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Use of Sinter-Feed Tailings as Aggregate in Production of Concrete Paving Elements

Ayrton V. Costa, Adriana G. Gumieri

Department of Materials Engineering and Construction; Federal University of Minas Gerais, Rua Espírito Santo, 35, Belo Horizonte, MG, CEP 30160-030, Brazil. E-mail: <ayrton@evise.com.br>,< adriana@demc.ufmg.br>.

ABSTRACT

Brazil holds the world's sixth largest iron ore deposits and is the second largest producer of iron. Sinter-feed tailing is a residue from the iron ore production process. During this process, the material is subjected to washing and sieving operations. This waste is dumped around mining areas, harming the environment. This paper discusses a study of the use of sinter-feed tailing employed as fine aggregate in the production of pre-molded concrete destined for pavement applications. The tailing was subjected to physical, chemical, mineralogical, environmental and microstructural characterization and to a study of its durability and mechanical performance as aggregate. The waste is constituted of hematite, quartz and goethite-limonite and is classified as inert. It is considered an innocuous aggregate in terms of potential alkali-aggregate reactivity. The material displayed a satisfactory performance with respect to its technical and environmental properties, favoring its use in the production of concrete pavement elements.

INTRODUCTION

The search for a useful purpose for wastes from mining and ironworks has been a constant concern of companies that engage in these activities, as well as of environmentalists, research institutions and control agencies interested in preserving environmental quality. In the ironworks sector, major advances have been made in the use of certain types of slag as an important component in the production of some Portland cements, contributing to significant savings in their production, improvements of their characteristics, and particularly, the intelligent use of wastes generated in ironworks. In the rock quarrying sector, materials that in the past were crushed stone waste are gaining increasing market acceptance today as artificial sands, thanks to low investments and the establishment of another phase of treatment of the fine fraction from crushing.

Natural quartz sand extracted from river banks or beds is obtained by means of leveling or dredging. Both forms of extraction contribute enormously to the environmental degradation of quarrying sites and their surroundings, which are usually located near large urban centers. The environmental degradation caused by sand extraction is characterized principally by the removal of the vegetal cover, by widespread erosion of exploited areas, silting of water courses, and significant changes in the landscape. Natural sand is a finite and nonrenewable resource that has become increasingly scarce in the surroundings of large cities, and is also highly heterogeneous. Its extraction from more distant areas increases transport costs.

Brazil possesses the world's sixth largest iron ore deposits, representing almost 7% of the world's reserves [Quaresma 2001], and is the second largest producer or iron ore. In 2008, the country produced 380 million tons, equivalent to 19% of the worldwide production, which is almost 1.9 billion tons [IBRAM 2009]. The high iron content of Brazilian ore (60 to 67% in hematite and 50 to 60% in itabirite) places Brazil at the forefront of the worldwide scenario in terms of iron contained in iron ore. The state of Minas Gerais is responsible for more than 72% of these reserves, standing out for its large number of mining plants, especially iron mining, scattered throughout the region [Quaresma 2001].

Iron ore is used in the metallurgical industry (99%) and the remainder is used as filler in the ferro-alloy, cement and road construction industry. It can be used as granulated ore and agglomerates (sinter or pellets). Granulates (6 to 25 mm) are added directly into reduction furnaces, while agglomerates are the finer materials. The main agglomeration processes are sintering and pelletization. Sintering produces sinter feed (0.15 to 6.35 mm) while pelletization produces pellet feed (smaller than 0.15mm). Iron ore with an average content of 65% iron, 3% silica, 3% aluminum, and low phosphorus content is used in blast furnaces for the production of pig iron and in direct reduction furnaces for the production of sponge iron. Sinter feed is destined for integrated steel mills [Quaresma 2001].

Sinter-feed tailings are wastes from the iron ore production process, which, to date, serve no commercial purpose. During the iron ore production process, the material is subjected to washing and sieving operations, generating a waste without contaminants and with a reasonably regular granulometry. This material also contains a substantial amount of iron, which cannot be separated solely by the magnetic separation process. Over the years, this waste has been deposited on enormous slag heaps around mining areas, which are harmful to the environment and represent costs related to their disposal and environmental control.

