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Interlocking concrete blocks produced with sinter feed tailings

Piso intertravado produzido com rejeito de sinter feed



A. V. COSTA [a]
ayrton@ufmg.br

A. G. GUMIERI [a]
adriana@demc.ufmg.br

P. R. G. BRANDÃO [a]
pbrandao@demin.ufmg.br

Abstract

This paper discusses the technical feasibility and ecological advantage of using sinter feed tailings from iron ore mining as an aggregate in the production of concrete, initially to manufacture precast concrete pavers, but with the possibility of extending its use to other applications. To achieve this goal, the physical, chemical and environmental characteristics of the tailings were analyzed. The other aggregates used here were also characterized, and the tailings were quality tested when used as fine aggregate in the production of mortars, based on a comparison of their compressive strength. The interlocking concrete pavers were manufactured by a precast concrete plant, after which they were sampled and subjected to compressive strength, water absorption and abrasive wear tests, according to Brazilian technical standards NBR 9780 [33], NBR 12118 [34] and NBR 12042 [35]. The results of these tests indicated that, compared to the reference values, the compressive strength at 28 days varied from -2.5% to -11%; water absorption ranged from -14% to +3.8%; and abrasive wear varied from -80% to -62%. The main purpose of using sinter feed tailings as aggregate in concrete production is to ensure the sustainable development of the construction industry. For the iron ore mining industry, the productive disposal of these tailings represents a major advantage in cost-effectiveness, due to the elimination of stockpiles and of the costs involved in their operationalization.

Keywords: mining, wastes; sinter feed tailings; paving; interlocking concrete pavers.

Resumo

O presente trabalho apresenta a viabilidade técnica do aproveitamento e da conveniência ecológica do emprego do rejeito de sinter feed, oriundo de atividades mineradoras de ferro, como agregado na produção do concreto, inicialmente para a fabricação de elementos pré-fabricados destinados à pavimentação, com possibilidade de expansão para outras finalidades. Inicialmente, foram realizados os seguintes ensaios de caracterização dos materiais: caracterização física, química e ambiental do rejeito, caracterização física dos demais agregados utilizados e ensaio de qualidade do rejeito quando empregado como agregado miúdo na produção de argamassas, por comparativo de resistência à compressão das mesmas. Posteriormente, após a produção de peças para piso intertravado, em uma indústria de pré-fabricados, os mesmos foram amostrados e submetidos aos ensaios resistência à compressão, absorção e desgaste por abrasão, segundo as normas NBR 9780 [33], NBR 12118 [34] e NBR 12042 [35]. Quanto aos resultados, as resistências à compressão aos 28 dias, sofreram variações entre -2,5% e -11%; quanto às absorções de água, as variações ficaram entre -14% e +3,8%; quanto à abrasão, observaram-se variações entre -80% e -62%, percentuais estes referidos sempre aos valores de referência. A grande relevância do uso do rejeito de sinter feed como agregado na produção de concreto se refere ao desenvolvimento sustentável da indústria da construção civil. Para as indústrias mineradoras, o descarte desse rejeito de maneira produtiva significa grande vantagem na relação custo-benefício que se caracterizará pela ausência tanto das pilhas de estocagem em suas áreas quanto pela ausência de despesas com sua operacionalização.

Palavras-chave: mineração, rejeito, sinter feed, pavimentação, piso intertravado.

[a] *Universidade Federal de Minas Gerais, Campus Pampulha, Belo Horizonte, MG, Brasil.*

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1. Introduction

The search for a useful destination for wastes and tailings originating from the production of the mining and steel industries has been a constant concern of companies that engage in these activities, as well as of environmentalists, control agencies and research institutions interested in preserving the environment. As an example, in the steel manufacturing industry, the major advance resulting from the use of certain types of slag as important components in the production of Portland cement is already well established, contributing to significant savings in cement production and improving its properties, particularly in view of the intelligent use of wastes produced by this industry.

Also in the area of limestone and gneiss mining, materials that in the past were discarded tailings from the production of crushed rock for use in concrete are now, by dint of minor investments and the implementation of an additional beneficiation step of the fine crushed stone fractions, increasingly accepted by the artificial sands market. Calcareous sand, for example, which is used for the partial substitution of natural river sand, enables significant improvements in concrete and mortar properties, while also representing desirable savings in the consumption of this natural, finite and nonrenewable raw material. Not only in the mining and steel sectors but also in the construction industry, the constant quest to find applications for wastes and tailings currently occupies a prominent place in research and in the pursuit of new materials technology that will contribute to environmental sustainability. According to Alcântara [1]:

> "With the creation of cities, man's action upon the environment has resulted in the degradation of natural resources and in pollution, thus compromising the quality of his own life. [....] In the 21st century, it is up to construction professionals to ensure that daily work practices are aligned with the principles of sustainable construction, in view of this sector's significant responsibility for and share in sustainable development." (Alcântara 2009, p. 36)

In the early practices of mining companies, large volumes of tailings remaining after ore production and processing were discarded in riverbeds. Later, their disposal procedures evolved to containment systems, which were performed without any control. However, with the advance of environmental laws, and particularly after major environmental impacts were attributed to broken dams and stockpiles of tailings, mining companies began to design these systems as engineering works. As a result, they began to show greater interest in complying with legal requirements for safer alternatives for waste containment [2]. In this context, the use of tailings represents a cost reduction factor for mining companies, as well as an additional source of income and a step towards improving environmental quality.

This study aims to evaluate the use of sinter feed tailings as aggregate in the production of concrete pavers used in paving. The characteristics of the wastes are discussed, as well as the mechanical performance and durability of precast pavers manufactured with them.

2. Literature review

The central region of the state of Minas Gerais contains an area of approximately 7,160 km^2, known as the Iron Quadrangle, whose iron ore deposits, which have been estimated at about 29 billion tons, are of great economic and environmental importance. In addition to iron ore mining companies, numerous other types of rocks and minerals are mined in the Iron Quadrangle. This is one of the country's most productive mining regions and the most well known in geological terms [2, 3].

Brazil ranks in sixth place in terms of iron ore deposits, with almost 7% of the world's reserves, and is the second largest iron ore producer, producing 19% of the world's iron ore output. In 2007, the country produced 350 million tons, equivalent to 18.42% of global production, which is 1.9 billion tons [4]. The high iron content in Brazilian ores (60-67% in hematite and 50-60% in itabirite) has given Brazil a prominent position on the world stage, in terms of the iron content of its ore. The state of Minas Gerais, which holds approximately 75% of these reserves, stands out for its numerous mining plants, particularly of iron, scattered throughout the region.

