Evaluation of the Aggregate Produced From Wastes of Quartzite Mining Sites to Use in Concrete

E.G. Collares, I. Francklin Jr., L.A.C. Motta

Abstract. The quartzite found in rock formations in the Southwestern Minas Gerais - Brazil has been, along the years, explored and commercialized as "coating stone". The quantity of waste coming from the processing and exploration process, however, is superior to 90% from the extracted product in most of the mining sites, determining a serious environmental passive. This work presents results which can motivate the alternative use of the materials that are dumped on piles of waste. The research involved a petrographic analysis of quartzite occurring in the principal mines of the region; evaluation of aggregates produced in two kinds of crushers; evaluation of the physical and mechanical properties of the rock and evaluation of the physical and mechanical properties of the concrete manufactured with the quartzite aggregate. The results of the technological tests carried out on the rock material were satisfactory and meet all the specifications for the use in concrete. The samples of concrete prepared with the quartzite aggregate presented results of strength similar to the ones manufactured with the aggregate which are used commercially in the region today.

Keywords: quartzite, mining waste, aggregate for construction, concrete.

1. Introduction

The Southwestern Minas Gerais is known nationally by the production of quartzites used as the civil construction coating, which is called "pedra mineira". The extraction of the quartzite in the region occur, many times, on a clandestine basis and/or not meeting the requirements necessary for the environmental control of that activity.

Even the mining sites which exert their activities legally correct, obeying the specifications exposed in the environmental report approved by environmental bureaus, the quantity of waste generated in the extraction process, the so-called "mine dump" sites, is very big. According to information given by environmental bureaus, this waste may get to 92% of the extracted material. This happens because the quartzite is used, basically, as coating stone and thus, should be extracted in plaques, obeying width and length standards. All the material extracted not obeying this standard is disposed as "waste".

All the waste generated in the processing and extract process of the quartzite turns into a big problem to businessmen, because, due to the great quantity of material, it begins producing negative environmental impacts, such as: landscape disfiguration, alteration in the natural formation of reliefs, collapsing the water bodies, supplying the native vegetation, stabilizations on the slopes, to mention a few.

On the other hand, in case that waste obeys the normative standard established for the use of rock material in different possibilities of use in the civil construction, it can be seen as material feasible for other purposes, offering, thus, alternatives to exclusive use as a coating stone.

One of the alternatives could be the use of the waste of the quartzite as aggregate in the civil construction, as component material of concrete, railway or road buildings. Collares *et al.* (2008) present a paper in which they study rock material used as aggregate in the Southwestern Minas Gerais and they include a quartzite sample in their analysis, and in a previous evaluation, they describe that this lithological kind presents results similar to those which are used commercially in the region (diabase, gneiss and limestone).

This present paper presents results of a technological study carried out in material dumped as waste in mine dumps in quartzite mines of five municipalities of the Southwestern Minas Gerais and in concrete test specimen manufactured with aggregate obtained from these materials.

Few studies which involve the use of the quartzite as an aggregate in the civil construction are available in Brazil. Andrade (1997) studied several types of quartzite from different origins. The results presented correspond to the compressive strength, specific density and water absorption. Strength values varying from 54 MPa to 367 MPa and absorption almost always inferior to 1% were found.

Sbrighi Neto (2005) presents typical values of some properties of gneisses and quartzites used in the production of aggregate to concrete (Table 1). It is observed a high

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Table 1 - Some typical properties of gneisses and quartzite for the use as aggregate in concrete (Sbrighi Neto, 2005).

Rock	Compressive strength (MPa)			Absorption (%)	Specific density (g/cm^3)	Deformation modulus (GPa)
	Average	Maximum	Minimum			
Gneiss	150	240	100	0.2 a 0.8	2.55 a 2.70	40 a 70
Quartzite	260	400	130	0.1 a 0.8	2.55 a 2.70	50 a 100

variability for the compressive strength and low variability for absorption.