The suitability of the use of this waste as aggregate for concrete (obtained by the determination of the ideal trace, adjustment of the most adequate granulometry, eventual corrections of fines and of the maximum diameter of the aggregate), can be obtained easily by the practices of adjustment of production of the concretes.

The objective of this work is to characterize sinter-feed tailings, aiming at their application as small aggregates in the production of prefabricated concrete elements for paving. The tailings are evaluated based on their physical, chemical, mineralogical, and environmental characterization, according to quality parameters adopted for aggregates used in concretes. The sinter-feed tailings under study come from a mining plant located in the municipality of Sarzedo, state of Minas Gerais, Brazil, which is representative of the profile of iron ore mining developed in the region.

METHODOLOGY

Sampling of the waste was carried out following the recommendations of the Brazilian standards [ABNT NBR 10007; ABNT NBR 7216], by collecting partial samples from various points in the stockpiles (top, at half height and bottom of the piles) and from piles with various ages of formation, in order to obtain a homogeneous sample that would ensure the representativeness of the waste. The material was subjected to the following assays:

- Chemical characterization;
- Mineralogical characterization by X-ray diffraction;

- Obtainment of the leached extract of the waste [ABNT NBR 10005];
- Obtainment of the solubilized extract of the waste [ABNT NBR 10006];
- Classification of the solid waste [ABNT NBR 10004];
- Potential alkali-aggregate reactivity [ABNT NBR 9774];
- Accelerated durability test of the aggregate - soundness test [DNER ME 089];
- Granulometric composition of the aggregate [ABNT NM 248];
- Specific gravity [ABNT NM 52];
- Bulk density [ABNT NBR 7251];
- Clay content in clumps and friable materials [ABNT NBR 7218];
- Content of pulverizable material [ABNT NM 46];
- Content of organic impurities [ABNT NM 49];
- Quality assay of the small aggregate [ABNT NBR 7221]. For the quality assay of the small aggregate, the results of axial compression strength obtained for mortar using a natural quartz sand of known origin and recognized quality normally used in concrete works in the region were taken as reference;
- Polished sections and thin blades of mortar for optical microscopy analysis.

RESULTS AND DISCUSSION

Chemical Characterization

Table 1 presents the chemical composition of the sinter-feed tailing. After separation of the iron by the magnetic roll separation process, the material still contains a large quantity of this element in the non-magnetic condition, which is why this process is inefficient for a greater separation.

Table 1. Chemical Composition of the Sinter-Feed Tailing

Elements/Oxides					
Fe	SiO_2	Al_2O_3	P	Mn	PPC
55.85	14.78	1.65	0.16	0.44	2.68

Leaching and Solubilization of the Waste

Tables 2 and 3 present the results of leaching and solubilization of the sinter-feed tailings and the maximum values allowed according to the Brazilian standard [ABNT NBR 10004].

Table 2. Leaching Test of the Sinter-Feed Tailing

Parameter	Tailing (mg/l)	Maximum allowed value (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	< 0.0002	0.1
Selenium	< 0.0005	1.0

Table 3. Solubilization Test of the Sinter-Feed Tailing

Parameter	A (mg/l)	B (mg/l)	Maximum allowed value (mg/l)
Silver	< 0.01	< 0.01	0.05
Aluminum	< 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	< 0.0002	< 0.0002	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

None of the constituents of the sinter-feed tailings were solubilized at concentrations exceeding the standards of water potability, according to the Brazilian standard [ABNT NBR 10004]. Based on the results, the sinter-feed tailings were classified as Class II B, which corresponds to inert wastes.

Mineralogical Characterization

The mineralogical characterization of the waste by X-ray diffraction indicated that the major constituent minerals were hematite (Fe_2O_3) and quartz (SiO_2) and the minor constituents were goethite/limonite (FeO(OH)), anatase (TiO_2), aluminum phosphate ($AlPO_4$) and manganese oxide hydrate (MnO(OH)).

