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Production of gold mine tailings based concrete pavers by substitution of natural river sand in Misisi, Eastern Congo

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ABSTRACT

For nearly a decade, the artisanal and small-scale gold mining (ASGM) in Misisi, eastern Congo, has been storing piles of gold mining tailings (GMT) from cyanide leaching. These tailings are stored carelessly in the nature without respect for environmental and sanitary standards, leading to soil and underground pollution risks. In order to valorize the GMT of Misisi, they were incorporated in concrete and from this concrete, pavers were produced. In addition to GMT, these pavers are made of gravel, cement and water. The compressive strength of the GMT-based pavers was compared with that of the natural river sand (NRS)-based pavers made up of NRS, gravel, cement and water. Both types of pavers were produced under the same drying conditions (7 days) with different dosages of gravels, cement and water for each type. More gravel and water were used for the GMT-based pavers with the same amount of cement for both types of pavers. The compressive strength was similar between GMT and NRS pavers with a breaking stress of 27 N/mm^2. It was found that the use of a specific dosage for GMT-based pavers that differs from the dosage of NRS-based pavers had a positive impact on their compressive strength, specifically due to the larger amount of gravel used for GMT-based pavers. This paper shows that the production process of pavers also had an impact on their compressive strength. The particle size, elemental chemical characteristics and organic content were favorable for GMT to substitute NRS. The GMT consist of 75% sandy aggregate with an organic matter content of 4.49% and 52% of silica. This study consists of a first global vision of the possibility of total substitution of NRS by GMT in concrete pavers. The study's aims is to provide a perspective of the substitution of NRS by GMT in concrete paver production. Further studies of mechanical properties and durability will be necessary before considering a large scale adoption.

1. Introduction

Artisanal and small-scale mining (ASM) contribute significantly to the economic development of several countries (The World Bank, 2008). It provides an important source of livelihood for rural communities throughout the world (Bansah et al., 2016) and generates employment and small businesses (Doucouré, 2014).

In some countries, ASM is the leading sector of the economy and can employ up to 85% of the population (Lankoande and Maradan, 2013). In Burundi, for example, ASM has been backup sector for the country's economic growth as well providing a source of income and employment after a long period of conflict that the country has experienced (Midende, 2010). In Doucouré's study (Doucouré, 2014), it was shown that ASM has led to demographic and economic transformations in south-eastern Senegal and have contributed to an increase in financial and economic autonomy of local communities.

The benefits of ASM are unfortunately overlooked due to a lack of guidance and assistance. Hinton et al. (2003) have pointed out that the economic contributions of ASM could be enormous if local governments assisted artisanal miners with proper mineral extraction techniques and provided them with specialized supervision. Unfortunately, more often than not ASM is clandestine and seems to be kept underground in complicity with some local authorities leading to a poor enforcement of environmental and health regulations (Goh, 2016).

With such a lack of monitoring and regulation in ASM, chemical products such as mercury and cyanide are often used in artisanal and