Most of the iron ore mined in Brazil is destined for the steel industry (99%), while the remainder is used as filler by the ferroalloy, cement and road construction sectors. This ore can be used in the form of granules or agglomerates (sinter or pellet). The granules (6 to 25 mm) are fed directly into the reducing furnace, whereas the agglomerates are finer ores. The main agglomeration processes are sintering and pelletizing. The product of sintering is called sinter feed (0.15 to 6.35 mm) while that of pelletizing is called pellet feed (smaller than 0.15 mm). Iron ore with average contents of 65% iron, about 3% each of silica and aluminum, and low phosphorus content is used in blast furnaces to produce pig iron and in direct reduction furnaces to produce sponge iron. Sinter feed is used in integrated steel mills [5]. Both processes generate significant amounts of wastes; granulates are discarded in piles and powdery fines in dams. The steel industry is of great economic importance, generating wealth and thousands of jobs. However, this industrial activity produces huge quantities of wastes, thus requiring the use of clean technologies to reduce their generation and the development of research and technologies that allow for their safe, economical and environmentally friendly reuse and/or recycling. A feasible solution to reducing the environmental impact of these wastes is to use them as aggregates in construction [6].

The construction industry has accounted for about 20% of the extraction of natural resources and, in this context, the use of wastes in place of raw materials can reduce the amount of this extraction, substituting a large part of the natural aggregates used in concrete, mortar, blocks, pavers, containment barriers and paving bases [7].

Sinter feed waste is a granular residue of the iron ore production process for which, so far, there has been no regular commercial demand. During the iron ore production process, this material is washed and screened, generating tailings without contaminants and with a reasonably uniform particle size distribution. Over the years, these tailings have been deposited in huge piles adjacent to mining areas, damaging the environment and involving costs relating to their handling, internal transport, disposal and stocking, as well as environmental control and monitoring. The average height of a sinter feed tailings stockpile is equivalent to that of a five or six story residential building occupying a considerable area. Sinter feed tailings usually still contain a substantial amount of iron, which cannot be further separated using only the magnetic rollers that are commonly used in the iron ore beneficiation process. To do so would require a jig installation to allow for better separation of the iron ore by means of a gravimetric system, which would involve

high water consumption as well as investments, and its cost-benefit ratio has so far not justified its widespread adoption.
Aggregates for concrete are classified as natural or artificial, the latter consisting of sand and stones from crushed rock. Examples of natural aggregates are sands extracted from rivers or ravines and pebbles. Another factor that determines the classification of aggregates is their unit mass (or bulk density). These aggregates can be classified as lightweight (expanded clay, pumice, vermiculite), normal weight (crushed stone, sand, pebbles) and heavyweight (hematite, magnetite, barite). Aggregates that weigh less than 1,120kg/m^3 are generally considered lightweight and are applied in the production of various types of lightweight concretes. Normal weight aggregates have densities varying from 1520 to 1680 kg/m^3 and produce "normal weight concrete" with a unit weight of approximately 2,400 kg/m^3. Compared to normal weight aggregate, heavyweight concrete varies from 2900 to 6100 kg/m^3, and is normally used at nuclear radiation sites [8]. Kamal et al. [9] described the influence of particle size distribution of aggregates in the distribution of voids in flexible pavements. Based on the results of their research, the authors propose adjustments in the gradation of certain aggregates to improve the performance of pavements.
Due to the occurrence of iron (non-magnetic) in sinter feed tailings, the unit mass of this material is higher than that of the sandy materials currently used in the production of concrete. Today, the greater weight of this material does not, in principle, favor its use as aggregate in reinforced concrete, since this would result in structures with higher structural self-weight than is usually considered in common construction designs and works, entailing its scaling and its consequences. However, when used as an aggregate in the production of concrete blocks or pavers and other applications directly on the ground, in addition to its ecological advantages, it would also contribute to increase the stability of the paving, insofar as it would result in paving with slightly higher self-weight and lower risk of deformation resulting from external loads.
Although industrial wastes have various applications in road and pavement construction, the advantages of their application are often not understood, since the majority of wastes are not regulated and are usually applied according to individual solutions [10]. The disposal of mining tailings leads to economic, environmental and legislative problems for mining companies. To become sustainable, these wastes require effective applications [11]. Ismail and Al-Hashmi [12] demonstrated that iron mining tailings used as a substitute of fine aggregates in concrete led to higher mechanical strength than that of conventional concrete. Ismail and Al-Hashmi [13] also present studies of applications using a mixture of iron mining and plastic wastes in concrete.
Interlocking pavers, which are composed of precast concrete blocks, are an effective solution for use in streets, driveways, sidewalks and squares. This is a growing market in Brazil, both in construction and in the reconstruction and rehabilitation of this type of urban facility. According to Oliveira and Souza [6], when properly installed, interlocking pavements are resistant to movement, subsidence or breakage, thus providing excellent surfaces for walking, cycling, car and truck traffic, and even for industrial forklifts. The use of gapped pavers is environmentally friendly, because the gaps allow rainwater to seep back into the ground, preventing its runoff. Pigmented pavers allow for permanent markings in parking lots, at pedestrian crossings, traffic lanes and other areas that require identification. Paver maintenance is simple, since the blocks in a pavement are replaced in their original location after repair, without the need for additional pavers.
In Brazil, the interlocking pavement technique emerged in the 70s, but its application often failed to follow the minimum recommended technical criteria, thus impairing the image of concrete pavement components. Meanwhile, several other countries showed a growing use of pavements made of precast concrete blocks, with a notable development in sizing techniques, construction, materials and standardization [14]. According to Copel [15], interlocking paving systems using concrete pavers for both foot and vehicle traffic offer several benefits, such as permeability and thermal comfort; immediate use for traffic after installation; easy maintenance; removal and reuse; safety, since their surface is non-slip; architectural versatility, presenting several types, colors and combinations; easy installation, and high durability.
The absence of limitations on the carrying capacity of these pavements, allied to the numerous available choices of shape, patterns, colors and hues to allow for countless aesthetic possibilities, ensure their complete success in squares, parks, gardens, sidewalks, parking lots, city streets, courtyards, warehouses, industrial buildings, roads, berms, etc. [7]. According to Piorotti [16], precast concrete pavements have a very long service life. Considering designs suitable for sub-bases, good quality elements and proper installation, the service life of this type of pavement may be at least 25 years. The vertical deformation of paving blocks (also called pavers or interlocking concrete pavements) is lower than that of flexible pavements (asphalt) of the same thickness. The Brazilian standard NBR 9781 [17] establishes characteristics, dimensions and other requirements for this material.

3. Experimental program

3.1 *Characterization of the sinter feed tailings and aggregates*

The first step of the experimental program consisted of the physical, chemical and environmental characterization of the tailings used in the manufacture of the interlocking concrete pavers. The waste was sampled at its disposal site in the mining area, as specified by the Brazilian standards NBR 10007 [18] and NBR 7216 [19]. The material was quartered and prepared for the characterization tests. The sinter feed tailings come from a mining plant in the municipality of Sarzedo, state of Minas Gerais, Brazil, and represents the typical profile of the wastes generated by iron ore mining in the region.

3.1.1 Chemical composition of the tailings

Table 1 describes the chemical composition of the sinter feed tailings obtained by the wet chemistry technique. After the material undergoes the magnetic roll separation process, it still contains a large amount of this element in the non-magnetic condition, which is why this process is not entirely effective for a higher concentration of Fe.

