Case Studies in Construction Materials 15 (2021) e00634

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Case study

Mechanical properties of a mortar with melted plastic waste as the only binder: Influence of material composition and curing regime, and application in Bamako

Moussa Thiam [a], Mamadou Fall [a,*], M.S. Diarra [b]

[a] Department of Civil Engineering, University of Ottawa, Canada
[b] National Engineering School (ENI-ABT) of Mali, Bamako, Mali

ARTICLE INFO

Keywords:
Plastic waste
Pavers
Curing conditions
Aggregate size
Construction materials
Cement

ABSTRACT

In recent years, serious environmental problems induced by plastic wastes have drawn considerable attention across the world and new initiatives have been adopted to recycle plastic wastes into construction materials. One of the promising initiatives is the use of plastic waste as the only binding phase to make concrete/mortar-like construction materials. However, how key engineering properties of concrete/mortar-like materials with melted plastic as the only binder change with material composition and curing conditions are not well known. This paper aims to investigate the effect of curing conditions and granular material size on the mechanical properties (compressive and splitting tensile strengths) of a mortar with melted plastic waste (high density polyethylene (HDPE) and low density polyethylene (LDPE)) as the only binder (MPB: **m**ortar with melted **p**lastic waste **b**inder). Moreover, it presents a study conducted in the city of Bamako (Mali) to evaluate the use of MPB to make interlocking paving blocks for use on non-traffic areas in residential or municipal construction projects. Two curing conditions, namely, air dry at ambient temperature and water curing were used for this research. Moreover, the size of the granular materials (sand and gravel) was varied in order to assess its impact on the properties of the corresponding MPB sample formulations with given plastic content and HDPE/LDPE (H/L) ratio. Granular material size and curing conditions were found to have significant impact on the mechanical strengths of the MPB materials. Regardless of age and H/L ratio, the MPB samples cured in water showed lower strength (compressive and tensile) than the specimens cured at ambient temperature under controlled laboratory conditions, while adding coarse granular materials helped to improve these strength properties. Furthermore, the mechanical performance of the proposed MPB-interlocking paver is superior to that of the interlocking Portland cement-based pavers that are commercially available on the Bamako's market. Moreover, the cost of the Portland cement-less MPB-paver will be substantially lower than that of the Bamako's commercial Portland cement-paver. The obtained results place this MPB material as a promising candidate for making interlocking pavers or other products, while reducing the amount of plastic waste to be managed and the cost of interlocking pavers.

* Corresponding author at: Department of Civil Engineering, University of Ottawa, 161 Colonel by, Ottawa, Ontario, K1N 6N5, Canada.
E-mail address: mfall@uottawa.ca (M. Fall).

https://doi.org/10.1016/j.cscm.2021.e00634
Received 9 May 2021; Received in revised form 12 July 2021; Accepted 19 July 2021
Available online 21 July 2021

1. Introduction

The global demand for plastics was nearly 212 million tons in 2013 and was expected to reach 304 million tons by 2020 (GVR, 2015). Most of these plastics end up in the landfills and ocean, contributing to the pollution of the environment and endanger aquatic animals [1,2]. By considering wastes as resources instead of a problem to be solved, some researchers come up with alternatives providing social, environmental and economic benefits. Among these, is the use of plastics wastes (melted or not) to develop construction materials, such as mortar or concrete.

Indeed, several researchers (e.g., [3–11]) showed the possibility of using plastic waste aggregates as substitute of sand/gravel or additive (e.g., fiber) in concrete/mortar. With the density and compressive strength ranging between 1000–2000 kg/m^3 and 5–60 MPa, respectively, they come to the conclusion that the compressive strength decreases with an increase of plastic aggregate proportion in the given concrete/mortar when the replacement ratio is higher than 0.5 %, and the corresponding material is more resistant to cracks than the conventional concrete. Al-Manaseer and Dalal [12] observed ductile behaviour for concrete containing car bumpers plastic as aggregate, which contribute to reduce cracks in the corresponding concrete. Marzouk et al. [8] found that using plastic aggregates in concrete can lead to an attractive low-cost material, which can be an alternative to conventional concrete and contribute in solving solid wastes related problem, especially its high pollution. Soloaga et al. [13] observed lower emission (footprint) for 1 m^3 of concrete mix containing 20 % of plastic waste aggregates compared to the same amount of conventional concrete with natural aggregates.

In contrast to the studies devoted to the incorporation of plastic waste in concrete as aggregates or additives, there is a scarcity of studies on the use of plastic as a binder in mortar or concrete materials. In recent years, some initiatives have been proposed to use melted plastic wastes to form different products, such as road signs, soil pavers, slabs for gutters and latrines (e.g., [14–17]). Doublier et al. [14] proposed various examples of artisanal products (paving materials) that use plastic waste as the binding phase. Moreover, some previous studies (e.g., [18–21]) assessed the use of an unsaturated polyester resin (derived from recycling polyethylene terephthalate (PET) by a glycolysis process) as the only binding phase to develop concrete or mortar materials. The results obtained indicated an increase in compressive strength with increasing resin content. A refinement of the pore structure or porosity reduction due to the use of resin was also observed. However, the high cost and high energy requirement related to the preparation of the unsaturated polyester resin have restricted the application of the aforementioned polyester resin concrete materials in building and construction practice. Moreover, the other types of plastic wastes (high density polyethylene (HDPE), low density polyethylene (LHPE)) were ignored in the aforementioned studies. Thus, other researchers (e.g., [15,16,22]) performed experimental studies to assess the potential use of recycled plastics (e.g., HDPE, Polypropylene (PP)) to make recycle plastic-only bounded cemented materials/structures, such as pavers. They obtained encouraging results with respect to the mechanical performance of the proposed cement-less concrete. However, long curing time ($\geq$2.0 h) at high temperatures ($\geq$195 °C) is required in most of the previous studies to prepare the proposed recycle plastic-only bounded concrete. This high energy consumption associated with this curing time negatively impacts the cost of this product, thereby impeding its quick adoption in construction practice.