Alkali-Aggregate Reactivity

Table 4 presents the results of the potential alkali-aggregate reactivity test for the sinter-feed tailings. Based on a chemical method, the test serves to ascertain the potential reactivity of aggregates with alkalis of Portland cement, by means of the reaction between a sodium hydroxide 1N solution and the aggregate. The results are expressed by the quantity of dissolved silica and by the reduction of alkalinity, and are classified as innocuous, deleterious or potentially deleterious. The results obtained indicate that sinter-feed tailings can be considered innocuous.

Table 4. Alkali-Aggregate Reactivity of the Sinter-Feed Tailing

Sample	Dissolved silica (millimoles/liter)	Reduction of alkalinity (millimoles/liter)
1	7	446

Accelerated Durability Test

This accelerated chemical test serves to measure the total wear of the aggregate, by granulometric range, based on its mass loss after five cycles of washing in sulfate solutions (magnesium sulfate). The sinter-feed tailings showed a wear of 2%, which is well below the maximum value of 12% allowed by the specifications.

Granulometric Composition

Table 5 presents the granulometric compositions of sinter-feed tailings and washed sand obtained by the sieving method, and the values specified for concrete aggregates according to the Brazilian NBR 7211 standard [ABNT NBR 7211].

Table 5. Granulometric Composition: Sinter-Feed Tailing and Washed Sand

Mesh Size (mm)	Accumulated Retained (%)					
			Usable range		Optimal range	
	Tailing	Sand	Lower	Upper	Lower	Upper
9.5	0	0	0	0	0	0
6.3	2	0	0	7	0	0
4.8	7	0	0	10	0	5
2.4	25	2	0	25	10	20
1.2	47	8	5	50	20	30
0.6	68	42	15	70	35	55
0.3	77	91	50	95	65	85
0.15	83	99	85	100	90	95
Fineness Modulus	3.07	2.42				
Maximum Dimension	6.3	2.4				

The waste presents a coarse sand granulometry close to the upper limit of the usable range, with the sample presenting a maximum diameter of 6.3 mm and a fineness modulus of 3.07. The sand taken as reference is intermediate, falling almost entirely within the usable range, with a maximum diameter of 2.4 mm and a fineness modulus of 2.42. Therefore, the sinter-feed tailing is coarser than the washed sand, as depicts the Figure 1.

