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Recovery of Industrial Waste: Paving Stones Made from Hardened Cement Base

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Abstract

Industrial waste management constitutes a major challenge for sustainable development. This study aims to transform hardened cement waste stored in cement warehouses and in real estate construction sites into paving stones. This innovative solution will contribute to the protection of the environment and the reduction of inert industrial waste. To do this, paving stones based on hardened cement have been developed and characterized. The raw materials were subjected to physical and mechanical characterization tests. The hardened cement aggregates previously crushed with the 5/15 granular class were used as substitutes to replace the natural 5/15 aggregates in the hardened paving stones at contents ranging from 0 to 100%. The mechanical characterization results on the raw material showed that the hardened cement aggregate is made from lightweight aggregates. On the prepared mortar, in the fresh state, the Abrams cone slump test showed an increase in the quantity of waste water with the increase in the content of hardened cement aggregate. In the hardened state, physical (porosity, absorption and dry density) and mechanical (compression, splitting traction, 3-point bending traction and wear) characterization tests were carried out at periods of 7, 14 and 28 days of maturation in water on the cobblestones. These results show that the substitution of natural aggregates by hardened cement aggregates in increasingly large proportions leads to an improvement in compressive, flexural, splitting and wear resistance. In addition, the incorporation of hardened cement aggregate considerably slows down the mechanical degradation of the paving stones. They can, therefore, be used in road and interior or exterior floor coverings.

Keywords

Paving Stones, Hardened Cement, Innovative, Waste, Recovery, Substitution

1. Introduction

Due to the environmental problems linked to the management of inert waste from the building and public works sector in recent years, several research projects have focused on the reuse of this waste for the manufacture of new construction materials. Indeed, Sérifou, in his thesis work, reused waste rubber, glass and hardened cement as aggregates for the production of concrete [1]. When Vrijders and Bock [2] showed in their work, the use of recycled concrete aggregates in concrete following the demolition of old construction. It is in this context that this study takes place. To limit the negative impacts on the living environment, the reuse of industrial construction waste in the design of new paving stone formulations appears as an alternative. This alternative helps alleviate problems associated with effects such as recycling of materials from demolition of old civil structures and debris from the construction industry [3]. Faced with all these problems, it would be possible to recover hardened cement waste, which is also one of the types of inert industrial waste, in the incorporation of new paving stones or concrete as an addition or substitution in order to improve certain mechanical and physical properties [4]. When cement becomes hard on construction sites, it is unusable as a binder. Then, it can be crushed and used as concrete aggregate or in mortar. With the aim of providing a lasting solution to this problem, we initiated this research work with the following topic "Recovery of industrial waste: hardened cement-based paving stones". This not only better protects the environment but also solves the problem of depletion of natural resources and creates jobs. Furthermore, it is necessary to recover this waste in order to reduce the risk of environmental pollution [5].

The objective of this study is to use crushed hardened cement as aggregate in the making of paving stones. This work presents an experimental study on the formulation and physico-mechanical characterization of these paving stones.

2. Material and Methods

2.1. Raw Materials

The raw materials used to make paving stones are Portland cement, natural gravel, sand, water and crushed hardened cement (see **Figure 1**). These raw materials were characterized before their use. For the characterization of these raw materials, the laboratory equipment used consists of a hammer for crushing the hardened cement, an electronic balance for weighing, an electric oven for drying the materials, paving stone molds, a vibrating machine, a CBR mold, a sieve machine, a pycnometer, an electric stirrer, a sieve column, a Los Angeles machine and a Micro-Deval machine.

- The specific weights of gravel, hardened cement and sand were determined by the pycnometer method according to standard NF EN ISO 17892-3 [6].
- The sand equivalent is obtained according to standard NF EN 938-8 [7].
- The particle size analysis test by sieving was carried out on the aggregates (gravel, hardened cement and sand) according to standard NF EN 933-1 [8].

- The NF EN 12620 [9] standard allowed us to have the sand fineness module.
- The Los Angeles test made it possible to measure the combined resistance to impacts and progressive deterioration by reciprocal friction of the elements of an aggregate. It is described by standard EN 1097-2 [10].