A very important aspect to be evaluated when using the quartzite in concrete is the reactivity. The Alkali-Aggregate Reaction (AAR) according to Hasparyk (2005) can be defined as a chemical reaction which occurs in a concrete structure, involving the alkaline hydroxide coming principally, from cement and some reactive minerals present in the aggregate used. As a result from this reaction, products are formed, which in the presence of humidity, are able to expand, generating fissures, deviation, and may endanger the concrete structure.

Hasparyk (2005) analyzed the concrete of a structure from the dam at the Hydroelectric Power Plant in Furnas in São José da Barra, in Southwestern Minas Gerais, produced with quartzite aggregate. That dam, constructed between 1950 and 1963, has already presented problems coming from AAR. The study consisted of an investigation with witnesses of concrete checking the properties in the hardened state, micro-structural analysis of the concrete and of the quartzite aggregate to investigate the deleterious reactions.

There are different laboratory methods to determine the deleterious potentiality of the aggregate combined with cement alkalis and according to Hasparyk (1999) the most common are: petrographic analysis, Osipov Test (thermical), Chemical Test, bar test, accelerated test, carbon rock test, concrete prism test and scanning electronic microscopy. One of the most common tests carried out in laboratories to check the deleterious potentiality of aggregates is performed by the accelerated test, which uses bars of mortar in alkaline solution. This method is used in this study.

2. The Quartzites in the Southwestern Minas Gerais

According to COMIG (1994), the geological formations that occur in the Southwestern Minas Gerais are the following:

- Araxá Group: schists, amphibolites, quartzites, gneisses and iron formation;
- São Bento Group: (Serra Geral Formation): basalts and diabases;
- Canastra Group: quartzites, phyllites and schists;
- Carmo do Rio Claro Group: carbonaceous or not carbonaceous phyllites and quartzites;
- Campos Gerais Complex: banded gneisses, migmatites, granite-gneisses, amphibolities, quartzites, schists, meta-ultramafics.

The quartzites of the groups Araxá and Canastra were used in this study, which arise in the Mid-North of the Southwestern Minas Gerais and are used as "coating stones". A survey of the principal mines that are exploring this quartzite was conducted. The studies went forward to mining sites located in the municipalities of São João Batista do Glória, Capitólio, São José da Barra, Alpinópolis and Guapé.

2.1. Preliminary study to select the study places

This preliminary study was done with the purpose of selecting samples to carry out the most specific technological studies, which constitute the subject matter of the research. Table 2 presents the information concerning the samples collected in the mines visited.

Soon after a petrographic approval (macroscopic analysis) in each lithological kind, according to ABNT (1992a), it was observed that the samples selected in each mine present some particularities concerning the texture, structure, and mineralogical composition. It was observed in almost all the mines, two types of quartzite: Type 1: white-yellowish and varied, foliated, with medium mica content (muscovite) and it is used as "coating stone"; Type 2: gray, pretty silicified, with lower muscovite content and less evident foliation. Type 2 is not used as "coating stone" and constitute of residues in mines.

In order to verify the mineralogical and structural differences of Quartzite types 1 and 2, a microscopic analysis (in thin sections) of the selected samples was performed.

The thin sections were made in the Rock Laboratory at the Technological Center of Civil Engineering, located in Aparecida de Goiânia - GO at Furnas Centrais Elétricas S/A. The descriptions of the thin sections were performed by the Rock laboratory at UNESP - Rio Claro Campus - SP and confirmed the existence of two types of quartzite (Types 1 and 2). Type 1 presents a little higher mica content (around 4%) and more emphasized foliation (Fig. 1 and Table 3). Further details about the quartzite petrographic characteristics can be checked in Francklin Jr. (2009).

2.2. Selection of higher strength samples

All samples collected were received tests with the objective of measuring the strength to rock rupture using the Method for Determining Point Load Strength - $I_{s(50)}$ (ISRM,

Table 2 - Location of the mines visited.