3.1.2 Environmental characterization of the tailings

The sinter feed tailings were characterized environmentally based

Table 1 – Average chemical composition (in %) of the sinter feed tailings

Elements/oxides – contents %					
Fe	SiO_2	Al_2O_3	P	Mn	LOI
55.85	14.78	1.65	0.16	0.44	2.68

LOI = loss on ignition.

on solubilization and leaching tests, as prescribed by the Brazilian ABNT 10005 [20] and ABNT 10006 [21] standards and were classified according to the criteria of the ABNT 10004 [22] standard. Tables 2 and 3 describe the results of the leaching and solubilization tests of the tailings and the maximum limits established by the standards. None of their extracts presented a concentration of constituents exceeding those established in the standards, and the tailings were classified as Class II B waste, corresponding to inert wastes.

Table 2 – Leaching of the tailings and maximum permissible limits

Parameter	Concentration (mg/l)	Maximum limit (mg/l)
Silver	<0.01	5.0
Barium	0.007	70.0
Chromium	<0.04	5.0
Arsenic	<0.0003	1.0
Cadmium	<0.0005	0.5
Lead	<0.005	1.0
Mercury	<0.20 (µg/l)	0.1
Selenium	<0.0005	1.0

3.1.3 Mineralogical composition of the tailings

The mineralogical phases in the tailing sample were identified qualitatively by X-ray diffraction (XRD). Figure 1 shows an XRD diffractogram of the sample, which contains crystalline phases consisting mostly of hematite (Fe_2O_3) and quartz (SiO_2), as well as minor amounts of goethite (FeO(OH)) and traces of gibbsite ($Al(OH)_3$). The current literature lacks data on the minerals identified in the composition of this waste, since most studies have focused on the sinter feed product instead.

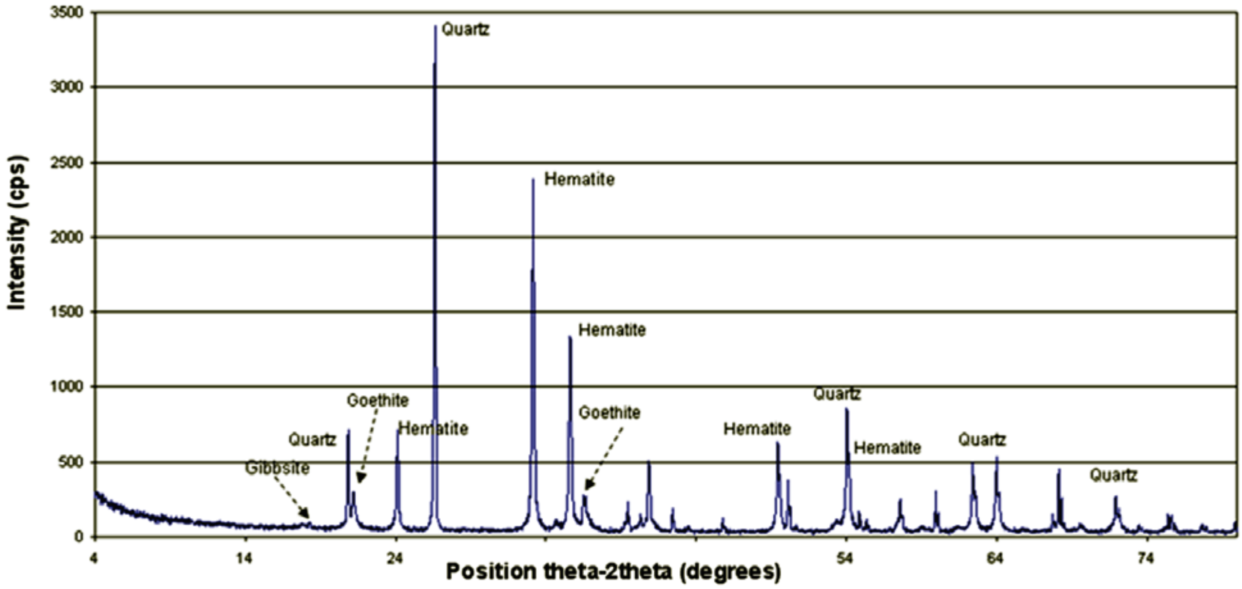
3.1.4 Physical characterization of aggregates, stone dust and tailings

Table 4 summarizes the main properties of the materials used in the manufacture of the pavers. Figure 2 illustrates the particle sizes determined according to the NBR 7217 [31] standard of the tailing sample and of the natural sand used as reference for testing the quality of the aggregate, in the comparative test of compressive strength of mortar.
The sand used as reference was comprised almost entirely within the usable range prescribed by the Brazilian NBR 7211 standard

Table 3 – Solubilization of the tailings and maximum permissible limits

Parameter	Route A (mg/l)	Route B (mg/l)	Maximum limit (mg/l)
Silver	<0.01	< 0.01	0.05
Aluminium	<0.10	< 0.10	0.2
Barium	0.005	0.007	0.7
Chromium	<0.04	< 0.04	0.05
Copper	<0.004	< 0.004	2.0
Iron	<0.03	0.08	0.3
Manganese	0.012	0.018	0.1
Sodium	0.45	0.93	200.0
Zinc	0.05	0.15	5.0
Mercury	<0.20 (µg/l)	<0.20 (µg/l)	0.001
Selenium	<0.0005	<0.0005	0.01
Arsenic	<0.0003	<0.0003	0.01
Lead	<0.005	<0.005	0.01
Cadmium	<0.0005	<0.0005	0.005

Figure 1 – XRD diffractogram of the tailings



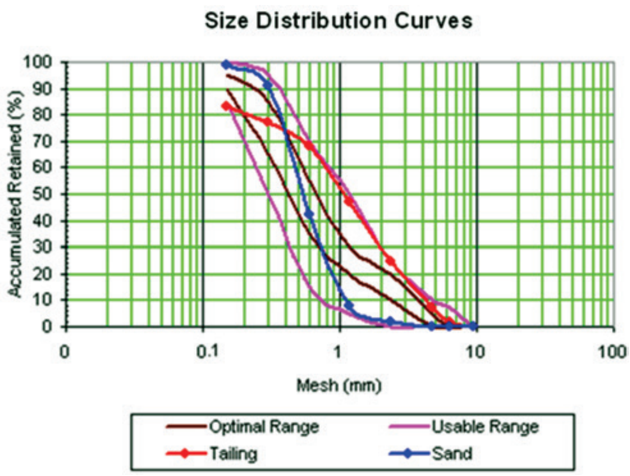
[23], presenting a maximum dimension of 2.4 mm and fineness modulus of 2.42. The tailings presented coarse sand characteristics, within the upper limit of the optimum range specified by the NBR 7211 standard [23], and this sample showed a maximum characteristic size of 6.3 mm and a fineness modulus of 3.09. Moreover, in the particle size test, the tailings exhibited a sharp inflection in the