The wear resistance of the aggregates was measured using the Micro-Deval test according to standard NF EN 1097-1 [11].

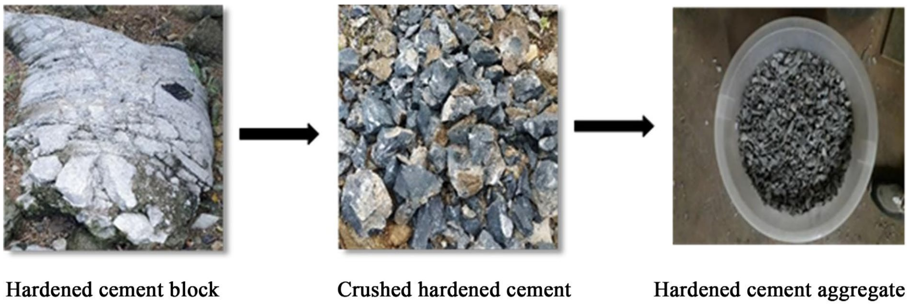

Figure 1. Process for obtaining hardened cement aggregate.

2.2. Production of Paving Stones

2.2.1. Formulation

The paving stone samples for the different series were developed by keeping the masses of sand and binder constant. The mass of gravel is variable due to the substitution of a fraction of the gravel by crushed hardened cement from 30% to 100%. The sand/gravel and binder/sand ratios are respectively S/G = 0.5 and L/S = 1. Depending on the content of the crushed hardened cement and the different ratios, five (5) series of paving stones were made:

- PT: Control paving stone without hardened cement;
- PHC 30%: Pavement containing 30% hardened cement;
- PHC 60%: Pavement containing 60% hardened cement;
- PHC 90%: Pavement containing 90% hardened cement;
- PHC 100%: Pavement containing 100% hardened cement.

These different series were carried out in order to study the effect of hardened cement aggregates on the physical and mechanical properties of the paving stones. The mass composition of the different paving stones is given in Table 1.

Table 1. Mass composition of paving stones.

Composition	PT	PCD 30%	PCD 60%	PCD 90%	PCD 100%
Sand (kg)	14.1	14.1	14.1	14.1	14.1
Cement (kg)	14.1	14.1	14.1	14.1	14.1
Natural gravel (kg)	28.15	19.71	11.23	2.81	0
Aggregates HC (kg)	0	8.44	16.92	25.34	28.15

2.2.2. Determination of the Quantity of Mixing Water

For the manufacture of paving stones, the emphasis is placed on obtaining constant workability with a slump at the Abrams cone set at 9 cm. Thus the quantity of mixing water for each series is determined by continually adding water, in order to obtain this slump.

The Abrams cone slump test is carried out on the fresh mixture. The aim of this test is to determine the slump of the mixture and know its consistency class. It is produced in accordance with standard NF EN 12350-2 [12].

2.2.3. Shaping the Paving Stones

To produce the control paving stones, the natural gravel and sand are mixed beforehand, then the cement is added and mixed afterwards. For paving stones containing hardened cement aggregates, in addition to natural gravel and sand, the gravel is partially replaced by crushed hardened cement. The mixing water determined above is added to each series. After mixing the mixture, the fresh paving stones are poured into the different molds measuring 20 cm × 10.15 cm and placed on a vibrating table for 2 minutes to evacuate the air bubbles. After 24 hours, these pavers are unmolded and placed in a tank of water for wet curing as shown in **Figures 2 and 3**.

Figure 2. Paving stones unmolded after 24 hours.

Figure 3. Paving stones placed in a tank of water.

The paving stones, removed from the mold after 24 hours, are immersed in water to mature. They are kept for 7, 14 and 28 days.

2.3. Physical and Mechanical Characterization of Samples

2.3.1. Physical Characterization

Hydrostatic weighing of paving stones is the physical test carried out on paving stones. It made it possible to determine the porosity, dry density and water absorption of the paving stones using a hydrostatic weighing device according to standard NF P94-064 [13]. The porosity (η), density (ρ) and water absorption (Abs) are given by the formulas:

$$\rho = Ms/\ (Mair - Mw) \times \rho w \quad (1)$$

$$\eta = 100\ (Mair - Ms)/\ (Mair - Mw) \quad (2)$$

$$Abs = 100\ (Mair - Ms)/\ Ms \quad (3)$$

with, Mair: mass in air; Ms: dry mass of the sample; Mw: mass in water and ρw: density.