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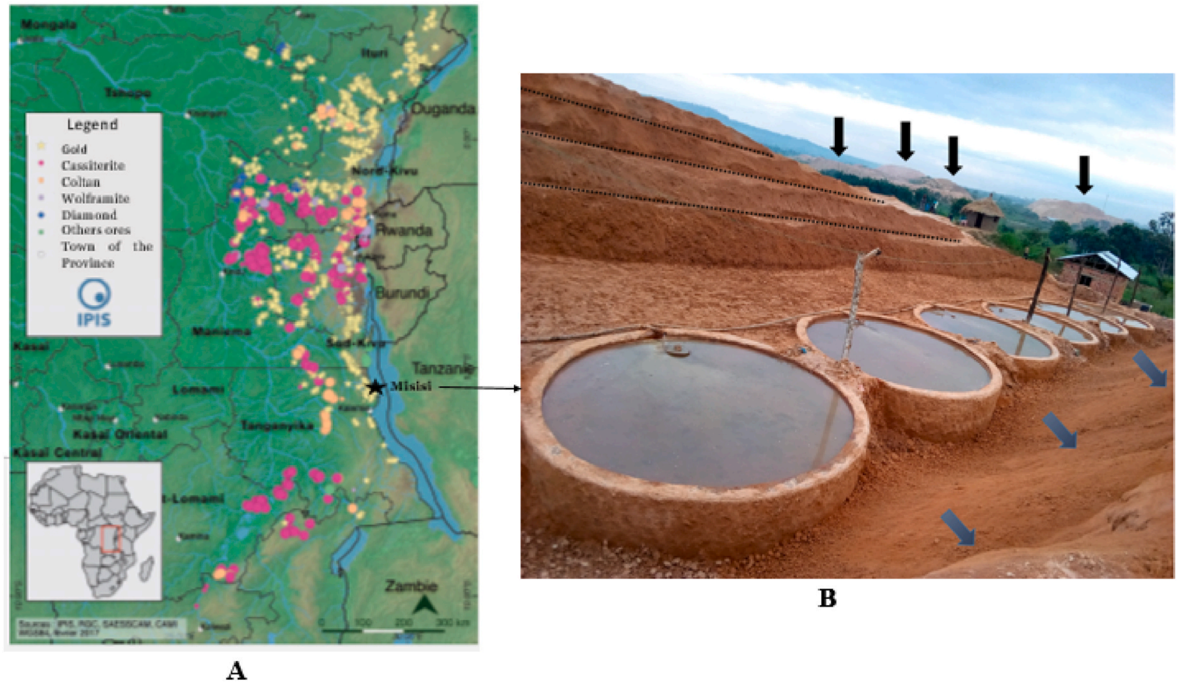

Fig. 1. A. Mining sites in eastern DR Congo. B: Cyanide leaching tank at a Treatment Unit (TU) in Misisi, South Kivu Province. Treatment Unit (Cyanidation and storage site for gold mine tailings after cyanide leaching) located at least 10 m from dwellings in Misisi. The black dotted lines show the contact limits between the deposits of previous leaching. Black arrows show four other cyanidation and GMT storage sites in the study area. The blue arrows indicate the storage of GMT from the diggers' cooperatives prior to leaching (with cyanide). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

small-scale gold mining (ASGM) with carelessness and ignorance of the harmful effects they can generate (Nkuba et al., 2019). It has been shown in the study by Lankoande and Maradan (2013) that mercury and cyanide used in gold mining result in human health costs of up to 13.6% of the value added from ASGM.

Apart from the direct environmental impacts related to the exploitation and processing of minerals, the remaining tailings are also responsible for environmental pollution particularly water and soil contamination, but also acid mine drainage when in contact with water and/or air (Aubertin and Bussière, 2001). This pollution problem is also observed both in the artisanal and industrial sector (Dolega et al., 2016) and is often caused by the erosion of waste piles (Higueras et al., 2004).

However, mine tailings management differs a lot between the artisanal and the industrial sectors. In the industrial mining sector (LSM), collaborations with research centers are often taking place to study and find solutions on management mine tailings management issues (Charbonneau, 2014). This was the case in Canada, for example, where mining companies and the government worked together on an integrated management of mine tailings (Aubertin and Bussière, 2001). Under these conditions, preliminary studies of storage sites on the mineralogy, stability and bearing capacity of these sites are also undertaken before any storage (Tremblay and Hogan, 2000). Unfortunately, such integrated tailings management practices are generally absent in ASM where tailings are carelessly stored in the nature with the no environmental standards for storage of mine tailings. In the ASM, managing tailings is even an important problem due to the lack of compliance with environmental standards (Goh, 2016) and its informal nature.

The environmental problems associated with mine tailings has been observed several decades ago. Nowadays, the valorization of mine tailings has gained interest as it seems to offer a sustainable solution to reducing their polluting effects. This valorization provides a solution to the problem of storing mine tailings in tailings impoundments, which is costly because requiring regular and expensive maintenance (Gratton, 2019). Valorizing mine tailings can also help avoid facility failure accidents that cause not only environmental damage but also the loss of life.