Thus, Thiam and Fall [23] developed a less-energy intensive method or technology, in which melted (recycled) low density polyethylene (LDPE) and high density polyethylene (HDPE) as the only binder are used to make mortar-like material, i.e. mortar with melted plastic waste binder (MPB: **m**ortar with melted **p**lastic waste **b**inder). Their results showed that the strength of the MPB can reach a value of up to 18 MPa depending on the curing time, HDPE/LDPE ratio and the plastic content. These interesting mechanical properties of the MPB would make it suitable for many construction and buildings applications, however a fundamental understanding of the effect of key influencing factors on the mechanical properties (strength, deformation behavior) of MPB is still far from complete. For example, what is the effect of different granular material size on the mechanical (compressive, splitting) strength of MPB? How would different curing conditions (ambient air, water curing) affect the mechanical strength of MPB? To date, there is no investigation that addresses these key design or material performance issues. It is timely to address this research gap. Addressing the above-mentioned questions or issues is crucial for reliably assessing the performance of the MPB and its suitability for construction application.

Hence, the main objective of the present manuscript is to present and discuss the results of the experimental investigations carried

Fig. 1. Samples of a) HDPE and b) LDPE plastic wastes used during the experiments.

out:

- to assess the effect of curing conditions (ambient air, water curing) on the mechanical (uniaxial compressive strength, splitting tensile strength) properties of MPB;
- to evaluate the effect of grain size distribution of the granular material on the mechanical properties of MPB.

Moreover, the potential use of the proposed construction material (MPB) to produce interlocking paving blocks for use on non-traffic areas will be evaluated and discussed.

2. Experimental program

2.1. Materials

2.1.1. Plastic wastes

High-density polyethylene (HDPE) and low-density polyethylene (LDPE) plastic wastes (Fig. 1), collected from wastes transit stations in Bamako (Mali), washed and cut to the corresponding sizes for experiment purposes, were used to prepare the MPB specimens.

2.1.2. Granular material

Natural sand form Niger River in Bamako (Mali) (Fig. 2) was used as natural aggregates for preparing the MPB samples. The grain size distribution of the sampled natural sand, determined according to ASTM C136 / C136 M, is shown in Fig. 3. The sampled sand was sieved to create two gran size classes corresponding to (finer) sand, S (< 2 mm) and GS granular material (composed of 70 % of sand (< 2 mm) and 30 % of coarse material between 2 mm and 4.75 mm) for various formulations of the MPB specimens (Fig. 3).

2.2. Preparation and curing methods of the MPB samples

Natural river sand and gravel, as the only mineral aggregates, were mixed with different proportions of molten HDPE and LDPE using the optimal plastic contents for mortar with plastic binder determined by Thiam and Fall [23]. Plastic materials in small pieces (less than 6 cm in length) and dried granular materials (sand and gravel) were employed to prepare MPB samples with various plastic contents and H/L ratios. The size of the granular material was varied to understand the effect of the particle fineness or coarseness on the mechanical strength of the MPB. The coarser granular material, called GS, contains of 70 % of finer sand (< 2 mm) and 30 % of sand and gravel (2 mm < size < 4.75 mm), whereas the finer granular material (S) consists of 100 % of finer sand (< 2 mm) (Fig. 3).

A plastic content of 50 % of total dry mass of granular material and three HDPE/LDPE ratios (H/L of 40/60, 50/50 and 60/40) were employed and melted in the oven. The mix design compositions of various MPB samples are presented in Table 1. The melting time took 20−45 min depending on the type and amount of plastic. The plastic melting temperature was found to be about 250 °C for an initial ambient temperature between 24–30 °C. Cylindrical samples (10 cm in diameter and 20 cm in height) were prepared and cured under different conditions for the purpose of the experiments (Fig. 4). Prior to pouring the liquid MPB, the inner surface of the cylindrical molds was coated with lubricant to facilitate extraction. Once granular material was added to the melted plastic and mixed, the obtained homogeneous MPB paste is poured into the molds and kept under pressure using manual press to ensure proper compaction and limit sagging. Half an hour later the various MPB specimens were demolded and cured for 1, 3, 7 and 28 days. After the specific curing times, the MPB specimens were subjected to various tests as described later.

The MPB specimens were cured under two different conditions or regimes, ambient air curing and water curing. A set of the prepared MPB samples were allowed to cure under laboratory-controlled ambient temperature conditions (about 27 °C). Another set of hot MPB samples were subjected to water curing. This water curing enables to achieve a rapid or faster cooling of the initially hot MPB

Fig. 2. The location and sample of the sand used during the experiments.

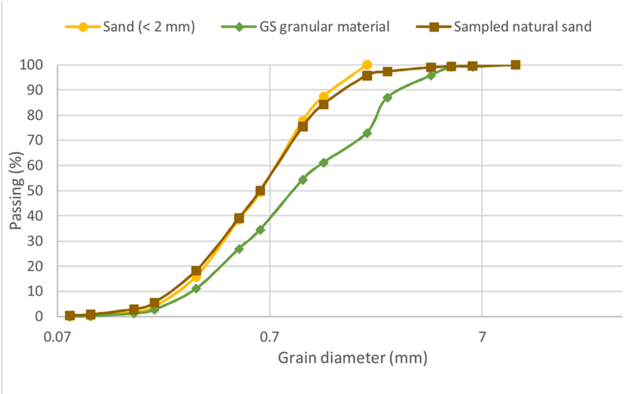


Fig. 3. The particle size distribution of the sampled sand and used granular materials for MPB preparation.

Table 1
Mix composition and curing time of the MPB using melted HDPE and LDPE plastic wastes as the only binder.

Mortar with plastic binder sample*	Plastic binder type	Plastic binder content (%)	HDPE / LDPE	Granular material	Curing time (days)
S 50 % P – H/L 60/40	HDPE – LDPE	50	60/40	Sand	1, 3, 7, 28
S 50 % P – H/L 50/50	HDPE – LDPE	50	50/50	Sand	1, 3, 7, 28
S 50 % P – H/L 40/60	HDPE – LDPE	50	40/60	Sand	1, 3, 7, 28
GS50 % P – H/L 50/50	HDPE – LDPE	50	50/50	Sand-Gravel	1, 3, 7, 28

P: plastic content in in (wt %) by reference to the dry mass of sand, H/L ratio of HDPE to LDPE. * The letters S at the beginning of the sample names refer to MPB, which has only sand smaller than 2 mm in their composition. The samples commencing with GS correspond to MPB samples prepared using 70 % of sand (smaller than 2 mm) and 30 % of sand and gravel (which sizes are between 2 to 4.75 mm).