Table 4 - Main properties of the materials

Properties	Results			
	Sand	Tailing	Rock dust	Cruched stone
Maximum characteristic dimension (mm) NBR 7211 (ABNT 2005) (18)	2.4	6.3	6.3	9.5
Finessess modulus NBR 7211 (ABNT 2005) (18)	2.42	3.09	3.38	6.13
Alkali-aggregate reaction (mmol/liter) NBR 9774 (ABNT, 1987) (19)	–	*Ds = 7 *Ra=446	–	–
Resistance to sulfates (%) DNER ME-089 (20)	–	2.01	–	–
Specific mass (kg/dm^3) NBR 9776 (ABNT, 1987) (21)	2.65	3.76	2.72	2.69
Unit of mass (kg/dm^3) NBR 7251 (ABNT, 1982) (22)	1.33	1.86	1.30	1.43
Clay lump content (%) NBR 7218 (ABNT, 1987) (23)	0	0	0	0
Powdery materials (%) NBR 7219 (ABNT, 2003) (24)	0.6	13.7	–	–
Organic impurities (ppm) NBR 7220 (ABNT, 2001) (25)	≤300	≤300	–	–

*Ds = Dissolved silica; *Ra = Reduction of alkalinity; mmol = milimoles

Figure 2 – Particle size distribution of the sand and tailings



curve of the cumulative percentages retained in 0.3 and 0.15 mm sieves, which corresponds to a marked reduction of the percentages retained in these sieves. Eventually, this may require some correction of fines by mixing in fine sand in order to improve this aspect of the granulometric composition during the production of concrete. However, if this mixture is needed, the technologist must be aware of the possibility of segregation occurring when blocks are molded, due to the difference in the specific weights of these aggregates, and take the appropriate steps to prevent this occurrence.
In the physical characterization tests for fine aggregates as established by the NBR 7211 standard [23], the tailings were in compliance with the standard, except for the content of powdery material. However, this did not affect their performance, as indicated by the results of the comparative compressive strength test of the mortars.
In the case of interlocking concrete components, a high content of fines contributes to the continuity of the particle size, contributing to the filler effect and favoring particle packing during the pressing of concrete blocks. Although powdery material does not necessarily constitute contamination, if it is present in excessive amounts, and depending on the desired characteristics of particle size distribution, it may eventually impair the workability and mechanical strength of the concrete. The NBR 7211 standard [23] specifies a maximum of 3% of material passing through a 75µm sieve for concretes subject to surface wear and of 5% for concretes protected from such wear. For aggregates deriving from industrial processes, such as the tailings under study, these percentages are increased to 10% and 12%, respectively. The inclusion of 14% of powdery material in the tailings of this study in no way compromised the use of this waste in the production of pavers. The large majority of concrete mix designs for the production of pavers include up to 25% of rock dust (limestone dust) relative to the total aggregate. A significant portion of this rock dust can be reduced advantageously, since the pulverulent material from the tailings replaces it partially and acts as filler, promoting the nucleation effect and improving the cementitious matrix.
According to Mehta and Monteiro [8], the specific density of heavyweight aggregates ranges from 3.4 to 6.5 kg/dm^3. According to the mineralogical compounds found in the tailings, such as hematite and goethite, the material can be classified as heavyweight aggregate [8].

3.1.5 Quality of the tailings used as aggregate, by comparison of the compressive strength of the mortars

Although these tailings contained no organic matter, in this research it was decided to test the quality of the aggregate according to the NBR 7221 standard [27]. The results of compressive strength obtained in mortars made with quartz sand of known origin and recognized as good quality, which is commonly used in concrete works in the metropolitan region of Belo Horizonte, were taken as a reference for this test. Due to the significant difference in density of the compared materials, the weighing of the fine aggregate had to be adjusted in order to equalize the volumes of material in the mortars for the quality test of the fine aggregate. Thus, the mortars under study were produced in the following mix designs (cement, aggregate, and water/cement ratio), which corresponded to the same volume of aggregate of 1,772 dm^3 in both mix designs:
- Mortar with sand: **1 : 2.35 : 0.6**
- Mortar with tailings: **1 : 3.30 : 0.6**

CPII E-32 Portland cement was used. Four 50 mm x 100 mm cylindrical specimens were molded for each mix and rupture age. The test specimens were ruptured at the ages of 3, 7, 14 and 28 days. Figure 3 shows the compressive strengths obtained with these mortars.
At all the ages, the mortar containing tailings showed higher compressive strength than the mortar containing sand, demonstrating the good quality of these tailings as fine aggregate for mortar.
To assess the magnitude of the increase in weight due to the specific gravity of the tailings, a comparison was made of the densities of the mortars using densified and hardened test specimens produced with washed sand and with the tailings. The reference mortar had an average density of 2.11 g/cm^3, while the mortar with tailings showed an average density of 2.78 g/cm^3, i.e., the mortar with tailings was found to be 31.65% heavier.

Figure 3 – Compressive strength of mortar made with sand and tailings

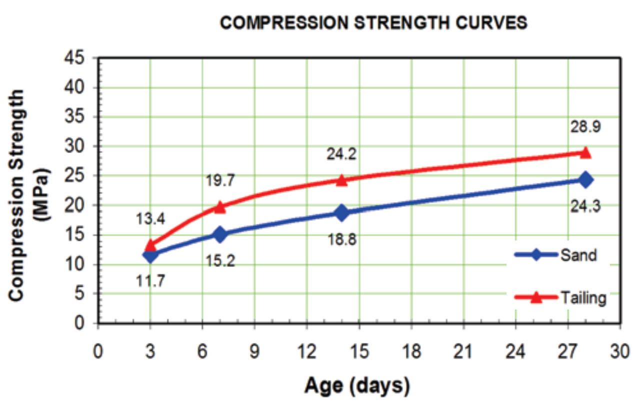


Table 5 – Characterization parameters of the cements used

Test		Cement CP II E 32	Cement CP V ARI
Insoluble residue (%)		2.4	0.73
Loss on ignition (%)		5.4	3.8
MgO (%)		2.3	0.76
SO^3 (%)		2.8	2.84
Normal consistency water (%)		28.6	31.0
Fineness # 200 mesh (%)		1.9	0.0
Fineness # 325 mesh (%)		11.8	1.8
Specific area (cm^2/g)		4021	4770
Onset of hardening (min.)		138	120
End of hardening (min.)		192	180
Hot expandability		–	0.0
Compressive strength – MPa	3 days	26.0	41.5
	7 days	29.6	45.9
	28 days	36.3	54.5

3.2 Characterization of the cements used in this study

This study was performed using CP II E 32 and CP V ARI Portland cement, respectively, in the first and second stages of the experimental program, whose characterization data are listed in Table 5.

3.3 Preparation of precast concrete pavers

The second phase of the experimental program, i.e., production of precast pavers, focused on verifying the performance of pavers (blocks) produced with concrete using the tailings, in a real situation of industrial production of these precast concrete paving blocks, compared with the conventional industrial production.

Figure 4 – Conventional Paver 8 concrete blocks

The aggregates currently used on a precast concrete production line were substituted partially and totally with the tailings, while the other routine production parameters established by the manufacturing plant were kept constant. The same parameters were adopted as those used in the production of one of the concrete blocks, called *Paver 8*, such as the concrete block design mix, materials, additives, amount of water, and vibropressing and curing times.

The *Paver 8* is an intermediate rectangular block on the production line, with dimensions of 10 x 20 x 8 cm. Figure 4 shows *Paver 8* blocks produced by the factory using conventional materials.