Valorization of mine tailings includes three options: recycling (giving back a market value to these tailings); reuse (using it differently from its first use) and recycling followed by reuse (Charbonneau, 2014; Silya and Célia, 2014). Mine tailings are valorized in several ways depending on their nature and the nature of the mined ores (Almeida et al., 2020). Mabroum et al. (2020) in their paper review, it is specified that the recycling of mining taillings is one of the effective means to mitigate their negative impact on the environment. It is indicated in their paper that the valorization of mine waste in the geopolymerization technology offers many advantages including the stabilization of polluted mine tailings in the geopolymer matrix, the reduction of the negative environmental impact as well as the significant reduction of greenhouse gas emissions. Taha (2017) states that the valorization of tailings happens on the mine site more often than elsewhere. In his study, the mining tailings were valorized in the production of cooked bricks. This study revealed scientific, environmental, economic and social benefits. From an environmental point of view, producing these bricks reduced of mining drainage, volumes of rejections as well as the consumption of non-renewable natural materials. From an economic and social point of view, the production of bricks reduced the cost of storage of mining waste for industries, the price of bricks for consumers and the creation of jobs for society.

In their review article Almeida et al. (2020) show that mining tailings can be revalorized as alkali-activated as well as new polymer-based construction materials, ceramic tiles, bricks, mortars, aggregates for pavements and concrete. For gold mine tailings (GMT), few studies have investigated their reuse and none focused on the ASGM. Most of these studies investigated mechanical properties of concrete and show that GMT can substitute natural river sand (NRS) up to 30% in a mortar typically consisting of cement and sand. These studies showed that the compressive strength can decrease beyond 30% of substitution; but other characteristics like water retention can be improved with increased GMT in the dosage (Vignesh et al., 2015). Widojoko et al. (2014) investigated the reuse of GMT as fine aggregate for the production of shotcrete in a green technology design. Optimal compressive strength was achieved at 25% of substitution by adding an admixture in the mortar, which increased the compressive strength of the concrete. Preethi et al. (2017) studied the substitution of natural sand with GMT and found that the substitution is valid up to 20%. They stated that the reuse of GMT in concrete would conserve nearly 20M t of natural sand and reduce pollution. It was shown that the reuse of GMT is environmentally friendly because it reduces air, land and water pollution, and it's cost-effective and energy efficient. Ince (2019) found that at 30% substitution of GMT with natural sand, the CO2 emission is reduced at 9% and this contributes to environmental clean-up. Ramalinga Reddy et al. (2016) showed that substitution of natural sand with GMT is an alternative solution to be explored in a context where it is difficult to meet the demand of natural sand. Ahmed et al. (2021) showed that GMT substituted quartz sand in the manufacture of ultra-high performance concrete. With this substitution, the authors showed that CO2 emission can be reduced by up to 12.1%. And in the area near the mine site, the use of tailings can be a better solution from an economic and environmental point of view, as well as in terms of sustainability.

Concrete is the most widely used building material in the world. Natural sand is one of the elements that make up its skeleton. Natural sand is a natural and non-renewable raw material that is in great demand in the construction industry.

In this study we investigated the reuse of GMT from ASGM as a construction material by comparing the compressive strength of GMT-based concrete pavers with that of NRS-based concrete pavers. The study specifies the constituents of the produced pavers, the proportions of constituents, the drying conditions of the pavers as well as their compressive strength which was used as a comparison factor between GMT-based and NRS-based concrete pavers. This study aims is to provide a perspective of the substitution of NRS by GMT in concrete paver manufacturing.

2. Description of the study area

The Eastern DR Congo is known for its mining wealth and a large artisanal activity that constitutes an important sector of development in the country (Nkuba et al., 2017). However the environmental policies and regulations are not followed by the miners in their gold extraction processes and carelessness in the use of mercury is observed. Under these conditions, in addition to the legal and political risks that miners face, they are exposed to diseases related to the misuse of products like mercury and cyanide (Bucekuderhwa et al., 2013). Nkuba et al. (2019) found that mercury is used more in and around the miners' homes rather than in gold mines. They show that this mercury misuse is linked to ignorance and lack of consistent supervision of diggers. Similarly, the storage of GMT does not follow any standards or rules.