2.3.2. Mechanical Characterization

Destructive tests are carried out on the hardened paving stone according to standard NF EN 1338 [14]. These are compression, splitting and bending tests. These tests are carried out using the hydraulic press by applying a maximum force of 1500 KN. Furthermore, the abrasion wear test made it possible to highlight the wear resistance of the paving stones.

The compressive, splitting and bending strengths are given by the formulas:

$$Rc = F/S \quad (4)$$

$$R_F = 2F/Lh \quad (5)$$

$$Rf = 3FL/2le^2 \quad (6)$$

With, Rc: compressive strength (MPa); RF: splitting resistance (MPa); Rf: bending strength (MPa), F: maximum force; S: surface area (mm^2); L: the length of the sample mm); h: the height of the sample (mm); l: the width of the mold (mm); e: the thickness of the mold (mm).

3. Results and Discussion

3.1. Physical and Mechanical Characteristics of Aggregates

The results which concern the physical properties of the aggregates are contained in Table 2.

Table 2. Physical properties of aggregates.

	C_u	C_c	D_{50}	M_f	d/D (mm)	D.A (g/cm^3)	E.S (%)	MV (g/cm^3)	M_{DE} (%)	L_A (%)
Sand	2.59	1.1	0.37	1.99	0/2	1.68	97	2.63	-	-
NG*	1.8	1.04	12.5	-	5/15	1.51	-	2.62	7	31.4
HC**	1.52	1.02	9.5	-	5/15	1.05	-	2.00	22.8	23.46

NG: Natural Gravel; HC: Hardened Cement.

From the table, it appears that class 0/2 sand has an average diameter (D50) of 0.37 mm. Its uniformity coefficient (CU) is 2.59 and its curvature coefficient (CC) is 1.1. These values are respectively greater than 2 and included in the interval [1; 3], this sand has a spread and well-graded grain size. The fineness modulus is included in the interval [1.8; 2.2], this sand gives the made paving stone good workability and poor resistance depending on the granular spindle [15], which could be corrected by adding cement.

As for natural gravel and crushed hardened cement of granular class 5/15, with respective average diameters of 12.5 and 9.5 mm. Their uniformity coefficients (CU) are 1.8 and 1.52 and curvature coefficients (CC) 1.04 and 1.02. These coefficients are respectively less than 2 and greater than 1. These samples of natural gravel and hardened cement have a uniform or poorly graded grain size. The incorrect gradation of hardened cement, that is to say the predominance of a particular fraction, leads to the same failures as that of the inadequate granular class. These two defects are one of the causes of the increase in porosity and even the drop in mechanical strength and durability of materials, caused by the phenomena that De Larrard [16] describes as the loosening effect and wall effect.

Regarding the density, sand, gravel and hardened cement have respectively equal values 2.63 g/cm^3, 2.62 g/cm^3 and 2 g/cm^3. According to standard NF EN 13055-1 [17], the actual density of common aggregates varies between 2.5 and 2.6 g/cm^3 and their apparent density is between 1.4 and 1.6 g/cm^3. Also, for Lunk *et al.* [18], common aggregates have their actual density between 2.5 and 2.7 g/cm^3. However, the specific weight of hardened cement classifies it in the category of lightweight aggregates according to this same standard.

The Micro Deval (MDE) test values of natural gravel and hardened cement are 7% and 22.8%, respectively. According to standard NF EN 1097-1 [11], the Micro Deval coefficient of an aggregate must be less than or equal to 25% for it to be used in concrete. With these values, the wear coefficient obtained shows that natural gravel is more resistant than hardened cement. But these results give good resistance to wear.

For the Los Angeles test, standard NF EN 1097-2 [10] requires that fragmentation losses be less than 50%. **Table 2** indicates that all the materials studied meet this criterion. The results of natural aggregates and hardened cement aggregates are respectively 31.4% and 23.46% losses, these values show that hardened cement aggregates have better resistance to fragmentation compared to natural aggregates.