In this phase of the research, the following sequence of procedures was established as the methodology:

a) Determination of the particle size distribution of the aggregate in the mix currently used by the factory;
b) Definition of the experimental concrete mix designs to be produced with the tailings;
c) Production of blocks with the defined alternative mix designs;
d) Characterization and properties of the concrete blocks:
    - Dimensional determination – NBR 9781 [17];
    - Compressive strength – NBR 9780 [33];
    - Water absorption – adapted from the NBR 12118 standard [34];
    - Abrasive wear – adapted from the NBR 12042 standard [35].

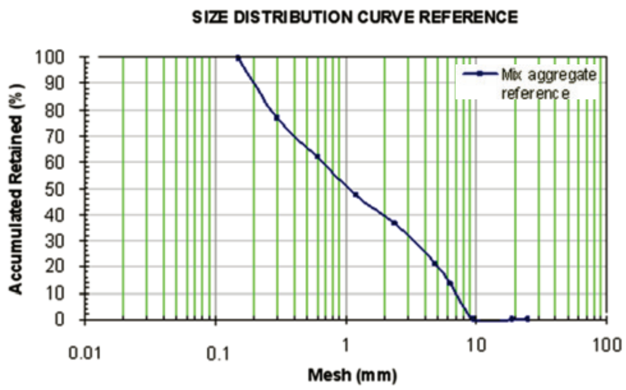
3.3.1 Materials used in the blocks

The following materials were used in the production of the reference blocks:

- Intermediate size washed quartz sand from Inhaúma, MG;
- Limestone dust from Pedro Leopoldo, MG;
- Calcareous crushed stone from Pedro Leopoldo, MG;
- CP V ARI Portland cement;
- Rehomix 610 surfactant base plasticizer additive;
- Water.

Figure 5 – Vibropress used in the production of the concrete blocks

Figure 6 – Particle size distribution of the aggregates the production of the blocks



3.3.2 Fabrication of the *Paver 8* blocks by the factory's current production process

Specifically with regard to its paving blocks line, the plant operates with a Trillor model MBX-975 Multiblock automatic hydraulic vibropress. Figure 5 shows the aforementioned press.

According to the concrete mix design used in the factory's current production, the cement was measured in terms of mass and the aggregate in volume. The concrete mix design used in the production of blocks, by concrete feed, consisted of:

- 2 handcarts of sand – 400 kg;
- 1 handcart of stone dust – 200 kg;
- 1 handcart of crushed stone – 200 kg;
- 160 kg of cement;
- 59 liters of water;
- 5 liters of plasticizer additive solution composed of 20 liters of the concentrate in 180 liters of water (≈ 3% of the cement mass);
- Water/cement ratio = 0.397.

The materials were mixed in a concrete mixer and the amount of water was controlled by sensors inside the mixer, to ensure that its moisture content remained in the range of 6.5 to 7.0% at the most, including the moisture from the sand. Figure 6 shows the particle size distribution of the aggregates of the adopted mix design.

After loading the mixer of the vibropress, the sequence of operations consists of:

1. Pouring of the concrete into the molds and vibropressing under a pressure of approximately 90 bar for 5 to 7 seconds;
2. Transfer of the tray containing the pavers to shelves, to rest for 24 hours;
3. Palletization of the precast concrete blocks and transfer to the curing areas (wet chamber or wetting yard) for 7 days;
4. Transfer of the finished palletized product to the stocking area.

To sample the blocks made of conventional concrete, a date and time was defined randomly during the factory's production operation, from which samples of the *Paver 8* blocks were collected. After these blocks were processed according to the above described manufacturing sequence, they were used as the reference blocks that were subjected to compressive strength, water absorption, and abrasive wear testing.

A total of 18 blocks were selected for the compressive strength tests, i.e., 6 test specimens of each of the curing ages of 7, 14 and 28 days, according to the NBR 9781 standard [17]. Six test specimens were tested according to the NBR 9780 standard [32] and ruptured at each curing age. The characteristic compressive strength was calculated using Equation (1):

$$f_{pk} = f_p - t * s \quad (1)$$

where:

f_{pk} = characteristic compressive strength, in MPa;
f_p = average compressive strength of the blocks, in MPa;
s = standard deviation of the sample, calculated by Equation (2);

$$s = \sqrt{\frac{\sum (f_p - f_{pi})^2}{n - 1}} \quad (2)$$

where:

f_{pi} = individual compressive strength of the test specimens, in MPa;
n = number of blocks in the sample (6 blocks);
t = Student's coefficient, which varies according to the number of tested specimens.

The Student's coefficient adopted in this test was 0.920, as a function of the number of test specimens at each age, according to the NBR 9781 standard [17].

The water absorption tests were applied to three test specimens at the age of 28 days. The results were analyzed based on the calculated average absorption of the 3 tested specimens. The individual water absorption of each test specimen was calculated using Equation (3):

Table 6 – Compositions studied

Composition 1	Composition 2	Composition 3	Composition 4	Composition 5	Composition 6
100% tailings	75% tailings	75% tailings	75% tailings	50% tailings	50% tailings
25% rock dust	25% crushed rock	25% sand	50% sand	25% sand	25% rock dust

$$a = \frac{m_2 - m_1}{m_1} * 100 \quad (3)$$

where:
a = total absorption, in %;
m_1 = mass of the oven-dried test specimen, in kg;
m_2 = mass of the saturated test specimen, in kg.
Four blocks were selected for the abrasive wear tests, comprising 2 samples of 2 test specimens each, for analysis at the age of 28 days. A cubic test specimen with dimensions of 6 x 6 x 8cm was prepared from each block. Sample 1 consisted of a pair of cubes comprising two test specimens, CP1A and CP1b. Sample 2 also consisted of two cubes comprising two test specimens, CP2a and CP2b. Partial wear was measured after 250 cycles of the abrasive disc, corresponding to 500m, and total wear after 500 cycles of the abrasive disc, corresponding to 1000m. In both steps, the absolute values of wear were expressed as mass loss of the specimens, calculated by equation (4):

$$d = \frac{m_i - m_0}{m_0} * 100 \quad (4)$$

where:
d = abrasive wear expressed by mass loss, in %;
m_i = mass of the test specimen after the partial or total wear test, in g;
m_0 = initial mass of the test specimen, in g.
To analyze the data, the average wear of the four test specimens after the 500 cycles of the abrasive disc was also calculated. The abrasive wear test was performed using a Pavitest Amsler abrasion tester illustrated in Figure 7.

3.3.3 Production of *Paver 8* blocks with sinter feed tailings

To develop this research within the parameters of established objectives, the following procedures were defined:

- Study of granulometric compositions, taking as reference the company's production of blocks (Figure 6);
- This study considered the conditioning and convenience factors of the factory's routine production process, in which the unit volume adopted for the aggregate was equivalent to one handcart normally used.
- The composition containing tailings that most closely resembled the company's reference was the base mix design of this research, considering that the closest approximation was the highest tendency of superposition or proximity to the respective particle size curve.
- Two other compositions that closely resembled the company's reference were the second and third mix design of this research, and were established simply for the purpose of studying compositions and comparing the results.