The GMT used in this study are the tailings from the artisanal sector of eastern DR Congo in the Province of South Kivu in the Misisi mining area (Fig. 1 a). The Misisi antenna is one of eight mining antennas in South Kivu Province where artisanal gold mining is more developed in terms of annual gold production. Artisanal miners are grouped into cooperatives as described in the Congolese mining code in Article 1, point 19 bis (*Code Minier Congolais*, 2018).

Less than a decade ago, cyanide started being used in the Misisi mining area through new facilities locally called "Unités de traitement (UT)" for cyanide-based extraction of residual gold from the tailings left by the miners. The principle of processing the tailings from the miners is done in a semi-artisanal manner in tanks dug into the ground using mainly cyanide and other chemicals like activated carbon and lime (Fig. 1 b) (Kashongwe, 2017). The tailings produced by the UT are the focus of our research. As mentioned above, these tailings are carelessly stored in the nature, not far from homes and without any form of environmental protection (Fig. 1 b).

3. Materials and methods

3.1. Materials

In October 2019, 800 kg of GMT were collected from the tailings storage sites of a TU in Misisi and transported to Bukavu (367 km away) in the northeast of South Kivu Province (Fig. 1). According to local respondents, these GMT had been stored for over five years after being leached twice with cyanide before being declared uneconomic by the TU owners. The GMT sample were collected in black plastic bags and transported to the paver production facility in Bukavu.

For the purpose of this study, concrete consists of GMT or NRS, cement, gravel and water. The grain size of GMT, NRS, and gravel was determined by a series of sieves (opening according to AFNOR –Association Française de Normalisation-standard in mm) and by the hydrometric method in the laboratory of public works of the Office des Routes in Bukavu (CEAEQ, 2015). Organic matter was determined using the Walkey and Black method (Centre d'expertise en analyse environnementale du Québec 2003) for GMT and NRS. The method is based on the principle that potassium dichromate oxidizes the carbon in the sample. Density and water content were calculated according to standard methods in accordance with NF EN 1097-5. The water content is calculated after drying the sample in a ventilated oven and the density considered is the mass of the sample for a given volume that contains the sample.

GMT were used in concrete for paving and substituted for 100% NRS (concrete consisting of GMT, cement, gravel and water). The chemical composition characteristics of GMT were determined by x-ray fluorescence (FRX). The analyses were performed three times the same sample and then the average was considered.

Cement and gravel were added to both NRS and GMT to produce the concrete from which pavers were made. The GMT were used as they came from the storage site and were not sieved before being used. The NRS was first sieved to remove particles above 5 mm of grain diameter. It is a washed sand coming from Idjwi (one of the territories of the province of South Kivu) and commonly used in the construction in the city of Bukavu.

The cement used in this study was Portland pozzolan of the CEM II/B-P 42.5N class, as this is locally preferred for its performance in water resistance. The gravel used came from the basaltic formations of Kivu, rich in olivines (Pécrot et al., 1962). The gravel size was determined by sieving using a series of sieves according to the AFNOR opening between 16 and 2.5 mm.

Finally, water was obtained from the public distribution network.

3.2. Method: experimental procedure

3.2.1. Mixture and manufacture of concrete pavers

The mixture adopted for the manufacture of GMT-based concrete pavers is the one used to produce NRS-based concrete pavers in Bukavu. In our experiment we used for 6 kg of GMT 12 kg of gravel, 3.3 kg of cement and 2.7 l of water; and for 6 kg of NRS, 8 kg of gravel 3.3 kg of cement and 1.7 l of water. In this dosage, more gravel was used in GMT-based pavers referring to the experiments of de Larrard (1999) that specifies that for a fine sand, a large quantity of gravel improves its compressive strength.

We first mixed cement and GMT or NRS; then we added gravel and finally water. For both kinds of concrete (GMT based and NRS based), we added water in order to have a firm concrete according to the slump test of the NF EN 206-1 standard. After getting a homogeneous concrete mixture, we fill it in molds. The used molds were made of plastic with a hexagonal shape, 5 mm high and 12.1 mm on each side (12.1 mm × 12.1 mm x 5 mm), with a grooved base that provides the paving stone with a non-slippery and airy top face.