Fig. 4. Samples of MPB with melted plastic wastes as binder.

samples. This was done by immersing the specimens in fresh water tanks (initial temperature of the water was about 26 °C) right after pouring and compacting them in the molds and kept in for a period of time before the test. These samples have the same nomenclature as the ones in the Table 1, with the letter "W" appended at the end of the sample name.

2.3. Testing of the MPB specimens

2.3.1. Mechanical tests

Uniaxial compression and split tensile tests were performed on the MPB samples. ASTM C39 / C39 M – 18 and ASTM C496 / C496 M – 17 instructions were followed for the determination of the compressive and splitting tensile strengths, respectively. The tests were performed at a rate of 1 mm/min to record the deformations under variable applied force until reaching the failure and/or full disintegration. Each mechanical test was repeated at least two times to ensure the repeatability of the results.

2.3.2. Microstructural analyses and tests

Two different techniques were combined to gain insight into the microstructure (pore structure) of the studied MPB samples. These techniques include scanning electron microscopy (SEM) observations and water absorption tests.

The SEM observations were carried out on relatively square MPB specimens by using the Joel JSM-6610LV scanning electron microscope. Prior to SEM examinations, the MPB specimens were cut and carbon coated. SEM examinations with different magnifications were used to evaluate the pore structure/porosity of the MPB, its morphology and texture.

Water absorption tests were conducted on MPB samples to indirectly determine the fineness or coarseness of their pore structure or porosity. Indeed, the permeation properties of a porous material is strongly dependent on its pore structure [24]. In other words, the results or parameters (e.g., sorptivity, capillary water absorption) gained by conducting absorption tests give information about the pore structure inside a porous medium, and thus, the ease with which fluids can enter into and move through this porous medium [25,26]. The MPB samples for water absorption test were dried in the oven at 60 °C for two days to eliminate of any water they might contain. Then, the samples were immersed in distilled water tanks for 48 h to determine the immersion absorption in accordance to ASTM C97 / C97 M – 18 specifications. The rate of absorption by immersion in percentage (%), is equal to the difference between the weight of the sample after 48 h and the initial weight divided by the initial weight.

2.3.3. Hardened density tests

The mechanical strength of cemented material (e.g., concrete, mortar) is highly influenced by its hardened density. A denser cemented material usually provides higher strength and less amount of voids and lower porosity [27,28]. Therefore, the hardened density of various MPB samples was determined using ASTM C 138 / C138 M - 17a procedures. Each density value for various formulations was determined as an average of at least three measurements from different samples to ensure the repeatability of the results.

3. Results and discussion

3.1. Impact of curing conditions on the mechanical properties of MPB

Figs. 5 highlights the impact of curing conditions on the development of the uniaxial compressive strength of MPB samples with different HDPE/LDPE (H/L) ratios.

From this figure, it is obvious that, irrespective of the curing regime and sample composition, the compressive strength of the MPB increases with time. For example, the 28-day compressive strength of the MPB is 1.6–2.9 times higher than that of the 1-day sample, representing a strength increase of approximately 60%–180%, respective. This increase is mainly related to the increase of the degree of crystallinity and solidification of the used polymer blend (HDPE/LDPE) as the cooling time increases [23,29–31]. It is well-established that LDPE and HDPE are both semicrystalline polymers (degree of crystallinity is higher in HDPE, due to the different number of polymer branches) and their degree of crystallinity increases as the polymers cool down or solidify, thereby enhancing their strength or cementation ability [23,29,30].

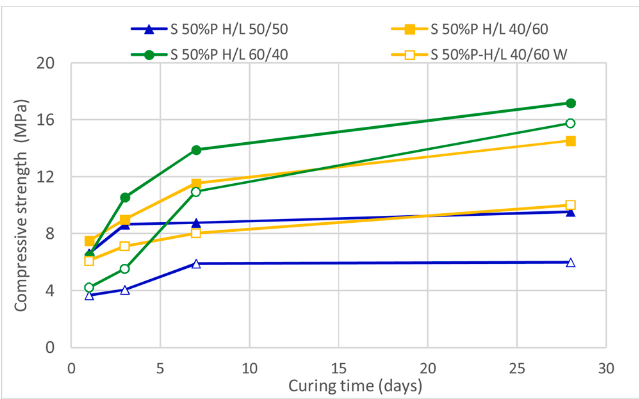


Fig. 5. Effect of curing conditions on the compressive strength development vs time of MPB for various HDPE/LDPE ratios.

Furthermore, Fig. 5 shows that, regardless of age and H/L ratio, the MPB samples subjected to water curing showed lower compressive strength (up to 45 % lower) than the specimens cured at ambient air temperature (Fig. 5); in other words, ambient air curing is superior to water curing for the studied MPB specimens. The water curing induced reductions of 28 day-compressive strengths were about 10%–45% depending on the H/L ratio. This indicates that the curing regime has a significant impact on the MPB compressive strength.

This reduction in compressive strength due to the water curing can be attributed to the difference in cooling rate of the MPB specimens. MPB specimens cured in the fresh water were subjected to a faster cooling rate than samples cured under ambient air temperature. This because water's (0.6 W/(m·K) thermal conductivity is higher than air's (0.025 W/(m·K)), in other words, water transfers heat 24 times faster than air [32].

This faster cooling rate results in a decrease of the degree crystallinity of the plastic waste binder of the MPB cured in water, thereby reducing the cementation effect of the plastic binder. This argument is supported by the results of numerous previous experimental studies on the effect of cooling rate on the degree of crystallinity and properties of polymer HDPE/LDPE blends (e.g., [33,34]). These studies concluded that fast cooled HDPE/LDPE blends exhibit lower crystallinity and mechanical properties (e.g, Young modulus) than slow cooled polymer blends.