3.2. Characteristics of Paving Stones

3.2.1. Fresh Paving Stones

1) Influence of hardened cement on mixing water

Figure 4 indicates the evolution of the quantity of mixing water on the paving test specimens.

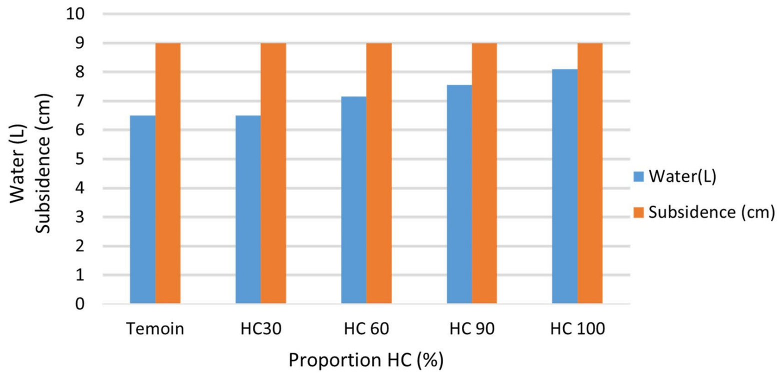

Figure 4. Evolution of the quantity of mixing water depending on the dosage of HC aggregates.

Figure 4 shows an increase in the quantity of mixing water with the proportion of hardened cement. At a 100% crushed content, the quantity of water is 81 L. Unlike the control paving stone, where the quantity of water used is 62 L, an increase of 24.6% compared to the control paving stone. Indeed, according to [19], lightweight aggregates absorb a lot of water when using concrete and mortars. This explains the increase in absorption with the increasing quantity of hardened cement in the paving stone.

3.2.2. Paving Stones in Hardened State

1) Physical properties

- **Porosity**

Figure 5 shows the porosity results as a function of the curing time of the paving stones and the different proportions of hardened cement.

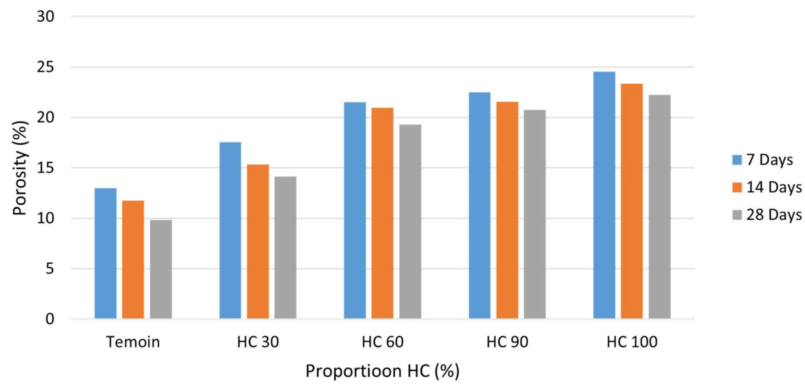

Figure 5. Porosity of the paving stones as a function of maturation time.

Generally speaking, **Figure 5** shows an increase in porosity with the proportion of HC and a decrease in this porosity with time during the curing period for each paving stone specimen. The increase is significant for 60%, 90% and 100% specimens. In previous work, several authors have indicated that this increase in porosity with the increase in the quantity of recycled aggregates is due to the fairly high shape and roughness of the recycled aggregates. In fact, when the shape and roughness are high, this prevents air bubbles from escaping from the block when placing the test pieces on the vibrating table. Thus, the incorporation of hardened cement into the paving stone has a double impact on the structure of the material. First of all, it increases the volume of the voids by facilitating the connections between the different aggregates present in the matrix. Then, it also helps to increase the volume of the voids by promoting the connections between the aggregates and the matrix of the paving stone. This combination of factors results in a more complex microstructure which affects the physical strength of the paving stones. This is what pushes [20] during their study to say that recycled aggregates cause the formation of occluded air in the composites and leads to an increase in the interfacial transition zone between the hardened cement aggregates and the cement matrix.