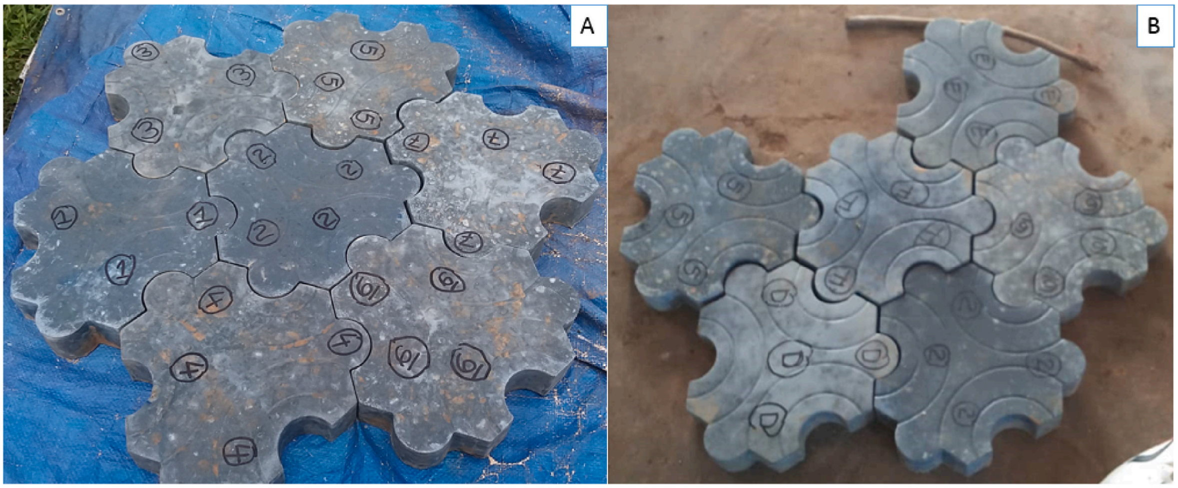

Fig. 2. A. GMT-based concrete pavers demoulded on the seventh day after the date of manufacture. B. GMT-based concrete pavers (2, 5 and 6) with the same appearance as NRS-based concrete pavers (D, E and F).

At the base of the molds, we put a thin layer of cement and water mixture before adding the concrete. This layer is called "top face" defined as an upper layer of a concrete paver, made of different material and/or having different characteristics than the mass concrete according to the AFNOR standard (2004).

Once in the molds, the concrete was manually vibrated to allow the cement and water to mix properly.

3.2.2. Drying and demolding

For both types of pavers, the concrete was dried in the molds through two steps. The first step included watering the concrete (starting 24 h after production) twice a day (morning and evening) for three days. At this step the concrete was in an open shed covered by a roof in temperature conditions between 20 and 24 °C. The second step was to dry the concrete in the molds on the ground for four days after turning them upside down.

The demolding of the concrete was carried out on the seventh day after the production. After they were demolded, pavers were stored and commercialized.

3.2.3. Compression strength

To compare GMT-based and NRS-based concrete pavers, we used compression testing, as these are commonly used and for concretes with paving purposes (Jebli, 2016). We used a 200 t compressor in the public works laboratory of the Office des Routes de la Province du Sud-Kivu in Bukavu, DR Congo. The strength maintained was the average of 6 strengths obtained for each type of paving stone.

3.3. Statistical analyses

The variance test was applied to check the variation of the breaking load and breaking stress of GMT-based and NRS-based concrete pavers. This analysis was used after having checked the conditions of application of the analysis of variance by using the Levene test to check the homoscedasticity with the package lawstat of the software R.

4. Results and discussion

4.1. Characteristics of produced concrete pavers

The appearance of the GMT-based concrete pavers and the NRS-based concrete pavers is presented in Fig. 2. At first glance, it is difficult to distinguish the two types of pavers. This is due to the layer of cement mortar that envelops the entire surface of the pavers and gives them the same appearance according to the NF EN 1338 standard (AFNOR, 2004).