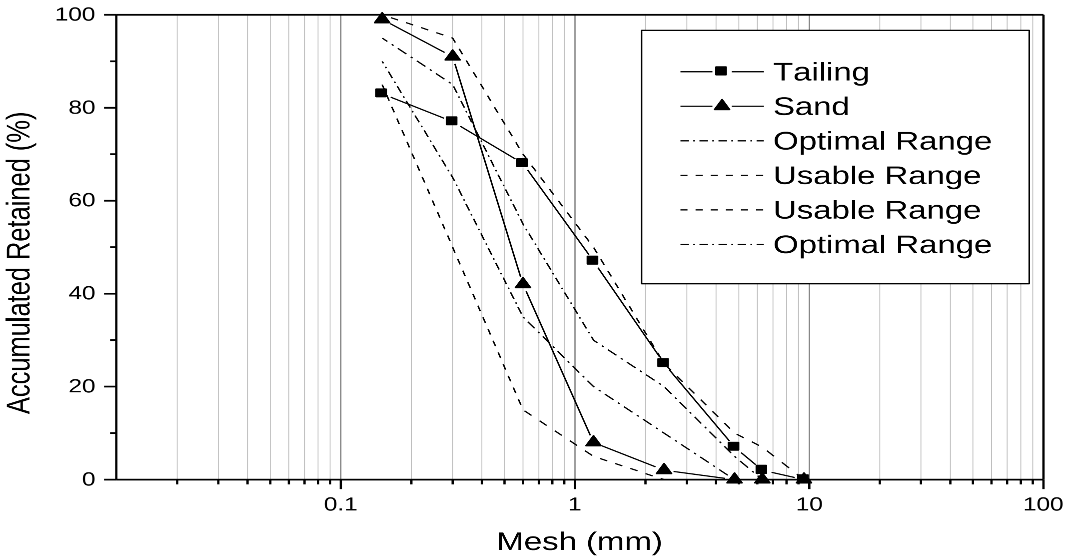

Fig. 1. Granulometric Curves of the Materials

Specific Gravity and Bulk Density

Specific gravity and bulk density are important parameters for classifying aggregates as light, normal or heavy [Mehta and Monteiro 2006]. Specific gravity is a parameter that allows for the theoretical calculation of the consumption of cement per cubic meter of the concrete traces [Carvalho 1989]. Sinter-feed tailings have a specific density of 3,756 kg/dm^3, which is higher than the 2,653 kg/dm^3 obtained for sand. Bulk density (apparent) is an important parameter for establishing the traces of concrete in volume, starting from the experimental dosages developed here. The sinter-feed tailings showed a bulk density of 1,862 kg/dm^3**,** which is higher than the 1,326 kg/dm^3 obtained for sand. This waste is therefore classified as a heavy aggregate, which will result in heavier concrete pieces. The high density of the waste is related mainly to its high iron content compared to that of sand, which could not be separated by the existing magnetic roll process. This would require setting up a jig installation that would allow for greater separation of the iron ore by the gravimetric system, but which, on the other hand, would result in high water consumption and high investments, whose cost-benefit ratio would certainly not have justified its adoption to date.

To evaluate the order of magnitude of this weight increase, comparisons were made of the densities of mortars using specimens produced with a conventional intermediary washed sand and with the sinter-feed tailings. The average specific density of the former was 2,112 g/cm^3, while that of the latter was 2,780 g/cm^3, i.e., the mortar produced with the tailings was 31.65% heavier. Therefore, in principle, its interest as an aggregate material for use in reinforced concrete works is not foreseen, since this would imply a much higher structural self-weight than that usually considered in the design of normal works, with the natural consequences that would imply.

However, as an aggregate in the production of concrete for paving elements for direct application on the ground, this material would represent not only ecological advantages in the use of these wastes but would also result in paving with greater self-weight, less subject to deformations resulting from external loads.

Another feasible application for this material would be in the production of concrete blocks for single-floor buildings, in which this increase in weight applied directly on the ground would not represent a relevant increase in costs. From the esthetical standpoint, in paving for example, the use of this waste gives the pieces a light brown coloring, which is very interesting and which, after it is laid down, renders pavements less subject to staining and eventual incrustation of dirt accumulated over time.

Clay Content in Clumps and Friable Materials

This test is important to quantify eventual contaminations of the aggregate by clay or friable materials which may, during the processing of concrete, break up into fines, compromising the dosage of water and cement, and the workability and mechanical strength of the concrete. The waste sample of this study is devoid of clay lumps and friable materials. The Brazilian standard establishes a maximum content of 3% in aggregates for concretes.

Content of Pulverizable Materials

Similarly to clay lumps, pulverizable material does not necessarily constitute contamination. However, if present in excessive quantities and depending on the desired characteristics of the granulometric composition, it may constitute an excess of fines, which may eventually impair the workability and mechanical strength of the concrete. For this element, the Brazilian standard establishes a maximum of 3% in concretes subject to surface wear and of 5% in concretes protected against wear. For aggregates originating from industrial processes, these percentages increase to 10% and 12%, respectively. The sinter-feed tailings of this study contain 13.7% of pulverizable materials, i.e., particles smaller than 75 µm, which is slightly above the specified limit.

Organic Impurities

Organic impurities may affect the hydration reactions of cement and the formation of its principal compounds, compromising the mechanical strength and durability of concretes. The Brazilian standard establishes a maximum of 300 ppm in aggregate samples (determined colorimetrically), and if a tested aggregate presents a higher value than this maximum, a quality assay of the aggregate should be done to evaluate the compressive strength of mortars containing the aggregate. The sodium hydroxide solution in contact with the sinter-feed tailings presented a paler coloring than the standard solution, thus indicating the low content of organic matter.