Figure 7 – Amsler abrasion tester

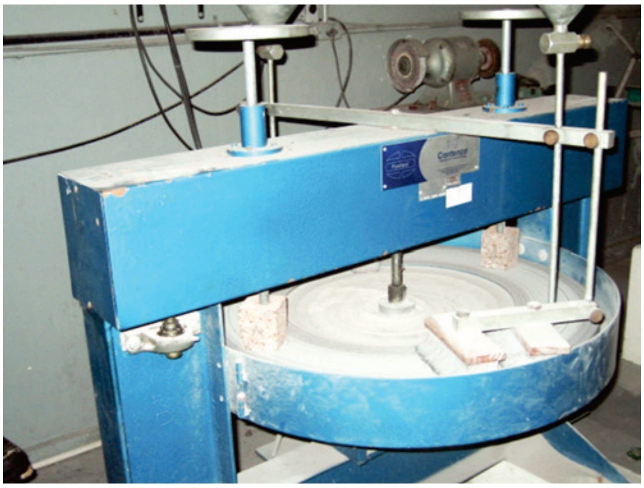


Figure 8 – Granulometric compositions closest to the reference composition

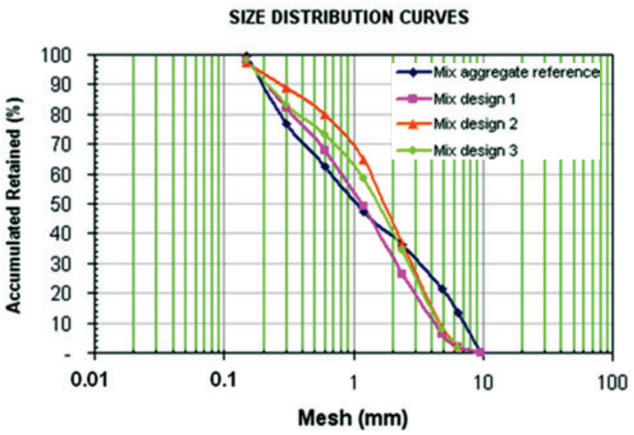


Figure 9 – Paver 8 blocks produced with sinter feed tailings

- The other production parameters were kept constant, without variation, in the proportion of the tested mix designs.

Six granulometric compositions were analyzed, and the ones whose curves were closest to that of the reference composition are shown in Figure 8. Table 6 summarizes the studied compositions.
Based on an analysis of the curves of the granulometric compositions, considering the respective fineness moduli, it was decided to adopt compositions 4, 5 and 6 and their respective mix designs. Therefore, blocks were produced using mix designs 1, 2 and 3, and samples were extracted with their respective test specimens. Figure 9 illustrates the Paver 8 block made with sinter feed tailings.
Mix 1/composition 4: 75% tailings + 25% sand;
Mix 2/composition 5: 50% tailings + 50% sand (mix whose granulometric composition was closest to that of the reference composition);
Mix 3/composition 6: 50% tailings + 25% sand + 25% rock dust.

4. Results and discussion

TABLES 7, 8 and 9, respectively, list the results of the compressive strength, water absorption and abrasive wear tests of each of the three mix designs of this study, produced with the tailings and the reference mix normally used in the factory's production process, in samples extracted from *Paver 8*. Figure 10 summarizes the average results of each of the performance tests of the blocks.
Based on the results listed in Tables 7 to 9 and in Figure 10, the following can be concluded:
At 28 days of age, the characteristic compressive strength of the blocks produced with sinter feed tailings, in mix designs established only with the composition adjustments cited in 3.2.3, presented compressive strengths very similar to those obtained in the production of reference of the factory, albeit slightly lower. No specific studies of technological adjustments of the concrete mix designs were developed in this research, and it was found that a production system with the mix design of aggregates in mass would undoubtedly contribute considerably to improve this performance.
The compressive strength of mix 1, containing the highest percentage of tailings (75%), was the one closest to that of the reference, showing a decrease in compressive strength of only 2.5%, which is negligible. The higher content of tailings, and hence of iron, in mix 1, due to its physical and mineralogical characteristics, explain its better performance compared to those of mixes 2 and 3. The latter showed a decrease in compressive strength of 6.6% and 11.0%, respectively. However, these results did not defeat the overall purpose of this research, which was to reach a conclusion about the technical feasibility and ecological

Figure 10 – Summary of the results of the mix designs of this study vs. the mix design of reference

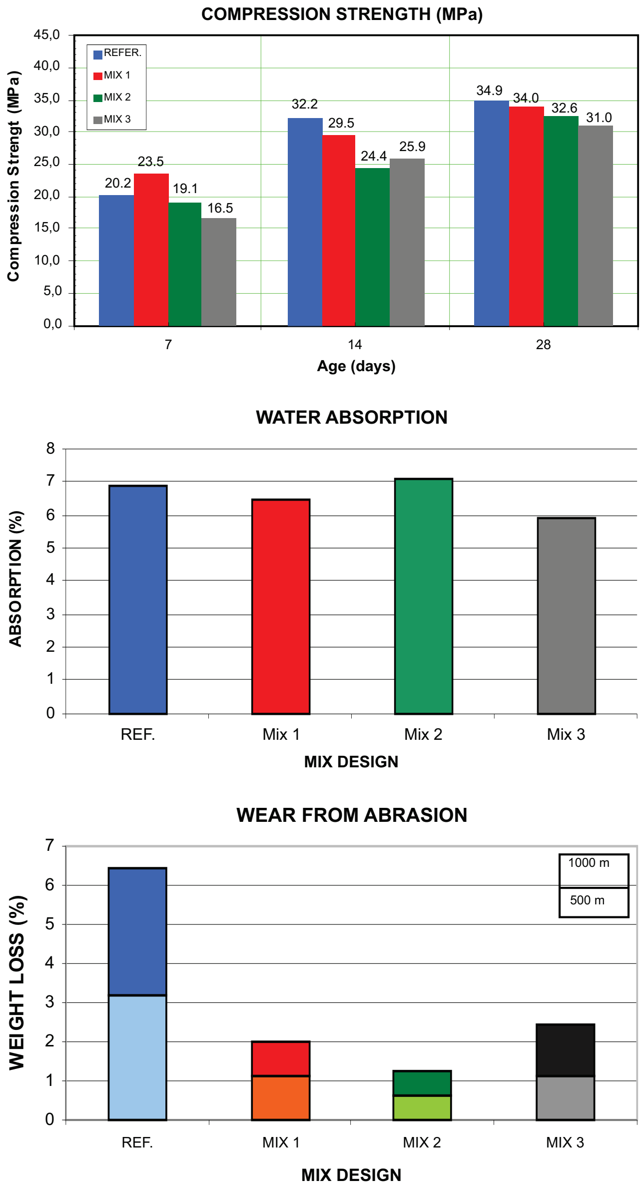


Table 7 – Compressive strength performance of the blocks

Compression strength (MPa)								
Specimens Paver 8		Results of strength						Characteristic strength
		Individual values/average value						
		1° Result.	2° Result.	3° Result.	4° Result.	5° Result.	6° Result.	
Ages	7	23.97	22.45	31.28	31.69	28.56	24.93	
				27.15				**23.54**
	14	35.29	37.78	38.27	31.12	29.71	28.48	
				33.44				**29.55**
	28	36.25	34.20	33.80	34.50	35.61	34.80	
				34.86				**34.02**
Mix design 1								