The coarsening of the pore structure of the MPB due to faster cooling is an additional factor that contributes to the decrease of strength for the samples cured in water. Indeed, the water (at 26 °C) in contact with MPB specimens (at temperatures higher than 100 °C), will create a temperature difference of more than 70 °C or a thermal shock, thereby impacting the internal pore structure and the interfacial transition zone (ITZ) within the MPB sample body ([35]; Mehta and Monteiro, 2006; [31,36–39]). Thus, the higher temperature difference and cooling rate imposed to MPB in water will lead to the development of tensile stress within the sample body, contributing to weakening the ITZ between different constituents' elements of the MPB and creating cracks, subsequently increasing its porosity, which, in turn, affect its strength properties [39,40].

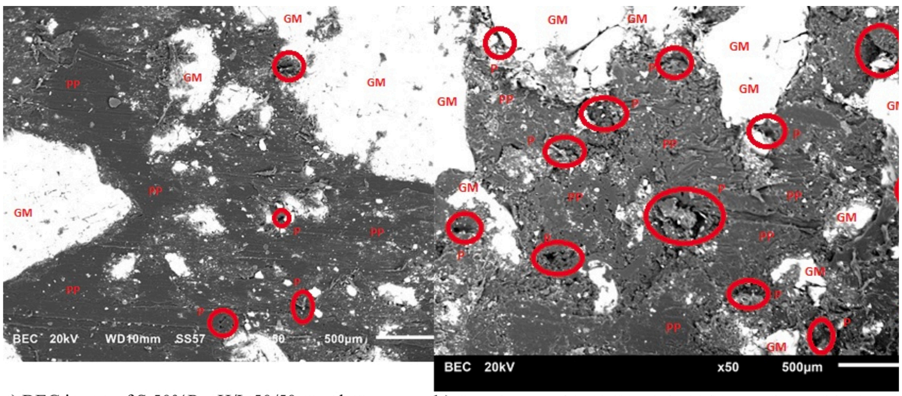
This temperature gradient and faster cooling rate difference induced coarsening of the pore structure of MPB is consistent with the results of SEM observations and absorption tests performed on MPBs subjected to different curing conditions, which are presented in Fig. 6 and Fig. 7, respectively. Fig. 6 presents SEM images of MPBs cured at ambient temperature and other subjected to water curing (thermal shock). More and lager voids/pores can be observed on the sample cured in water, which can be related to the sudden cooling or curing and the fact that all the MPB constituents do not have enough time to solidify properly and bind as it should be with required time [30,31,35,37,41]. Fig. 7 presents the influence of curing conditions on the immersion absorption behaviour up to 48 h for MPBs with equal amount of HDPE and LPDE. The absorption values are higher for MPB that was subjected to water curing (thermal shock), confirming its higher porosity and pores interconnectivity. For example, after 2-day immersion, the absorption value for the MPB subjected to thermal shock was 6.5 times higher than that for the MPB cured under ambient air conditions.

Fig. 8 illustrates the variations of splitting tensile strength with time of MPBs subjected to different curing conditions. The tensile strength of MPB samples subjected to thermal shock or water curing was found to be lower than that of the samples cured at ambient temperature regardless of age and H/L ratio. The magnitude of the decrease is in the range of 0.22–1.99 MPa in absolute values corresponding to the relative values of 10%–143%. The reasons for that decrease are the same as pointed out for the compressive strength above.

3.2. *Impact of fineness of granular materials on the mechanical properties of MPB*

Figs. 9 and 10 present the impact of granular material size on the compressive and splitting tensile strengths of MPB samples with 50 % of plastic content and H/L ratio of 50/50, respectively, and cured at ambient air temperature.

From Figs. 9,10, it can be observed that the MPB specimens made with coarser granular material (GS), i.e. coarser sand material,



a) BEC image of S 50%P – H/L 50/50 cured at ambient temperature

b) BEC image of S 50%P – H/L 50/50 cured at ambient temperature

Fig. 6. SEM (BEC) images magnified x50 of MPB cured (a) under ambient air temperature and (b) in water (GM: granular material, sand/gravel; PP: plastic paste; P: pore; BEC: Backscattered electron composition image).

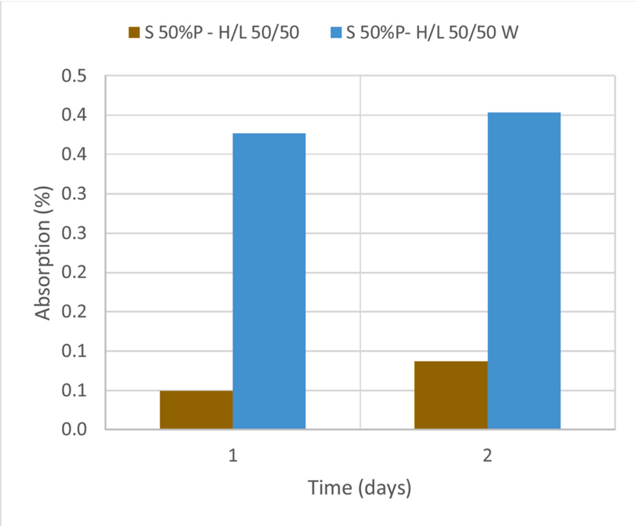


Fig. 7. Effect of ambient air temperature curing and water curing (W) on the water absorption by immersion vs time for MPB.