Quality Assay of the Aggregate Based on the Compressive Strength of the Mortars

Although the sinter-feed tailings showed a low content of organic matter, the mortars containing this waste and quartz sand were subjected to an axial compression test. Due to the significant difference in the density of the two materials, this test required an adjustment of the proportion used in the mortars in order to equalize the volumes of material contained in the produced mortars. Therefore, the mortars were produced with the following traces, in mass, (cement, aggregate and water), which corresponded to the same volume of aggregates:

- mortar with quartz sand: 1 : 2.35 : 0.60
- mortar with sinter-feed tailings: 1 : 3.30 : 0.60

The water/cement ratio adopted for the two mortars was 0.60 and the cement used was Portland CPII-E-32 [ABNT NBR 11578], whose composition may present up to 34% of blast furnace slag. Four (4) test specimens were molded with a diameter of 50 mm x 100 mm for rupture at the ages of 3, 7, 14 and 28 days. Figure 2 presents the results of the strengths obtained. The mortar containing the waste showed higher axial compression strength than the mortar of reference, indicating the good performance of mortar containing sinter-feed tailings, in terms of its mechanical properties.

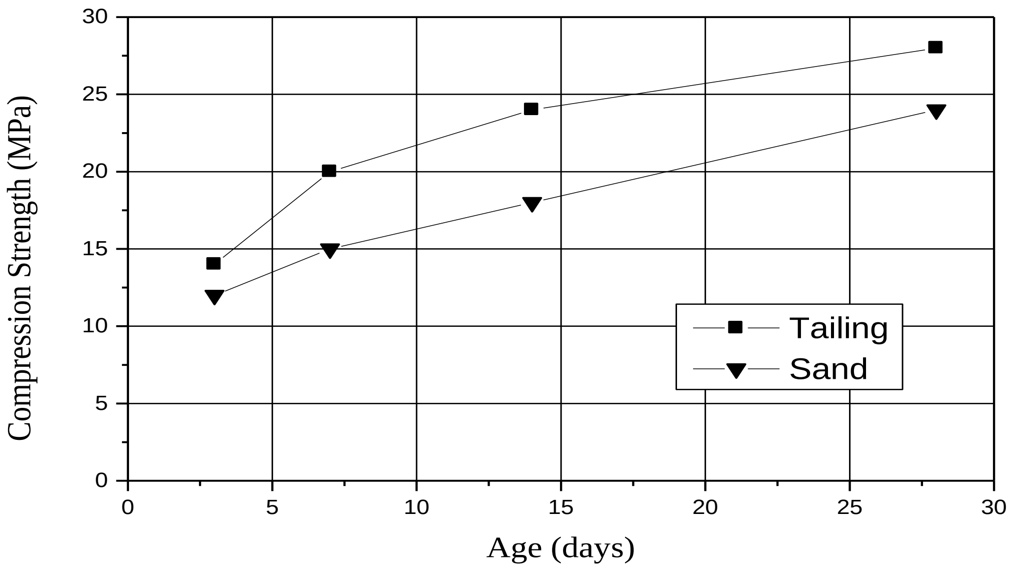

Fig. 2. Compression Strength of Mortars

Microstructural Analysis of the Mortar Containing the Waste

The mortar containing sinter-feed tailings was analyzed microstructurally by optical microscopy. Transverse cuts were made in the mortar and a polished section was prepared for reflected-light image analysis (Figure 3a) and a thin plate for transmitted-light analysis (Figure 3b). The optical microscopy technique was used aiming not only to check the existing minerals, including non-crystalline minerals not detected by X-ray diffraction, but also to quantify them volumetrically. The results are shown in Table 6. The primary minerals found were goethite, hematite and quartz. Accessory minerals were magnetite, kaolinite and tourmaline. The alteration processes were: magnetite in an advanced stage of alteration into hematite (martitization); hematite in an intermediary and advanced stage of alteration into goethite.