Mining	Altitude (m)	Latitude	Longitude	Sample
ALP 1	1100	20°51’05’’ S	46°21’14’’ W	5-A-A e 5-A-B
	1026			2-A-A e 2-A-B
ALP 2	1049	20°51’17’’ S	46°21’36’’ W	3-A-A e 3-A-B
	1106			1-A
	1110			4-A
SJB 1	919	20°42’33’’ S	46°17’48’’ W	7-A
SJB 2	1084	20°42’14’’ S	46°17’17’’ W	6-A-A e 6-A-B
GLO 1	1021	20°37’12’’ S	46°17’30’’ W	1-G
GLO 2	1126	20°36’17’’ S	46°18’42’’ W	3-G-A e 3G-B
CAP 1	1044	20°37’53’’ S	46°16’44’’ W	5-G
CAP 2	1216	20°34’57’’ S	46°16’50’’ W	4-G-A e 4-G-B
CAP 3	1324	20°34’47’’ S	46°17’34’’ W	2-G-A 2-G-B e 2-G-C
CAP 4	1285	20°35’11’’ S	46°17’59’’ W	7-G-A e 7-G-B
CAP 5	1233	20°36’36’’ S	46°16’26’’ W	6-G-A e 6-G-B
GUA	898	20º50’03’’ S	45º55’43’’W	A5

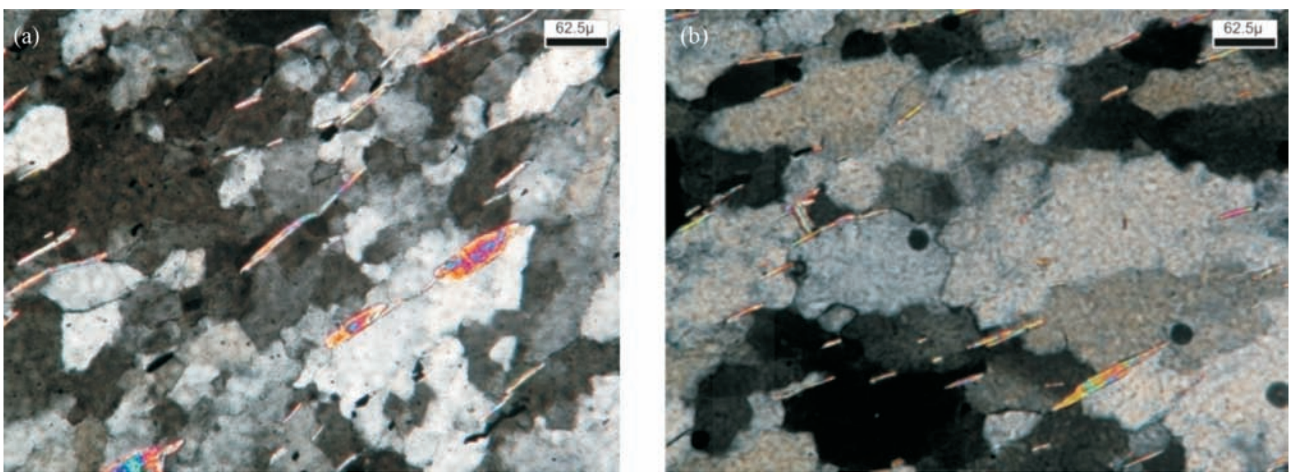

Figure 1 - (a) Microscopy quartzite Type 1; (b) Microscopy quartzite Type 2.

Table 3 - Petrografic description of the quartzites types 1 and 2 (analyzes of the Geociências Department of the UNESP, Rio Claro, SP).

Samples	Modal composition*	Classification
Quartzite Type 1	Quartz 95% Muscovite 4% Opaque Minerals % Turmaline - occasional occurrence Zircon - occasional occurrence Rutile - occasional occurrence	Muscovite Quartzite schistose
Quartzite Type 2	Quartz 97% Muscovite 1% Opaque Minerals 1% Turmaline % Zircon - occasional occurrence Rutile - occasional occurrence	Foliated Quartzite with Muscovite thin

* visually estimated.

1985). The objective was to select the most resistant samples.

In Fig. 2 it is possible to check the difference of the rupture loads, between Types 1 and 2 rocks. It is clear the higher strength to the samples Type 2 (gray) when they are submitted to the application of compression strength applied directly to the samples.