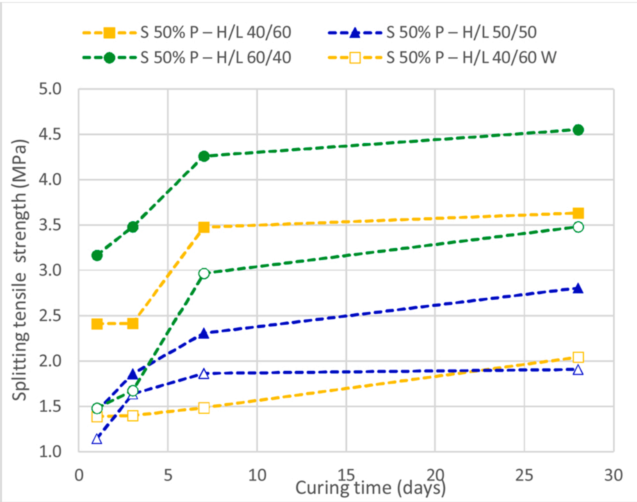


Fig. 8. Effect of curing conditions on the splitting tensile strength development of MPB.

show higher uniaxial compressive and splitting tensile strengths than those made with finer sand material (S). For instance, the compressive strength of the MPBs with GS is 50–60% higher than that of the samples with S. These higher strengths of the MPBs made with GS are due to the fact that the presence of coarser particles (gravel particle) in the GS material increases the packing density of the granular material, thereby increasing the hardened density of the MPB with GS. Higher hardened density is obviously associated with lower porosity of the construction material, which, in turn, leads to higher strength of the material (Mehta, 1986; [9,42]; Uysal et al., 2012; [43–45]). This argument related to the increase of the hardened density of the MPB with GS is experimentally supported by the results of the assessment of the impact of granular material size on the hardened density of MPB presented in Fig. 11. This figure shows that the density of MPB samples with GS is higher than that of MPB containing only fine grain aggregates (S). Indeed, with the presence of finer sand and larger grain particles (e.g., gravel) in the GS material, the small grains will occupy the void left by the large grains during the compaction with the applied force allowing to get close to the denser configuration. Further studies will be needed in the future to gain deeper insight into the impact of replacing fine sand with larger granular material.

3.3. *Further discussion and potential application of MPB as paving blocks for use on non-traffic areas*

The experimental results presented above allow fundamental knowledge to be gained about the strengths of MPBs as well as a better understanding of the impact of granular material size and curing conditions on their mechanical properties, which are critical technical information/data for optimal design and application of this proposed material in construction practice. The results obtained

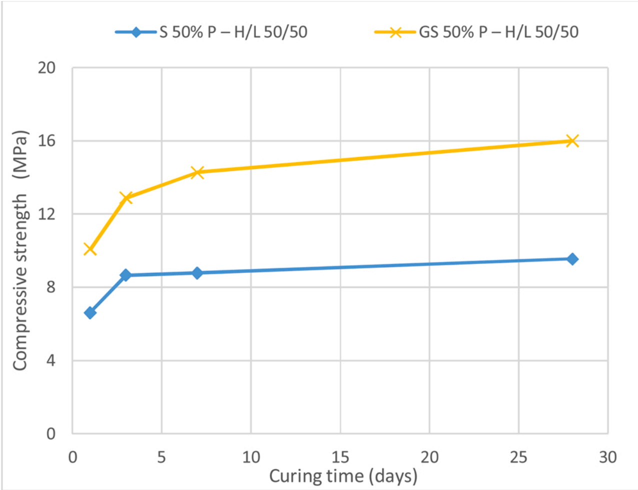


Fig. 9. Effect of granular material coarseness on the compressive strength development of MPB (The letters S at the beginning of the sample names refer to MPB, which has only sand smaller than 2 mm in their composition. The samples commencing with GS correspond to MPB samples prepared using 70 % of sand (smaller than 2 mm) and 30 % of sand and gravel (which sizes are between 2 to 4.75 mm)).

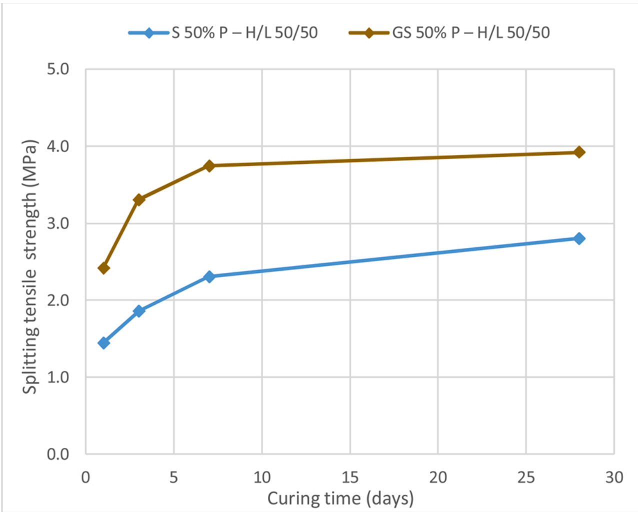


Fig. 10. Effect of granular material coarseness on the splitting tensile strength development of MPB.

suggest that ambient air temperature should be the preferred curing conditions for MPBs to achieve better mechanical properties. This means that neither the production of this construction material nor its curing requires water, which is a valuable benefit in many regions of the world that are facing fresh water scarcity, including many West-African countries. Moreover, the absence of Portland cement in the composition of MPB would offer significant economic benefits, particularly in developing countries, where high Portland cement prices often hinder many construction projects for local communities. Furthermore, the full replacement of Portland cement by plastic wastes, such HDPE and LDPE, would provide significant social, environmental and economic benefits in many developing countries in the world. Indeed, turning (HDPE or LDPE) plastic wastes into binding phase for construction materials would not only significantly reduce major environmental problems induced by plastic wastes (e.g. LDPE sheets, bags and water sachets) in developing countries, but can also contribute to create jobs and lead to community-driven waste management initiative that would impact local communities and local waste management.

From the results obtained and discussion above, it can be deduced that the possibilities of using MPB as construction materials, particularly in developing countries, appear to be very promising owing to their good mechanical properties and potential benefits discussed above. MPB could be appealing to costumers and local communities for the production of non-structural concrete-like materials. Consequently, a study was conducted in a local community in Bamako (Mali) to evaluate the use of MPB to make interlocking paving blocks for use on non-traffic areas in residential or municipal construction projects. In Mali and many other West-African countries (e.g., Senegal, Ivory Coast), interlocking paving blocks are highly demanded for use on non-traffic areas, such as

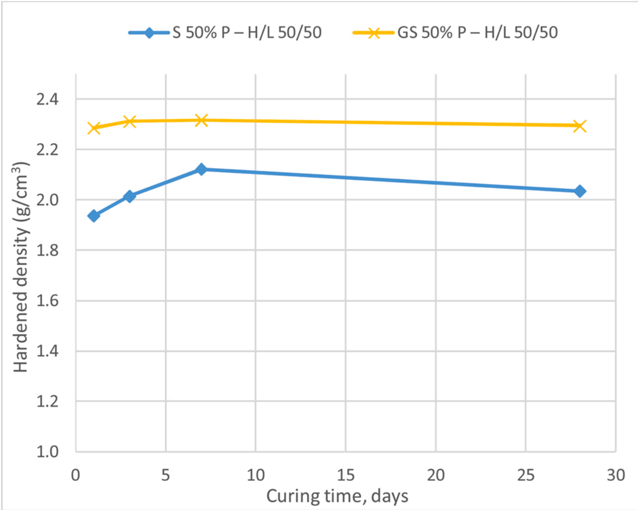


Fig. 11. Effect of the coarseness of the granular material on the hardened density development of MPB samples.

backyard paving, walkways, sidewalks, patios, a walkway through city park and playgrounds.