Table 1
Characteristics of produced pavers.

Characteristics of pavers	GMT	NRS
Length (mm)	121	
Width (mm)	121	
Height (mm)	50	
Volume (cm^3)	190.2	
Total surface compressed (cm^2)	380.384	
Weight (g)	3980	4060
Density (g/cm^3)	2.09	2.13
Breaking load (kg)	102 666.67	102 333.33
Breaking stress (kg/cm^2)	269.90	269.02
Breaking stress (N/mm^2)	26.99–27	26.9–27

GMT and NRS based pavers showed the same characteristics in terms of breaking load and breaking stress (Table 1). Indeed, though the lowest breaking stress of 25.6 N/mm^2 for GMT based pavers and 26.0 N/mm^2 for NRS based pavers, the analysis of variance showed no significant difference of the breaking load and breaking stress of GMT-based and NRS-based concrete pavers ($p > 0.05$).

According to the AFNOR (2004) standard on the regulation of pavers, these two kinds of pavers are described in Fig. 3.

The differences and similarities between the two kinds of produced concrete pavers are in terms of dosage and constituents are shown in Table 2.

Despite the difference in dosage and composition (GMT-based and NRS-based concrete pavers), the compressive strength was similar. The explanation for this evidence may be complex. Referring first to the water/cement ratio for which values are between 0.4 and 0.6 according to general rules, this ratio is 0.8 for GMT-based pavers and 0.5 for NRS-based pavers. The GMT-based pavers required a greater amount of water compared to the NRS-based pavers (Table 2). With this difference in water/cement ratio, the two kinds of pavers would have different compressive strength. Some studies on the substitution of natural sand by GMT show that the compressive strength of GMT-based concrete calculated on standard cubic specimens is very low compared to the compressive strength of natural sand-based concrete. Ramalinga Reddy et al. (2016) found that GMT based concrete's compressive strength was eight times lower than the NRS's and this was justified by the water/cement ratio. It was also noted that little cement was used in the GMT-based concrete compared to the other mixtures in their study.

The dosage and the way the pavers were made can explain the

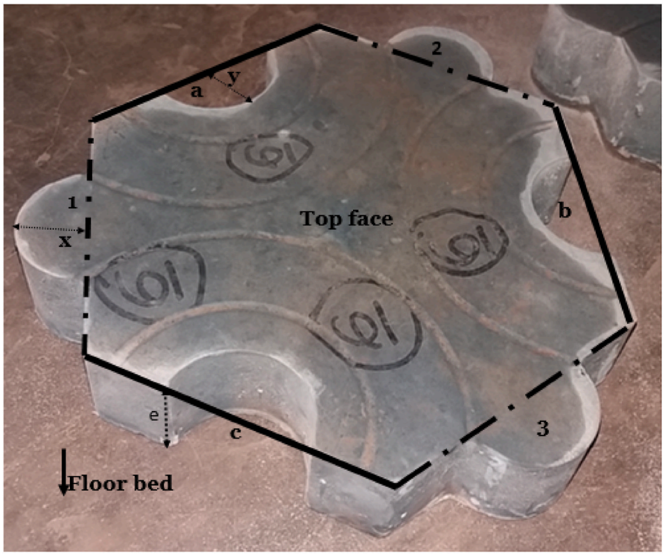

Fig. 3. Hexagonal paving stone with 8 edges. It includes: * A top face which is the face intended to be visible in service. * A face called "subface" which is the surface generally parallel to the top face in contact with the floor bed (this is supposed to be the paving as shown in the picture). * Three grooved side faces: these are the side faces with a recessed profile (the recesses are a, b and c). * Three side faces with spacing tenons (the spacing tenons are the small profiles protruding on a side face of a pavement. These spacer posts are 1, 2 and 3). (N.B.: the value of "x" of the spacer post is equal to the value of "y" of the grooved side lace). * Thickness " e " is the distance between the top face and the underside of the paver. * The overall length is the long side of the top face of the paver excluding any spacer. There is also the overall width for other shapes of pavers; it is the short side of the top face excluding any spacing tenons.