Compression strength (MPa)								
Specimens Paver 8		Results of strength						Characteristic strength
		Individual values/average value						
		1° Result.	2° Result.	3° Result.	4° Result.	5° Result.	6° Result.	
Ages	7	19.63	21.49	24.44	20.89	22.70	18.06	
				21.20				**19.13**
	14	25.31	22.92	27.02	26.09	29.09	27.98	
				26.40				**24.40**
	28	34.83	33.23	38.48	37.14	30.73	37.49	
				35.32				**32.60**
Mix design 2								

Compression strength (MPa)								
Specimens Paver 8		Results of strength						Characteristic strength
		Individual values/average value						
		1° Result.	2° Result.	3° Result.	4° Result.	5° Result.	6° Result.	
Ages	7	18.34	15.78	16.43	19.74	18.01	19.48	
				17.96				**16.50**
	14	24.56	31.23	26.64	28.91	28.56	27.91	
				27.97				**25.90**
	28	30.23	31.19	33.64	34.20	33.17	32.33	
				32.46				**31.06**
Mix design 3								

Compression strength (MPa)								
Specimens Paver 8		Results of strength						Characteristic strength
		Individual values/average value						
		1° Result.	2° Result.	3° Result.	4° Result.	5° Result.	6° Result.	
Ages	7	24.5	23.72	19.02	23.83	27.43	19.95	
				23.08				**20.22**
	14	32.69	34.83	32.4	35.18	31.99	33.45	
				33.42				**32.21**
	28	36.17	36.15	34.5	38.53	36.64	35.18	
				36.20				**34.92**
Reference								

Table 8 – Water absorption performance of the blocks

Specimens Paver 8		Water absorption			
		Water absorption results (%)			Average absorption
		Values of weight (Kg)			
		Dry weight (air)	Oven-dried	Saturated surface dry	
Specimen	CP 1	3.76	3.61 **6.87**	3.86	**6.46**
	CP 2	3.77	3.59 **5.46**	3.79	**6.46**
	CP 3	3.57	3.41 **7.04**	3.65	**6.46**
Mix design 1					

Specimens Paver 8		Water absorption			
		Water absorption results (%)			Average absorption
		Values of weight (Kg)			
		Dry weight (air)	Oven-dried	Saturated surface dry	
Specimen	CP 1	3.41	3.26 **7.29**	3.50	**7.12**
	CP 2	3.74	3.57 **6.68**	3.80	**7.12**
	CP 3	3.46	3.30 **7.39**	3.55	**7.12**
Mix design 2					

Specimens Paver 8		Water absorption			
		Water absorption results (%)			Average absorption
		Values of weight (Kg)			
		Dry weight (air)	Oven-dried	Saturated surface dry	
Specimen	CP 1	3.43	3.22 **5.28**	3.39	**5.90**
	CP 2	3.51	3.33 **6.31**	3.54	**5.90**
	CP 3	3.46	3.27 **6.12**	3.47	**5.90**
Mix design 3					

Specimens Paver 8		Water absorption			
		Water absorption results (%)			Average absorption
		Values of weight (Kg)			
		Dry weight (air)	Oven-dried	Saturated surface dry	
Specimen	CP 1	3.35	3.25 **6.15**	3.45	**6.86**
	CP 2	3.30	3.15 **6.35**	3.35	**6.86**
	CP 3	3.25	3.10 **8.06**	3.35	**6.86**
Reference					

Table 9 – Abrasive wear performance of the blocks

Wear from abrasion test								
Especimen extracted of Paver 8		Weight loss result (%)						
		250 laps = 500m of friction			500 laps = 1000m of friction			500 laps Average loss
		Initial weight	Final weight	Parcial difference	Initial weight	Final weight	Total difference	
Especimen	CP 1a	916.28	903.68 **1.38**	12.60	916.28	898.44 **1.95**	17.84	**1.98**
	CP 1b	839.90	833.26 **0.39**	6.64	839.90	822.96 **2.02**	16.94	**1.98**
	CP 2a	905.10	892.13 **1.43**	12.97	905.10	888.20 **1.87**	16.90	**1.98**
	CP 2b	815.30	807.11 **1.00**	8.19	815.30	798.11 **2.11**	17.19	**1.98**

Mix design 1

Wear from abrasion test								
Especimen extracted of Paver 8		Weight loss result (%)						
		250 laps = 500m of friction			500 laps = 1000m of friction			500 laps Average loss
		Initial weight	Final weight	Parcial difference	Initial weight	Final weight	Total difference	
Especimen	CP 1a	757.46	749.40 **1.06**	8.06	757.46	745.40 **1.95**	12.06	**1.26**
	CP 1b	846.12	842.80 **0.39**	3.32	846.12	838.40 **0.91**	7.72	**1.26**
	CP 2a	862.13	858.70 **0.40**	3.43	862.13	851.23 **1.26**	10.90	**1.26**
	CP 2b	961.25	955.03 **0.65**	6.22	961.25	949.20 **1.25**	12.05	**1.26**

Mix design 2

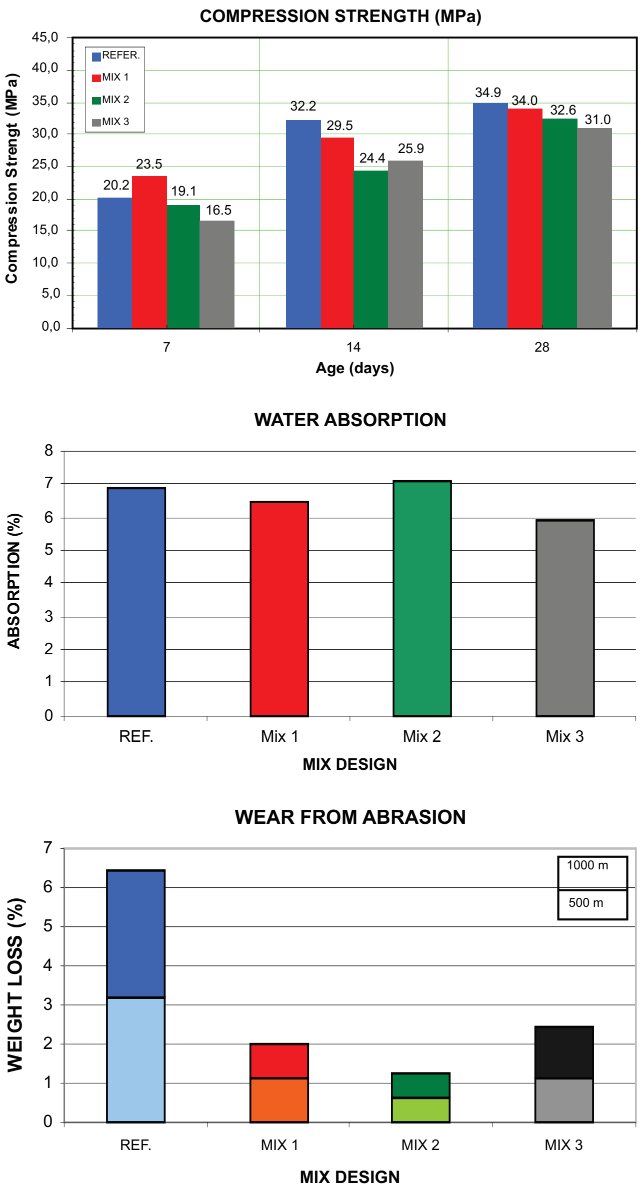
Wear from abrasion test								
Especimen extracted of Paver 8		Weight loss result (%)						
		250 laps = 500m of friction			500 laps = 1000m of friction			500 laps Average loss
		Initial weight	Final weight	Parcial difference	Initial weight	Final weight	Total difference	
Especimen	CP 1a	837.17	825.03 **1.45**	12.14	837.17	815.00 **2.65**	22.17	**18.85**
	CP 1b	774.75	766.35 **1.08**	8.40	774.75	753.77 **2.71**	20.98	**18.85**
	CP 2a	811.45	803.33 **1.00**	8.12	811.45	796.81 **1.80**	14.64	**18.85**
	CP 2b	744.30	735.96 **1.12**	8.34	744.30	725.45 **2.53**	18.85	**18.85**