However, calcium hydrosilicates and hydro aluminates (CSH and CAH) which result from hydration reactions gradually reduce the porosity of the composite over time. This explains the decrease in porosity with curing time. This result is confirmed by [21] who noted that the hydrates formed favor a rearrangement progressively occupying the voids within the block. Also, in his study, Belmokhtar [22] stated that the addition of nano-silica to cement pastes had a significant impact on their rheological and physicomechanical properties. He explained that the reduction in porosity was due to the hydration of clinker minerals present in the cement. However, the paving stones containing the hardened cement aggregates have a higher porosity compared to the control paving stone. This can be explained by the fact that hardened cement is completely inert. The HC0 and HC100 mixing water makes it possible to understand that hardened cement is more porous than natural gravel. According to the durability indicators defined by [23], cementitious materials with a porosity greater than 16% have a durability of less than 30 years. However, HC paving stones have a porosity at 7 days of between 17.55 and 24.55%, at 14 days between 15.33 and 23.36% and at 28 days between 14.13 and 22.22%. Following this indication of performance, these paving stones studied can be considered to be of less durability. However, at 30% substitution between 14 and 28 days, the paving stones have a porosity of less than 16%, which could give them good durability.

- **Dry density**

Figure 6 shows the results of dry density as a function of time and different dosages of HC.

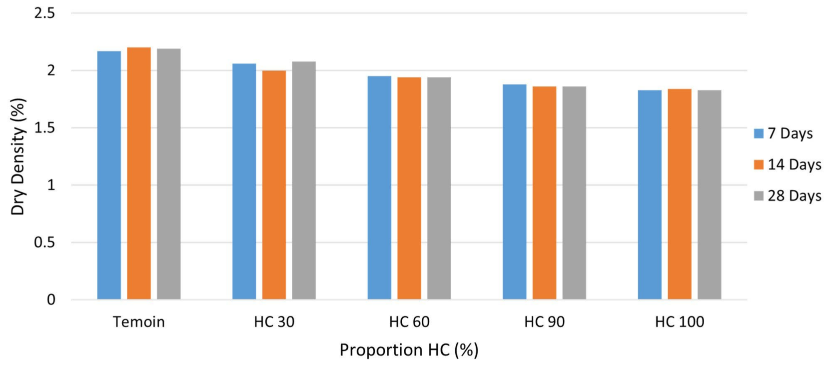

Figure 6. Dry density as a function of maturation time.

The results shown in **Figure 6** indicate a drop in dry density with an increase in the quantity of HC in the paving stone specimens. The presence of hardened cement aggregate in the paving stones specimens significantly influences the dry density. For the 30% HC specimen, we notice a density greater than 2 while in the specimens of 60%, 90% and 100% HC, the density is less than 2. In fact, hardened cement aggregates have a higher water absorption rate than natural aggregates. This is due to the presence of a large amount of pores within it. This observation was made by [1]. Generally speaking, the dry density values of paving stones are between 1.83 and 2.06. These different values place these paving stones based on hardened cement aggregates in the category of lightweight concretes which according to [24] are in the interval 0.8 to 2.5. They can therefore be used for covering floors, pedestrian areas and on class T2 traffic.

- **Absorption**

Figure 7 shows the water absorption rate of 7 days, 14 days and 28 days maturing pavers.

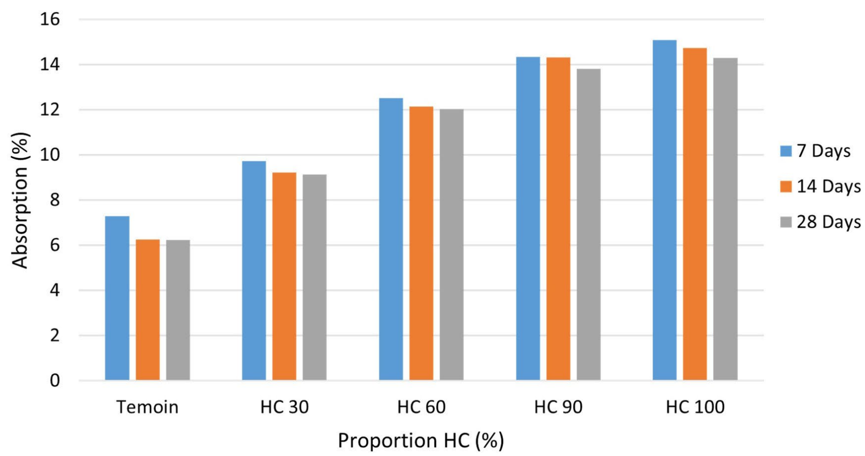

Figure 7. Water absorption as a function of the maturation time of the paving stones.