In this study, some interlocking pavers were made using the developed MPB material. Moreover, some conventional Portland cement-based pavers, which are available commercially on Bamako's market, were used as a control, in other words, to understand how the mechanical properties of the proposed MPB-pavers differ from those of the conventional Portland cement-pavers that are on sale on the Bamako's market. The fresh MPB material was prepared in the same manner as that described in Section 2.2. The mix composition of the MPB includes the GS granular material, a H/L ratio of 50/50 and plastic content of 50 %. The hot MPB material was cast into 180 × 180 × 40 mm steel moulds (Fig. 12a) that had been priory coated with lubricant to facilitate extraction. The moulds filled with MPB were then compacted with a mechanical press, sealed and subsequently cured under air ambient temperature for 28 days. Fig. 12 shows the used steel moulds (Fig. 12a), typical interlocking block pavers made from MPB (Fig. 12b), typical Portland cement-pavers on sale on the Bamako's market (Fig. 12c) and an example of house courtyard in Bamako (Fig. 12d) with interlocking MPB-pavers.

Mechanical tests (compressive and split tensile strengths tests) were conducted on the 28 day old MPB-paving block specimens to determine their uniaxial compressive and splitting tensile strengths as well as their deformation behavior (stress-strain behavior). Compressive and split tensile strength tests were performed according to ASTM C 140-90 and BS (BS EN 1338).

Fig. 13 shows typical compressive stress-strain behaviour curves of the studied MPB-paving block and Bamako's commercial paving bock (control). As it can be observed from Fig. 13, the MPB-paver sample is able to support much higher loads than the control sample. Indeed, the average peak strength of the MPB-paver samples was found to be equal to 16 MPa, whereas that of the control samples was found to be 8 MPa. Moreover, the control paver sustained much lesser stain under similar compressive loading than the MPB-paver. After the peak stress value, full disintegration with brittle failure was observed for the Bamako's (commercial) cement-based paver, while ductile behaviour with gradual deformation capable of supporting loads for a certain period of time after failure was observed for the MPB-paver, as illustrated in Fig. 14. This figure displays samples of MPB-pavers and Bamako's commercial Portland cement-pavers before and after testing for compressive strength, from which the mode of failure of the studied paving blocks can be evaluated. It can be observed that the control paver is fully disintegrated or broken after failure and its cracking pattern is well defined, confirming the brittle behavior of and rapid propagation of cracks through the studied cement-based paver. In opposite, the MPB-paver shows no disintegration after failure and is still able to support some load in the post-failure stage. This behavior is related to the ductile behavior of the MPB-paver due to the presence of melted plastic waste [23]. The ductile behaviour of MPB-pavers will be of great benefit towards the prevention of cracks and improvement of the durability of pavers on non-traffic areas. The results for splitting tensile strength also indicated that the splitting tensile strength of the MPB-paver sample (5.1 MPa) is higher than that of the Bamako's (commercial) paver (1.6 MPa). From the results of the mechanical tests presented above, it can be concluded that the mechanical performance of the proposed MPB-interlocking paver is superior to that of the interlocking cement-based pavers that are commercially available on the Bamako's market. Moreover, the cost of the proposed Portland cement-less MPB-paver for use on non-traffic areas will be substantially lower than that of the Portland cement-pavers that are available on the Bamako's market, since Portland cement is one of the key factors that significantly affect the price of interlocking pavers.

4. Summary and conclusions

In this paper, experimental program has been conducted to study the effect of curing conditions and fineness of granular materials on the mechanical properties of MPB samples with melted plastic contents waste (HDPE and LDPE) as the only binder with various H/L ratios. Moreover, the potential application of MPB as paving blocks for use on non-traffic areas has been discussed. The results led to

Fig. 12. (a) Used steel moulds for the MPB-pavers, (b) typical interlocking block pavers made from MPB, (c) typical Portland cement-pavers on sale on the Bamako's market, and (c) an example of house courtyard in Bamako with interlocking MPB-pavers.

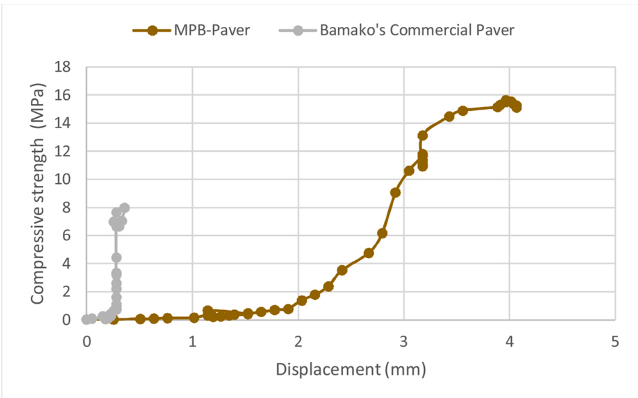


Fig. 13. Compressive stress-strain behaviour of the MPB-paver and Bamako's commercial Portland cement-based paver.

the following conclusions:

- Curing conditions was found to have a significant impact on the compressive and splitting tensile strengths of MPB. Ambient air temperature curing condition is superior to curing in water. Curing MPB samples in water decreases their compressive and splitting tensile strengths. This decrease in the strength of MPB samples cured in water, which is linked to increased porosity and coarser pore structure due to faster cooling rate of the samples cured in water, are in good correlation with the SEM observation and water absorption test results. The samples with lower strength were observed to have higher rate of absorption and coarser pore structure.
- The grain size distribution of the mineral aggregates plays a significant role in the mechanical performance of the MPB material. Adding 30 % of granular material (sand and gravel), with grain-size in the range of 2–4.75 mm, to a sand material, with grain size lower than 2 mm, significantly increases the compressive and the splitting tensile strengths of the MPB. This strength increase is

a) MPB-pavers before (left) and after (right) compressive strength tests

b) Portland cement-based pavers from the Bamako's market before (right) and after (left) compressive strength tests

Fig. 14. a) MPB-pavers and b) Portland cement-based pavers before and after compressive strength tests.

mainly related to the improvement of the packing density of the mineral aggregates, which, in turn, results in the production of MPBs with higher hardened density.

