/kg with polymeric fibers. Likewise, Kiki et al. (2023) noted a reduction of 20.5%, 38.6% and 60.6% with the incorporation of 0.5%, 1% and 1.5% of quackgrass straw respectively.

3.3. Abrasion resistance

Figure 5 shows that the coefficient of abrasion resistance (C_{ab}) increases with the increase from 10.9 to 16.9 cm^2/g for the GPU content between 0 and 0.5%, i.e. an increase of 55 %; then decreases to 12.7 cm^2/g with 2%. The increase in the abrasion coefficient is explained by the correction of the texture of the material with the GPU; by making the bricks more compact. There are therefore fewer pores and more contact between the grains. These results are contrary to those obtained by Kiki et al (2023) who noted a decrease from 29.7 cm^2/g to 7.11 cm^2/g with the increase in the content of fibers. Similarly, in study carried out by Ganou (2021), the addition of biosourced aggregates reduced the abrasion resistance of CEB by 26 cm^2/g to 8.9 cm^2/g between 0 and 15% of biosourced aggregates. According to the XP P13-901 standard, all CEB resists abrasion well (Cab >7 cm^2/g) and are of class CEB 60.

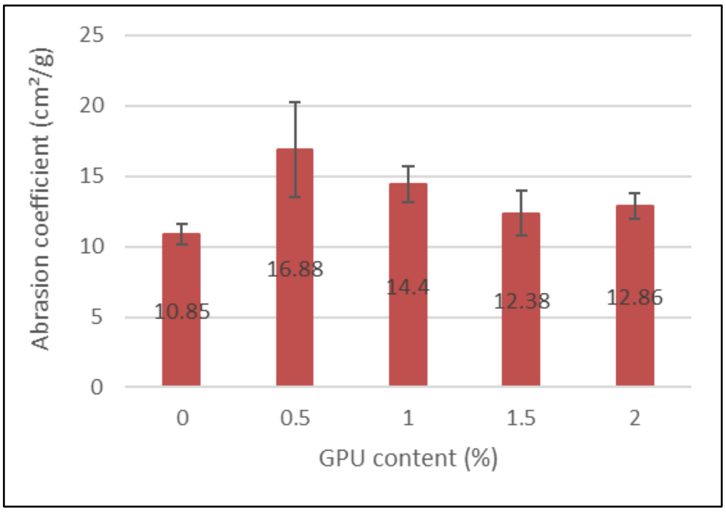

Figure 5 Abrasion coefficient with GPU content

4. Conclusion

Recycled tire aggregates, which were considered waste, are useful for improving the physico-mechanical and durability properties of CEB. This study made it possible to draw the following conclusions:

- The incorporation of GPU increased the apparent density slightly from 1697 to 1733 kg/m^3 with 0 to 0.5% GPU; then decreases to 1641 kg/m^3 with 2% GPU,
- The incorporation of GPU reduced the capillary absorption coefficient by 40% from 14 to 10 $g/cm^2.min^{1/2}$; water accessible porosity from 36 to 33% and total absorption from 21% to 19% for stabilized CEB. The capillary absorption coefficient was less than 20 $g/cm^2.min^{1/2}$ for very low capillary absorption ,
- The incorporation of GPU improved the dry compressive strength by 29% (3.5 to 4.5 MPa) and wet compressive strength by 59% 9 (1.1 to 1.7 MPa). The structural efficiency coefficient of CEB was also improved by 27% (2080 to 2651 $Pa.m^3/kg$),
- The incorporation of GPU improved the abrasion resistance by 55% ranging from 10.9 to 16.9 cm^2/g between 0 and 0.5%.

Future studies should evaluate the influence of GPU on the hygrothermal properties of CEBs incorporating GPUs. It would also be interesting to study the drying shrinkage behavior of CEB containing GPUs; given the high compressibility of rubber.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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