Table 2
Differences and similarities in the dosage and constituents of the produced pavers.

Concrete pavers based on GMT	Concrete pavers based on NRS	Similarities
Finer grain size	Required grain size of natural sand	Dosage and quality of the cement (3.3 kg)
More gravel (12 kg)	Less gravel (8 kg)	Presence and nature of the top face
More water (2.7 l); water/cement = 0.8	Less water (1.7 l); water/cement = 0.5	Curing conditions and time
		Same amount of GMT and NRS

similar breaking load and breaking stress in our study. As seen in Table 2, despite using a larger quantity of cement to increase compressive strength, we opted for the use of the same amount of cement for both types of pavers. In fact, cement production emits CO2 because of its high energy consumption. It can be seen in the study of Ince (2019) on the substitution of cement by GMT that at 30% of substitution, there is a reduction of 22% of emission of CO_2.

The difference between the two pavers was the amount of gravel and water used. According to de Larrard's study (de Larrard, 1999) and Néville (2000), using a larger amount of gravel for fine sand improves the compressive strength of concrete. In his book, Néville (2000) shows that the presence of gravel in a concrete promotes good compressive strength. Also, in Widojoko et al.'s study (2014), concrete without gravel had low compressive strength. Which is why they had to use an added material to improve the concrete's compressive strength.

The presence of the top face which is made differently in nature from the pavers concrete, with a mixture of only cement and water, played an important role on their resistance. The top face as defined by the AFNOR

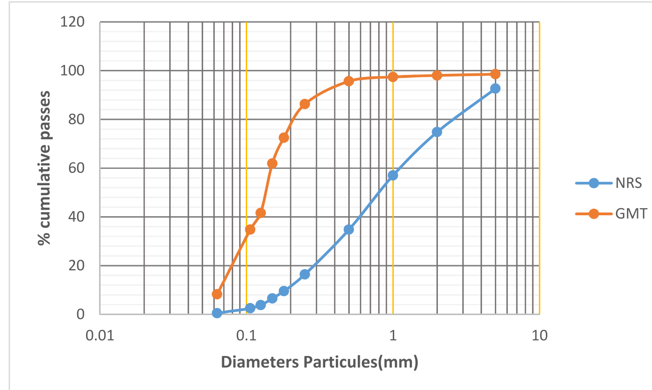

Fig. 4. Size curve of natural river sand in blue (NRS) and gold mine tailings in orange (GMT). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Particle sizes of NRS and GMT and water content and density of NRS, GMT and gravel.

Designation	% sand (2–0.05 mm)	% silt (0.05 mm–0.002 mm)	% clay (<0.002 mm)	Water content in %	Density in g/cm^3
NRS	95.1	0.7	4.2	7.1	1.2
GMT	75.2	18.7	6.1	1.2	1.5
Gravel	-	-	-	-	1.5

(2004) standard, is the surface or face that has been compressed. This face has a double advantage; it improves the compressive strength of the pavers and provide a better visual to people than the concrete would (AFNOR Standard, 2004).

The drying choice adopted as explained in section 3.2.2 does not require any heating. Taha (2017) in his study on the valorization of mining wastes for production fired bricks showed that the brick firing wasn't without environmental disadvantage. This assessment is often missing in the waste beneficiation process in general.

Currently, the valorization of plastic waste incorporated in concrete seems to give satisfactory results concerning the mechanical properties. In the study of Saifoullah et al. (2020) the plastic waste was melted in the production process of the pavers. Therefore, in this study heating should be involved in the production cycle but the issue of heating was not evaluated and addressed. Guendouz et al. (2015) had proposed an alternative heating of plastic to be incorporated into concrete using them in powder and fiber form and found satisfactory results on mechanical properties.

According to AFNOR standard (2004), for a good paver the ratio of the overall length and the thickness must be less than or equal to four. For our concrete pavers, this ratio is equal to 2.42 (overall length is 12.1 cm and thickness is 5 cm: 12.1/5 = 2.42).