Figure 7 generally shows that the water absorption rate of the paving stones increases with the proportion of HC 30%, 60%, 90% and 100%. Absorption evolves in a similar way to porosity, because the absorbed water is retained in the pores of concrete. The higher the quantity of recycled aggregate, the more significant the absorption becomes. This behavior is mainly attributable to the differences between the absorption of recycled aggregates and natural aggregates according to [25] and [26]. In fact, recycled aggregates have a higher specific surface area. Thus, the more aggregate there is recycled, the greater the quantity of water adsorbed on its surface per unit volume. Concerning the absorption rate, the standards tolerate an absorption of less than 7% for an average lifespan of around 50 years. The absorption obtained on the specimens of hardened cement paving stones is between 9.13 and 13.88%. Which is higher than the requirements of the standards. This big difference is due to the hardened cement aggregate which is hydrophilic. Also, the absorption rate of the paving stone samples decreases over time. It should be noted that during the maturation of the samples, the spaces are gradually filled thanks to the hydration reactions of the minerals present in the cement. Indeed, in the presence of water, these chemical reactions are triggered, stimulating the formation of new substances and strengthening the structure of the paving stone. Thus, the water absorption capacity of the different paving stones decreases over time, improving their durability and strength.

2) Mechanical properties

- **Compressive strength**

Figure 8 shows the variation in compressive strength as a function of the maturation time of the different paving stones.

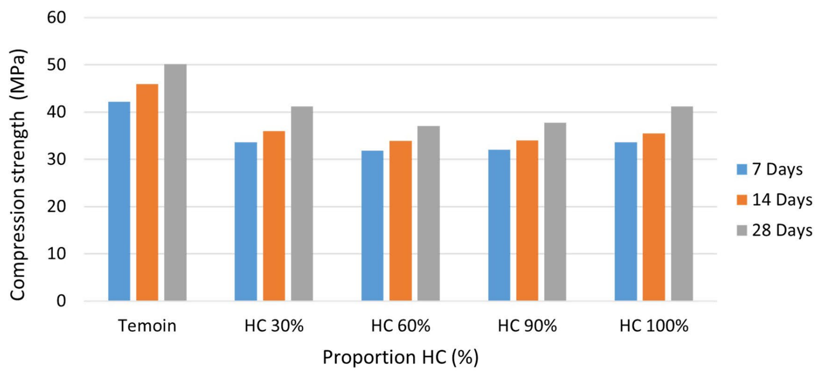

Figure 8. Compressive strength depending on the maturation time of the paving stones.

The results shown in Figure 8 show that the compressive strength of each series of paving stones increases from 7 to 28 days. The increase in compressive strength as a function of maturation time is linked to the hydration of the cement, which is a chemical phenomenon that continues over time. In fact, the more the maturation time increases, the more there is production of hydrate gel, which will promote the hardening of the paving stone. There is also a drop in compressive strength with the increase in the substitution of natural aggregates by hardened cement aggregates. Thus, the resistances change respectively by 50.17 MPa, 41.22 MPa, 40.1 MPa, 39.8 MPa and 38.2 MPa for the proportions of 0 HC, 30 HC, 60 HC, 90 HC and 100 HC. This analysis is explained by additional imperfections such as intergranular voids caused by the presence of hardened cement aggregates. These defects cause damage to the material, thus reducing its strength. These results are consistent with the work of Haddad *et al.* [27], who showed a similar proportion of reduction when natural aggregates were replaced by recycled aggregates. This is due to poor adhesion between natural aggregates and hardened cement aggregates. For substitutions of 90% and 100% with hardened cement aggregates, the compressive strength is less than 40 MPa, while for substitution rates of 30% and 60%, the strength is greater than 40 MPa.