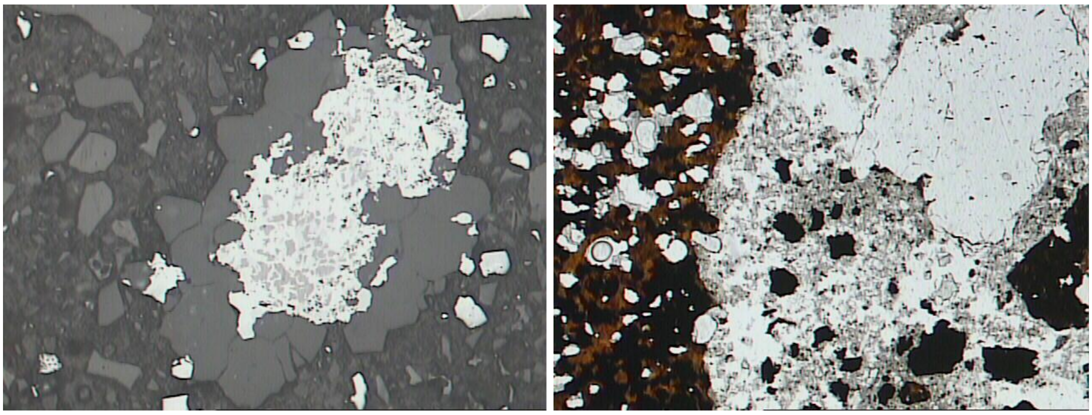

Fig. 3. Photomicrograph (a) Polished Section, Reflected Light, 200X Magnification; (b) Thin Plate, Transmitted Light, 50X Magnification

Table 6 – Volumetric Quantification of the Minerals

Mineral	**Polished Section**	**Thin Plate**	**Average**
Hematite	26.61%	22.00%	24.30%
Goethite/Limonite	44.96%	37.86%	41.41%
Quartz	19.74%	38.05%	29.89%
Magnetite	0.25%	0.10%	0.17%
Kaolinite	0.78%	0.36%	0.57%
Mixed quartz	7.66%	1.63%	4.66%
Tourmaline	anhydrous and subhydrous crystal agglomerates		rare

a) Description of the polished section:
– anhydrous quartz with grain sizes varying from very fine (< 0.01 mm) to very coarse (>0.22 mm), occurring freely throughout the sample;
– hematite with grain sizes smaller than the quartz, occurring freely;
– goethite/limonite with little to very high porosity, appearing with rests of hematite;
– magnetite occurring only as rests in hematites;
– mixed particles composed of goethite/limonite, hematite, and quartz;
– kaolinite associated with goethite.
The photomicrograph shows martitic hematite with rests of magnetite inclusion associated with quartz.

b) Description of the thin plate:
– Existence of all the constituents identified in the polished section, immersed in a very fine matrix of probable carbonate (cement matrix).
The photomicrograph shows particles of goethite, quartz and the aspect of the matrix.

CONCLUSIONS

The mineralogical studies of the samples of sinter-feed tailings and microscopy of mortar specimens defined the predominant composition of the waste as hematite, quartz and goethite/limonite.

With regard to the environmental classification, sinter-feed tailings are classified as Class II B, which corresponds to inert wastes.

The potential alkali-aggregate reactivity test revealed an excellent performance, allowing the waste to be considered as an innocuous aggregate. In the durability assay of the aggregate, which involved an evaluation of its resistance to sulfates, the waste met the requirements, showing a wear index far below the maximum limit established by the standard when subjected to magnesium sulfate, which is a highly aggressive medium.

The granulometry of the waste resembled that of coarse sand and was close to the upper limit of the usable range. The waste is devoid of clay lumps and friable materials, but its content of pulverizable materials is slightly higher than that established by the standard, without, however, compromising the performance of mortars.

With regard to density, the waste was classified as a heavy aggregate and will therefore lead to concrete pieces of heavier weight. The high density of the waste is related principally with its high content of iron, which could not be separated by the magnetic separation process. However, as an aggregate in the production of concrete for paving elements applied directly on the ground, this waste would constitute paving with higher self-weight, less subject to deformation resulting from external loads.

In the quality assay of the aggregate, the mortar containing the waste showed higher axial compression strength than the mortar of reference, indicating its good performance with respect to its mechanical properties.