Mix design 3

Wear from abrasion test								
Especimen extracted of Paver 8		Weight loss result (%)						
		250 laps = 500m of friction			500 laps = 1000m of friction			500 laps Average loss
		Initial weight	Final weight	Parcial difference	Initial weight	Final weight	Total difference	
Especimen	CP 1a	704.54	686.65 **2.54**	17.98	704.54	670.76 **4.79**	33.78	**6.45**
	CP 1b	658.64	637.61 **3.19**	21.03	658.64	619.66 **5.92**	38.98	**6.45**
	CP 2a	671.93	644.27 **4.12**	27.66	671.93	621.02 **7.58**	50.91	**6.45**
	CP 2b	596.33	578.85 **2.93**	17.48	596.33	551.58 **7.50**	44.75	**6.45**

Reference

Figure 10 – Summary of the results of the mix designs of this study vs. the mix design of reference



advantage of using sinter feed tailings, which can be inferred from the results achieved simply by adjusting the granulometric composition of the aggregates. The variations in the average results shown in Figure 10 are justified by the fact that they come from samples collected from the company's normal production line, operating in the aforementioned conditions, and do not represent a production lot of laboratory accuracy.

The NBR 9781 standard [17] establishes as a requisite a minimum characteristic compressive strength of 35 MPa for precast concrete blocks used for paving streets destined for light to moderate traffic of commercial vehicles. This compressive strength is easily achieved by means of a specific experimental mix design and by proportioning the materials by weight, as mentioned in the preceding paragraph.

At 28 days of age, the average water absorption rates of the blocks made of the mix designs containing sinter feed tailings were very close to those of the reference production blocks. Mix 1 showed a 5.8% decrease in water absorption, while mix 2 showed an increase of 3.8% compared to the reference mix. Mix 3 showed better performance than mixes 1 and 2, with a 14% decrease in water absorption compared to the reference blocks. The lower percentage of tailings in this mix (50%), allied to the percentage of sand and rock dust (25% and 25%, respectively), undoubtedly favored a more continuous particle size, with a lower voids index, thus leading to lower water absorption.

The abrasive wear at 28 days of age of the mixes produced with sinter feed tailings showed much lower mass losses than those of the reference mix, after both 250 cycles and 500 cycles of the abrasive disc. The abrasive wear of mix 2 (50% tailings and 50% sand) showed the best overall performance, reflecting an 80% lower wear than that of the reference mix. Mixes 1 and 3 showed lower percentages of total wear, i.e., 69% and 62%, respectively, than that of the reference mix. The higher abrasive wear performance of the blocks containing tailings in relation to that of the reference blocks is attributed to the significant Fe content in sinter feed tailings.

5. Conclusions

This study involved an evaluation of the technical feasibility of using sinter feed tailings as aggregate in the production of concrete for the manufacture of precast concrete pavers, as well as the ecological advantage of using this type of waste, given the huge amounts of this waste generated at iron ore mining sites.

The characteristic compressive strength of the blocks produced with sinter feed tailings was very close to those obtained in the industrial production of reference, thus indicating a promising potential for the development of this technology.

The results of the water absorption tests of the blocks made with sinter feed tailings were similar to that of the reference blocks, corroborating the aforementioned conclusion.

As for abrasive wear, the excellent performance of the blocks containing sinter feed tailings is attributed to the substantial Fe content still contained in this waste, favoring its application in floors and pavements subjected to surface wear and other forces, thus confirming the significant advantages of using this material.

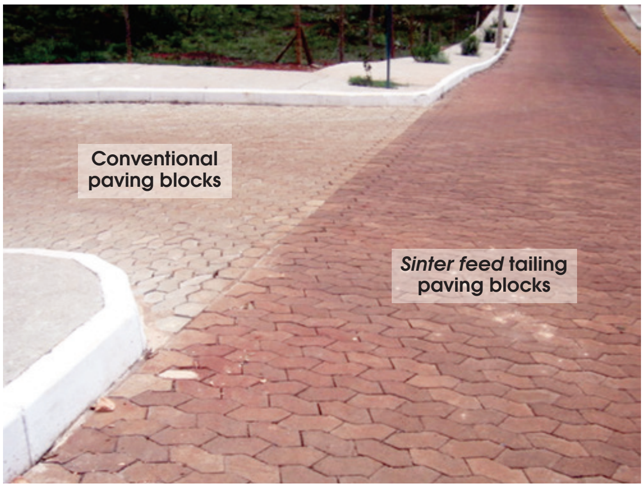
From an environmental standpoint, the use of this waste is also appropriate. Its use as an aggregate for concrete pavers, as an alternative substitute of natural sands, represents significant benefits to the environment as well as to mining companies.

6. Final remarks

Considering the higher density of sinter feed tailings compared to that of the aggregates currently used (sand and crushed rock), it is suitable to use this material in concrete pavers set directly on the ground, in the form of a variety paving elements, as illustrated in Figure 11. Other feasible applications for these tailings may be in concrete masonry blocks, also set on the ground, in floor beams or in continuous foundations. Additional applications could be evaluated, such as containment structures, in which weight is also a relevant and preponderant factor.

From the economic standpoint, it should be noted that a specific economic analysis is advisable on a case by case basis, due solely to the weight of the aggregate. Depending on the distance, a second transport of the finished product may diminish the economic advantages and thus prove not be the best alternative. Thus, the production of these concrete blocks may be more advantageous when they are manufactured at or near the site where they are to be applied, which is usually a feasible situation at larger projects such as housing developments, and the construction and/or paving of new streets or neighborhoods.

Figure 11 – View of an experimental section of pavement showing conventional concrete blocks and blocks containing sinter feed tailings



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