4.2. Characteristics of the concrete constituents

In terms of granulometry (Fig. 4), there were more fine particles in GMT than in NRS. The particle size analysis of the NRS and GMT showed a significant difference in the proportion of fine particles; up to 25% silt and clay in the GMT (Table 3). The NRS consists of 95% actual sand grain size and the GMT 75%. It should be remembered that the GMT used in this study is from artisanal mining, thus its grinding does not produce particles as fine those from the industrial mining. Indeed, (industrial) mining companies reprocess GMT from artisanal miners, grinding them further to extract the remaining gold (Muir et al., 2005).

The particle size plays a role on concrete compressive strength and influences the proportion to be considered in the concrete mix. Vignesh

Table 4
Chemical composition of GMT.

	Si	Cl	Fe	P	K	Ca	Al	Ti	S	Zr	Mg
Content (%)	54,1	21,6	8,9	5,5	4,2	2,2	2,0	1,0	0,3	0,1	0,1

et al. (2015) showed in that as the sand becomes finer in the concrete the compressive strength decreases. Preethi et al. (2017) suggest that despite the same water/cement ratio being considered while substituting natural sand by GMT, the compressive strength remained low for the GMT-based concrete. This was explained by the thinness of GMT. Ince (2019) on the other hand, found that as GMT substitute for natural sand, the compressive strength increases. She explains this by the pozzolanic nature of the GMT of the study area.

GMT, have lower water content than NRS but is denser than the latter (Table 3). The organic content of GMT and NRS was respectively 4.49% and 4.01%. Both organic contents are within the accepted range for materials used in public works, specifically in road applications (Hamouche, 2018). Vermulen et al. (2003) specified that materials containing between 2 and 4% organic matter are used for pavements.

Gravels size were between 4 and 12 mm, with more than 65% of the particles being between 8 and 10 mm of diameter. De Larrard and Belloc (1999) specifies that the dimensions of the gravel in the concrete play a role in the strength of the concrete. Néville (2000) completes that in addition to the presence of the gravel in the concrete and its dimensions, the nature of the gravel also influences the concrete's strength.

The x-ray fluorescence (FRX) results of GMT show that more than half is silica followed by chlorite (21.6%) (Table 4). Almeida et al. (2020) suggest that GMT can be effective in construction because of the high proportions of silica. In respect, this article's review has shown that the choice of the orientation of GMT in concrete is justified by their important proportions of silica. It is shown in Ahmed's study (Ahmed et al., 2021) that the significant quantities of silica in GMT allow their substitution for quartz sand in the manufacture of ultra-high performance concrete.

5. Conclusion and perspective

In the Eastern Congo's ASGM, policies for managing tailings are clearly not implemented on mining sites. Piles of tailings are carelessly stored in the wild without any environmental and health precautions. In the perspective of valorization of these tailings, we have incorporated the GMT in the concrete for pavers production.

In this paper, we compared the compressive strength of GMT and NRS based pavers. Both kinds of pavers had similar strength, measured at 27 N/mm^2 on the seventh day of drying. The use of different amounts of gravel, production process, grading characteristics of the GMT and their elemental chemical composition contributed to the compressive strength of the GMT-based pavers. In fact, the dosage used for 6 kg of GMT required 12 kg of gravel, 3.3 kg of cement and 2.7 l of water. It is shown in the document that the facing layer made of the mixture of cement and water that covers the entire surface of the pavers contributes to the compressive strength of the GMT-based pavers being identical to that of the NRS-based pavers. The grading of GMT, which consists of 75% sand and 25% silt and clay, also contributes to the strength of the pavers. The chemical composition of GMT showed more than 50% silica and 21.6% chlorite. This offered GMT an advantage to substitute NRS.

This study constitutes a first global view of the possibility of total substitution of NRS by GMT in the manufacture of concrete pavers. To make this substitution effective, a more advanced study of the mechanical properties and durability must be undertaken before considering a commercial production. The valorization of GMT in the production of concrete pavers would be an opportunity for job creation and could be beneficial in improving the living conditions of people living in mining sites. Since the characteristics of GMT appear to be favorable for substitution of NRS, GMT may become a secondary source of sand. Its reuse in construction for pavers' production could help improve paths and even roads in mining sites.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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