- The mechanical performance (compressive and splitting strengths, deformation behavior) of the MPB-based interlocking paver is superior to that of the interlocking cement-based pavers that are commercially available on the Bamako's market. The MPB-paver shows interesting post peak strength and its deformation is ductile compared to the brittle behaviour observed in the Bamako's Portland-cement pavers. Even after the failure, the MPB-paver is able to sustain some load. It is anticipated that the cost of this Portland cement-less MPB-paver will be significantly lower than that of the Bamako's Portland cement-paver, since Portland cement is one of the key factors that considerably affect the price of interlocking pavers.

The findings from this study are encouraging and offers basis for further research on the properties of MPB for extending its applications in the construction field. This work reinforces our pursuit to valorize plastic wastes in the construction sector by using it as a binder to develop new type of construction materials, which are cost effective and contribute towards protecting the environment from plastic wastes related problems as well as creating jobs in the local communities. Furthermore, the preparation method of this construction material is simple and requires only a low amount of energy. Additionally, no water is needed to make the MPB, which is a valuable characteristic in regions that are affected by water scarcity. However, further studies are still needed to fully understand the long-term behaviour of this product in order to ensure its optimal use for future large-scale commercial applications. It is also vital to study the life cycle and cost analysis of the MPB for a large scale production. Furthermore, for industrial or commercial application of the proposed MPB-paver technology, it would be important to consider that the gas produced during the melting of the plastic waste should be treated by using suitable techniques (e.g., scrubbing gas treatment) before being released into the atmosphere. This treatment will hinder any potential effect of the gas released on human health.

Declaration of Competing Interest

The authors report no declarations of interest.

References

[1] M. Abukhettala, M. Fall, Mechanical characteristcs of road subbase materials that contain plastic waste, in: Proc. 4th International Conference on Civil, Structural and Transportation Engineering (ICCSTE'19), June 11-12, Ottawa, Canada, 2019.
[2] M. Abukhettala, M. Fall, Geotechnical characterization of plastic waste materials in pavement subgrade applications, Transp. Geotech. 27 (2021), 100472.
[3] K.S. Rebeiz, Precast use of polymer concrete using unsaturated polyester resin based on recycled PET waste, Constr. Build. Mater. 10 (3) (1996) 215–220.
[4] P. Soroushian, A.I. Eldarwish, A. Tlili, K. Ostowari, Experimental investigation of the optimized use of plastic flakes in normal-weight concrete, Mag. Concr. Res. 51 (1) (1999) 27–33.