However, [14] recommends 40 MPa, for compressive strength. However, the values of the paving stones are respectively between 41.22 MPa and 40.1 MPa for the substitution rates of 30% and 60% of hardened cement. These paving stones can be used to cover industrial areas; sidewalks and parking lots. Beyond 60% of hardened cement aggregates, the resistance of the paving stones obtained does not respect this recommendation of the standard. But these paving stones can be used for other purposes. Furthermore, it has been demonstrated that paving stones with a compressive strength of 25 MPa or more can be used for paving purposes, parking lots and pedestrian areas.

- **Bending tensile strength**

Figure 9 shows us the results of the bending as a function of the hardening time of the different paving blocks.

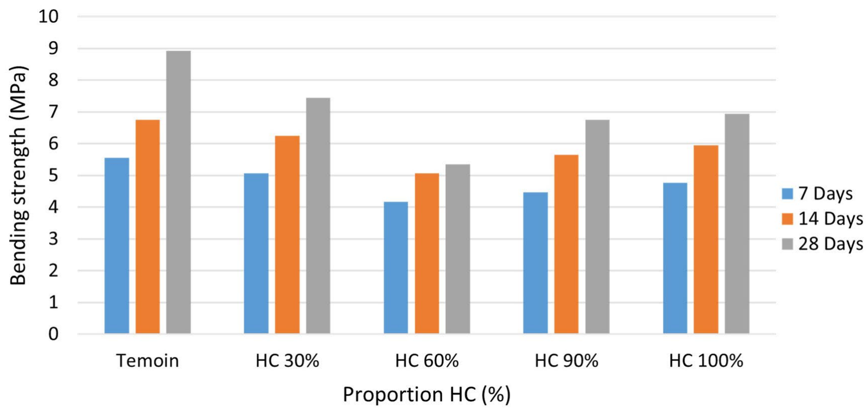

Figure 9. Bending resistance depending on the maturation time of the paving stones.

The results in Figure 8 show that the use of hardened cement aggregates in the paving specimens reduces the bending resistance. However, a general decrease with the increase in the proportion of recyclates is visible. It goes from 8.93 MPa, 7.44 MPa, 6.81 MPa, 6.74 MPa to 6.85 MPa respectively for 0 HC paving stones, 30 HC, 60 HC, 90 HC and 100 HC. This behavior was observed by [3] when he wanted to use recycled aggregates in concrete for paving and sidewalks. For Mari-Jo [28], this reduction in bending strength is due to the rapid breakage of the samples which is caused by the breakage of the recycled aggregates and also the compactness that exists between the grains.

The hardened cement aggregates are hard but when faced with impacts, they have linear cracking, which indicates that during the tests, the cracking plane of the samples crosses these hardened cement aggregates. However, the modulus of rupture is therefore controlled by the replacement rate and by the quality of the recycled aggregates used. It should also be noted that this resistance increases with maturation time. Also, according to [14], the flexural tensile strength at 28 days must be greater than 3.6 MPa. However, hardened cement paving stones have a bending strength between 6.74 MPa and 7.44 MPa. These results obtained are therefore higher than the recommended resistance.

- **Splitting tensile strength**

Figure 10 shows the results of splitting tensile strength from 7 to 28 days of different paving stones as a function of curing time.

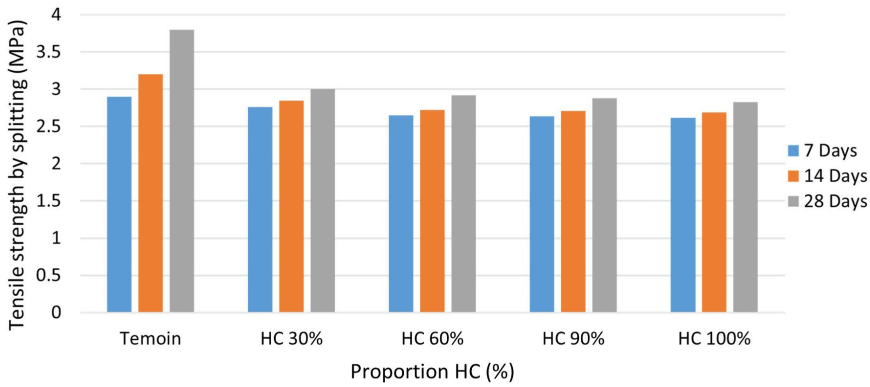

Figure 10. Tensile strength by splitting depending on the maturation time of the paving stones.