The samples which presented high values of rupture, described as Type 2 in the petrographic analysis, are exactly those rejected in the extraction of mines and were the specific subjects in this paper.

Samples for the specific studies (technological tests in aggregate and tests in the concrete produced with the aggregate) were chosen based on the preliminary study and were collected at dumps of mines in the coordinates presented in Tables 4 and 5.

In Phase 1 the samples were named A1, A2, A3 and A4, corresponding to the cities of São João Batista do Glória, Capitólio, São José da Barra and Alpinópolis respectively. In Phase 2 only in São João Batista do Glória the collection of samples was not done due to technical problems and it was replaced by mines in the municipality of Guapé. The samples collected in the second phase were named A2 - Phase 2 (Capitólio), A3 - Phase 2 (São José da Barra), A4 - Phase 2 (Alpinópolis) and A5 - Phase 2 (Guapé). The sample of gneiss was used as a reference because it is used commercially in the region as an aggregate. This sample was called AG and was collected in the municipality of Passos - MG.

3. Methodology

3.1. Sample collection and aggregate production

The collections were carried out in two phases:

Phase 1 (small sample volume): the samples were selected and collected manually at mine dumps. Samples of

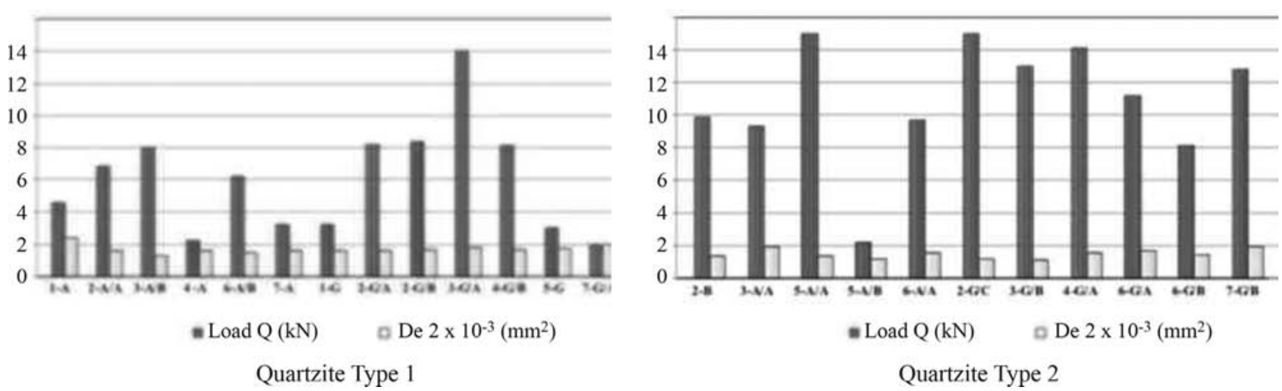

Figure 2 - Graph showing the rupture and sample areas of Type 1(a) and 2 (b). "De" refers to the diameter of the sample.

Table 4 - Coordinates of the samples in Phase 1.

Phase 1				
Municipalities	Altitude (m)	Latitude	Longitude	Sample
São João Batista do Glória	1126	20°36'17'' S	46°18'42'' W	**A1** - GLO
Capitólio	1324	20°34'47'' S	46°17'34'' W	**A2** - CAP
São José da Barra	1084	20°42'14'' S	46°17'17'' W	**A3** - SJB
Alpinópolis	1026	20°51'17'' S	46°21'36'' W	**A4** - ALP

Table 5 - Coordinates of samples in Phase 2.

Phase 2				
Municipality	Altitude (m)	Latitude	Longitude	Sample
Capitólio	1188	20º37'3.13" S	46º15'3.68" W	**A2** - CAP
São José da Barra	1072	20º42'6.25" S	46º17'10.26" W	**A3** - SJB
Alpinópolis	1019	20º50'53.11'' S	46º21'15.88 W	**A4** - ALP
Guapé	947	20º50'3.19" S	45º55'43.72" W	**A5** - GUA

Type 2 quartzite were selected. The samples were collected in the municipalities of São João Batista do Glória, Capitólio, São José da Barra and Alpinópolis and so-called: A1, A2, A3 and A4.