In general, the sinter-feed tailings presented a satisfactory performance in terms of physical, technical and environmental properties, favoring its use in the fabrication of concrete paving elements. Due to its higher weight in comparison with conventional aggregates, greater savings could be achieved by producing concrete elements directly at the site of their application, which is usually feasible in enterprises such as housing estates, in the establishment of new urban districts, and in the paving of new streets.

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REFERENCES

ABNT NBR NM 26. “Aggregates: Sampling.” *ABNT*, Rio de Janeiro, RJ, 10 pages. (in Portuguese).

ABNT NBR NM 46. “Aggregates: Determination of the Pulverizable Material.” *ABNT*, Rio de Janeiro, RJ, 3 pages. (in Portuguese).

ABNT NBR NM 49. “Fine Aggregate: Determination of the Organic Impurities.” *ABNT*, Rio de Janeiro, RJ, 3 pages. (in Portuguese).

ABNT NBR NM 52. “Fine Aggregate: Determination of the Bulk Specific Gravity and Apparent Specific Gravity.” *ABNT*, Rio de Janeiro, RJ, 5 pages. (in Portuguese).

ABNT NBR NM 248. “Aggregates: Sieve Analysis of Fine and Coarse Aggregates.” *ABNT*, Rio de Janeiro, RJ, 6 pages. (in Portuguese).

ABNT NBR 7211. “Aggregates for Concrete: Specification.” *ABNT*, Rio de Janeiro, RJ, 11 pages. (in Portuguese).

ABNT NBR 7218. “Agregates: Determination of Clay Lumps and Fiable Materials Content.” *ABNT*, Rio de Janeiro, RJ, 3 pages. (in Portuguese).

ABNT NBR 7221. “Agregates: Quality Testing of Fine Aggregates.” *ABNT*, Rio de Janeiro, RJ, 5 pages. (in Portuguese).

ABNT NBR 7251. “Aggregates: Determination of the unit weight.” *ABNT*, Rio de Janeiro, RJ, 3 pages. (in Portuguese).

ABNT NBR 9774. “Aggregate: Determination of Potential Alkali Reactivity by Chemical Method.” *ABNT*, Rio de Janeiro, RJ, 10 pages. (in Portuguese).

ABNT NBR 9781. “Peças de concreto para pavimentação.” *ABNT*, Rio de Janeiro, RJ, 4 pages. (in Portuguese).

ABNT NBR 10004. “Solid Waste: Classification.” *ABNT*, Rio de Janeiro, RJ, 71 pages. (in Portuguese).

ABNT NBR 10005. “Procedure for Obtention Leaching Extract of Solid Wastes.” *ABNT*, Rio de Janeiro, RJ, 16 pages. (in Portuguese).

ABNT NBR 10006. “Procedure for Obtention of Solubilized Extraction of Solid Wastes.” *ABNT*, Rio de Janeiro, RJ, 3 pages. (in Portuguese).

ABNT NBR 10007. “Sampling of Solid Waste.” *ABNT*, Rio de Janeiro, RJ, 21 pages. (in Portuguese). (in Portuguese).

ABNT NBR 11578. “Portland Composite Cement”. *ABNT*, Rio de Janeiro, RJ, 7 pages. (in Portuguese).

Carvalho, M. D. (1989). “ET 27: Precast Concrete Paving.” *ABCP*, São Paulo, SP, 16 pages. (in Portuguese).

DNER ME 089. “Aggregates: Determination of the Durability – Standard Test Method for Sulfate Solutions (Sodium or Magnesium Sulfate).” *DNER*, Rio de Janeiro, RJ, 6 pages. (in Portuguese).

IBRAM (The Brazilian Mining Association) (2009). “Statistic’s Brazilian Mineral Production.” <www.ibram.org.br> (Sep. 23, 2009).

Mehta, P. K. and Monteiro, P. J. M. (2006). “Concrete: Microstructure, Properties, and Materials.” 3rd Ed., McGraw-Hill.

Quaresma, L. F. (2001). “Mining Information Mineral Summary 2001 - Iron”. *National Department of Mineral Production*. <http://www.dnpm.gov.br> (Oct. 10, 2008).