[5] T.D. Sam, M.N. Tam, Polymer concrete based on recycled polyethylene terephthalate (PET). NOCMAT/3, Vietnam International Conference on Non-Conventional Material and Technologies (2002) 226–228.
[6] Y.W. Choi, D.J. Moon, J.S. Chung, S.K. Cho, Effects of waste PET bottles aggregate on the properties of concrete, Cem. Concr. Res. 35 (4) (2005) 776–781.
[7] M. Batayneh, I. Marie, I. Asi, Use of selected waste materials in concrete mixes, Waste Manag. 27 (12) (2007) 1870–1876.
[8] O.Y. Marzouk, R.M. Dheilly, M. Queneudec, Valorization of post-consumer waste plastic in cementitious concrete composites, Waste Manage. 27 (2007) 310–318.
[9] S.C. Kou, G. Lee, C.S. Poon, W.L. Lai, Properties of lightweight aggregate concrete prepared with PVC granules derived from scraped PVC pipes, Waste Manag. 29 (2) (2009) 621–628.
[10] H.M. Adnan, A.O. Dawood, Strength behavior of reinforced concrete beam using re-cycle of PET wastes as synthetic fibers, Case Stud. Constr. Mater. 13 (2020), e00367.
[11] A. Merlo, L. Lavagna, D. Suarez-Riera, M. Pavese, Mechanical properties of mortar containing waste plastic (PVC) as aggregate partial replacement, Case Stud. Constr. Mater. 13 (2020), e00467.
[12] A.A. Al-Manaseer, T.R. Dalal, Concrete containing plastic aggregates, Concr. Int. 19 (8) (1997) 47–52.
[13] I.S. Soloaga, A. Oshiro, M. Positieri, The use of recycled plastic in concrete. An alternative to reduce the ecological footprint, Rev. Constr. 13 (2014) 19–26.
[14] G. Doublier, M. Bowler-Ailloud, O. Sorgho, Valorisation des déchets de sachets plastiques, in: Utilisation comme liant dans la fabrication de matériaux composites : Application dans les villes subsahariennes. Conférence Internationale sur la Valorisation des Déchets et de la Biomasse Résiduelle dans les Pays en Développement, 9 11 Juillet 2009 – Ouagadougou, Burkina Faso, 2009.
[15] A.K.L. Jnr, D. Yunana, P. Kamsouloum, M. Webster, D.C. Wilson, C. Cheeseman, Recycling waste plastics in developing countries: use of low-density polyethylene water sachets to form plastic bonded sand blocks, Waste Manag. 80 (2018) 112–118.
[16] S. Agyeman, N.K. Obeng-Ahenkora, S. Assiamah, G. Twumasi, Exploiting recycled plastic waste as an alternative binder for paving blocks production, Case Stud. Constr. Mater. 11 (2019), e00246.
[17] A. Horáková, J. Novák, Utilization of recycled plastic for plastic-based concrete, in: IOP Conference Series: Materials Science and Engineering, Volume 596, FIBRE CONCRETE 2019 17–20 September 2019, Prague, Czech Republic, 2019.
[18] F. Mahdi, H. Abbas, A.A. Khan, Strength characteristics of polymer mortar and concrete using different compositions of resins derived from post-consumer PET bottles, Constr. Build. Mater. 24 (1) (2010) 25–36.
[19] J.M.M. Vidales, L.N. Hernández, J.I.T. López, E.E.M. Flores, L.S. Hernández, Polymer mortars prepared using a polymeric resin and particles obtained from waste pet bottle, Constr. Build. Mater. 65 (2014) 376–383.
[20] J.M. Mendivil-Escalante, J.M. Gómez-Soberón, A.J.L. Sánchez, Metamorphosis in the porosity of recycled concretes through the use of a recycled polyethylene terephthalate (PET) additive, Correlations between the porous network and concrete properties, Materials (Basel) 10 (2) (2017) 176–195.
[21] N.N.A. Tukimat, N.N. Sarbini, I.S. Ibrahim, Fresh and hardened state of polymer modified concrete and mortars – a review, International Symposium on Civil and Environmental Engineering 2016. MATEC Web Conf. Volume 103, 2017 (2017). Article Number 01025, pages 10, Section: Sustainable and Advanced Construction Materials, Published online: 5 April 2017.
[22] M.A. Dalhat, H.A.A. Wahhab, Cement-less and asphalt-less concrete bounded by recycled plastic, Constr. Build. Mater. 119 (2016) 206–214.
[23] M. Thiam, M. Fall, Mechanical, physical and microstructural properties of a mortar with melted plastic waste binder, Unpublished, Constr. Build. Mater. (2020).
[24] Z. Aldhafeeri, M. Fall, Sulphate induced changes in the reactivity of cemented tailings backfill, Int. J. Miner. Process. 166 (2017) 13–23.
[25] M. Fall, S.S. Samb, Pore structure of cemented tailings materials under natural or accidental thermal loads, Mater. Charact. 59 (5) (2008) 598–605.
[26] M. Fall, S.S. Samb, Effect of high temperature on strength and microstructural properties of cemented paste backfill, Fire Saf. J. 44 (4) (2009) 642–651.
[27] K. Fang, M. Fall, Shear behavior of the interface between rock and cemented backfill: effect of curing stress, drainage condition and backfilling rate, Rock Mech. Rock Eng. 53 (1) (2020) 325–336.
[28] P.K. Metha, Concrete: Structure, Properties and Materials, Prentice-Hall Inc, Englewood Cliffs, 1986.
[29] X. Sun, Y. Chu, Y. Mo, S. Fan, S. Liao, Experimental investigations on the heat transfer of melting phase change material (PCM), Energy Procedia 152 (2018) 186–191.
[30] D.J. da Silva, H. Wiebeck, Using PLS, iPLS and siPLS linear regressions to determine the composition of LDPE/HDPE blends: a comparison between confocal Raman and ATR-FTIR spectroscopies, Vib. Spectrosc. 92 (2017) 259–266.
[31] K. Ragaert, L. Delva, K. Van Geem, Mechanical and chemical recycling of solid plastic waste, Waste Manag. 69 (2017) 24–58.
[32] Y.S. Toulouklan, P.E. Liley, S.E. Saxena, Thermal Conductivity - Noometalllc Liquids and Gases. Data Book, TPRC Data Series/Vol. 3, 707 pp., 1970.
[33] E. Quero, C.C. Puig, C. Albano, A. Karam, Γ-radiation (0-150 KGy) effects on slow and fast cooled HDPE/LDPE blends, Polym. Bull. 59 (2007) 517–526.
[34] J. Minick, A. Moet, E. Baer, Morphology of HDPE/LDPE blends with different thermal histories, Polymer 36 (10) (1995) 1923–1932.
[35] D. Braun, Recycling of PVC, Prog. Polym. Sci. 27 (10) (2002) 2171–2195.
[36] A. Darquennes, S. Staquet, M.P. Delplancke-Ogletree, B. Espion, Effect of autogenous deformation on the cracking risk of slag cement concretes, Cem. Concr. Compos. 33 (3) (2011) 368–379.
[37] N. Volk, R. He, K. Magniez, Enhanced homogeneity and interfacial compatibility in melt-extruded cellulose nano-fibers reinforced polyethylene via surface adsorption of poly (ethylene glycol)-block-poly (ethylene) amphiphiles, Eur. Polym. J. 72 (2015) 270–281.
[38] D.A. Krishna, R.S. Priyadarsini, S. Narayanan, Effect of elevated temperatures on the mechanical properties of concrete, Procedia Struct. Integr. 14 (2019) 384–394.
[39] S. Duan, H. Liao, F. Cheng, M. Tao, Effect of curing condition and carbonization enhancement on mechanical properties of fly ash-desulfurization gypsum-steel slag blocks, J. Co2 Util. 38 (2020) 282–290.
[40] S. Türkel, V. Alabas, The effect of excessive steam curing on Portland composite cement concrete, Cem. Concr. Res. 35 (2) (2005) 405–411.
[41] N.H. Inai, A.E. Lewandowska, O.R. Ghita, S.J. Eichhorn, Interfaces in polyethylene oxide modified cellulose nanocrystal-polyethylene matrix composites, Compos. Sci. Technol. 154 (2018) 128–135.
[42] K. Hannawi, S. Kamali-Bernard, W. Prince, Physical and mechanical properties of mortars containing PET and PC waste aggregates, Waste Manag. 30 (11) (2010) 2312–2320.
[43] H. Jiang, M. Fall, Y. Li, J. Han, An experimental study on compressive behaviour of cemented rockfill, Constr. Build. Mater. 213 (2019) 10–19.
[44] BS 1881, Testing Concrete: Methods for Determinations of Density of Harden Concrete British Standards Institution, 1983.
[45] M. Fall, M. Pokharel, Strength development and sorptivity of tailings shotcrete under various thermal and chemical loads, Can. J. Civ. Eng. 38 (7) (2011) 772–784.