Phase 2 (big sample volume): The mines where the sample collection was performed were the same of the previous phase (except São João Batista do Glória, which was replaced by Guapé - sample A5). During this phase a big volume of sample was collected (around 4 tons), direct from mine dumps, with the help of a wheel loader and a dump truck was used for transportation.

With a good quantity of collect it was possible the crushing in an outstanding crushing site, which permitted to obtain more regular samples (those which fit better with the commercial product) and an analysis of the crushing process.

The samples were crushed in two different crushers: the jaw crusher and hydrocone crusher. The crusher specifications are in Table 6.

3.2. Preliminary tests with the crushing material

The preliminary tests performed were: Grain-size Analysis (ABNT, 2003b), whose final results were compared to the aggregate quality parameters established by ABNT (2005); Shape Index (ABNT, 1983a and ABNT, 1989) and Unit Mass in Loose State (ABNT, 1982) and Compact State (ABNT, 1983b).

3.3. Technological tests in aggregate

In order to achieve a technological characterization of the quartzite aggregates the following tests were performed: Dry Density; Density in Saturated and Surface-dry Conditions; Absorption and Porosity (ABNT, 2002); Artificial Water/Stove Cycling (ABNT, 1992b); Powdery Material Tenor (ABNT, 2001), “Los Angeles” Abrasion (ABNT, 2000); Crushing (ABNT, 1987); Uniaxial Compression (ABNT, 2007) and Potential Alkali Reactivity of Aggregates (ASTM, 2007).

3.4. Concrete manufacturing

With the results of the tests for material characterization in hands, concrete was manufactured according to ABNT (1993), analyzing the behavior in fresh and hardened state.

The concrete production was divided into two phases, the first one using processed aggregates in a Jaw Crusher (Phase 1) and the second one using the processed aggregates in a Hydrocone Crusher (Phase 2).

The main purpose was to analyze the quartzite aggregate behavior in concrete, both in fresh and hardened state.

For the production of the reference concrete traditional material was used such as CP II-Z-32 cement, river sand and gneiss crushing (the latter was used as a comparative reference). For the production of quartzite concrete of each sample, the gneiss used as coarse aggregate was replaced by the quartzite samples.

In order to have a coherent comparative analysis between the results of the concrete properties, the same processes of crushing and grain size classification to constitute the gneiss coarse aggregates and quartzite were used.

The reference trace was chosen with the intention of comparing its results with the other concretes produced with coarse aggregate of five different types of quartzite. The dosage study of this trace was carried out through the ACI/ABCP method, which aims at obtaining ideal minimum consume of mortar content, coming from the principle of the specific area analysis of the fine aggregate and from the smallest empties index of the coarse aggregate, with the objective of reducing the water/cement (w/c) ratio.

The representation of the reference trace chosen in dry material mass was 1 : 1.95 : 2.9 : 0.57 in Phase 1 e 1 : 1.95 : 2.9 : 0.55 in Phase 2.

For all the traces the w/c ratio was kept with the purpose of checking possible interferences of quartzite aggregate in the workability and consistency of concretes. Tables 7 and 8 show the abbreviations, the rock types, and the origin of the coarse aggregates, referring to the traces studied in Phases 1 and 2, respectively.

Seven 15 cm x 30 cm cylindrical specimens were casted for each of the five traces studied, aiming at testing at least two samples of the same concrete with 28 days for the mechanical tests proposed.

Table 7 - Identification of the concretes studied with reference to the coarse aggregate in Phase 1.

Trace denomination	Coarse aggregate	Origin of the coarse aggregate
AG	Gneiss	Passos/MG
A1	Quartzite - GLO 2	S. J. B. Glória/MG
A2	Quartzite - CAP 3	Capitólio/MG
A3	Quartzite - SJB 2	S. J. Barra/MG
A4	Quartzite - ALP 2	Alpinópolis/MG

Table 6 - Crusher specifications used in this research.