The results of the splitting traction test, as presented in **Figure 10**, indicate that the different series of paving stones (control, HC 30%, HC 60%, HC 90% and HC 100%) have a splitting resistance which increases as a function of time. maturation of each series and which generally decreases when the rate of hardened cement aggregates increases. Hence the presence of hardened cement aggregates considerably reduces the tensile strength by splitting. This can be explained by a lack of adhesion between the matrix and the substituted aggregate. These results are in agreement with those of [1], [21] and [29] who demonstrated the drop in tensile strength with the increase in the percentage of recycled aggregates. According to [14], the recommended splitting resistance is 2.6 MPa. However, the values of the paving stones are between 2.83 and 3.01 MPa at 28 days, which are higher than that recommended by the standard. Hardened cement aggregate paving stones therefore have good performance.

- **Wear resistance**

Figure 11 shows the wear of the paving stones (point depression) as a function of curing time.

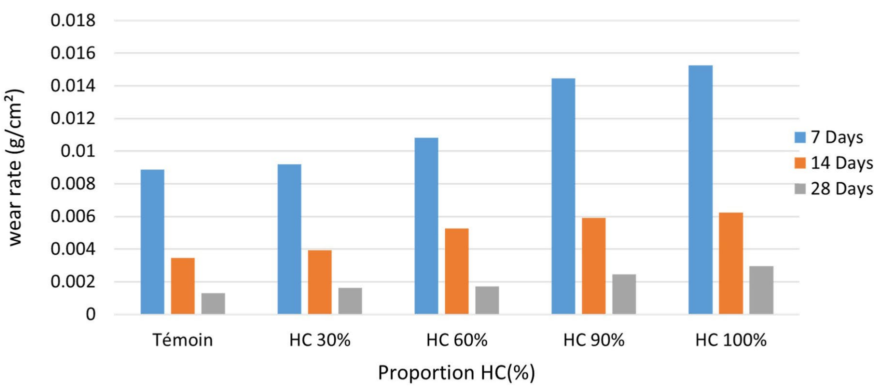

Figure 11. Abrasive wear rate of the paving stones depending on the maturation time of the paving stones.

According to **Figure 11**, the wear rate generally increases with the substitution rate of hardened cement aggregates. At 7 days of maturation, this progressive increase is 0.0089 g/cm^2 for the control and reaches a value around 0.0152 g/cm^2 for the paving stones containing 100% HC. At 14 days, the increase is from 0.0034 to 0.0062 g/cm^2 respectively for the control and the 100% HC paving stones and at 28 days it goes from 0.0013 to 0.0029 g/cm^2. Thus, the greater the quantity of hardened cement aggregate, the higher the wear rate. This is due to poor adhesion between the natural aggregates and the hardened cement aggregates and also the low resistance of the hardened cement aggregates observed during the wear test. For the control specimens, the cohesion between the particles is very strong, which therefore allows for better resistance to brushing.

4. Conclusion

This work made it possible to use hardened cement waste in the production of paving stones. It consisted of evaluating the influence of these aggregates in order to determine the right formulation to obtain a quality paving stone according to the required standards. The proportions of hardened cement (HC) are 0%, 30%, 60%, 90% and 100%. The results of the physical characterization of the hardened cement paving stones revealed that at 28 days, they had a high porosity and absorption rate compared to the controls, and a low dry density. These different physical parameters had a profound impact on the results of the mechanical properties, because the high porosity led to a drop in strength. The influence of the rate of substitution of natural aggregates by hardened cement aggregates on the physical and mechanical properties shows that paving stones containing 30% and 60% HC correspond to the best formulations. Consequently, these paving stones based on hardened cement aggregates can be used in buildings and on roads.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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