Crusher	Type	Model	Manufacturer	Size (cm)	Processing (T/h)
Phase 1	Jaw	02	Marumby	200(c) x 140(l) x 110(e)	10
Phase 2	Hydrocone	H 2000	Sandvik	216(h) x 980(Ø)	80

Table 8 - Identification of the concretes studied with reference to the coarse aggregate in Phase 2.

Trace denomination	Coarse aggregate	Origin of the coarse aggregate
AG (Phase 2)	Gneiss	Passos/MG
A2 (Phase 2)	Quartzite - CAP	Capitólio/MG
A3 (Phase 2)	Quartzite- S.J.B	S. J. Barra/MG
A4 (Phase 2)	Quartzite- ALP	Alpinópolis/MG
A5 (Phase 2)	Quartzite - GUA	Guapé/MG

The concrete properties in the hardened state analyzed in this paper were:

- Compressive strength (ABNT, 2007);
- Tensile Strength by diametral compression (ABNT, 1994).
- Modulus of elasticity (ABNT, 2003a), performed in Phase 2.

4. Results and Discussions

4.1. Technological characterization of gneiss and quartzite aggregates

The results are compared with the limits established by ASTM and ABNT, the guide for assessing the quality of the aggregate (Table 9) based on results of laboratory tests performed by Verhoef and Van De Wall (1998, apud Gomes, 2001) and studies of quartzite and other wastes for use in construction.

4.1.1. Shape index

Tables 10 and 11 show the results of the Shape Index Tests in Phases 1 and 2, respectively.

The results of the shape index presented in Phase 1 have confirmed the low uniformity of the jaw crusher, when producing irregular grains. Only samples A2 and AG have formed regular grains according to ABNT (1983a). The use of Hydrocone Crusher in Phase 2 has shown effective in producing cubic grains of aggregate and c/e ratio lower than 3, essential to produce high compactness concrete.

4.1.2. Density, water absorption and porosity rate

The results of Density, Water Absorption and Porosity Rate are presented in Table 12 for the aggregate processed in Phase 1 and in Table 13 for the aggregate processed in Phase 2.

The results of density (dry and Saturated and Surface-dry Conditions), for all the samples were satisfactory, with very small variations among the values.

Values between 0.5% e 2% are considered good absorption and values lower than 0.5% are considered excellent absorption according to the parameters established by Verhoef and Van De Wall (1998 *apud* Gomes, 2001), therefore in Phase 1 only sample A3 in the municipality of São José da Barra was considered good and all the others were considered excellent. In Phase 2 all the samples were considered to be excellent.

According to the parameters established by Verhoef and Van De Wall (1998 *apud* Gomes, 2001), values be-

Table 9 - Guidance for assessing the quality of the aggregate based on results of laboratory (Verhoef & Van De Wall, 1998 apud Gomes, 2001).

	Excellent	Good	Tolerable	Poor
Water absorption (%)	> 0.5	0.5-2.0	2.0-6.0	< 6.0
Porosity rate (%)	> 2	2-3	3-4	< 4
Crushing (%)	> 20	20-25	25-30	< 30
"Los Angeles" abrasion (%)	> 40	40-45	45-50	< 50

Table 10 - Aggregate shape index in Phase 1.

Phase 1					
Samples	ABNT NBR 6954:1989			NBR 7809:1993	
	B/A	C/B	Form	C/E	Condition
AG	0.67	0.59	Cubic	2.66	Acceptable
A1	0.58	0.65	Cubic	3.14	Rejected
A2	0.57	0.59	Cubic	2.8	Acceptable
A3	0.6	0.58	Cubic	3.7	Rejected
A4	0.54	0.63	Cubic	3.57	Rejected

Table 11 - Aggregate index form in Phase 2.

Samples	Phase 2				
	ABNT NBR 6954:1989			NBR 7809:1993	
	B/A	C/B	Form	C/E	Condition
AG	0.74	0.69	Cubic	2	Acceptable
A2	0.7	0.63	Cubic	2.68	Acceptable
A3	0.64	0.62	Cubic	2.52	Acceptable
A4	0.67	0.59	Cubic	2.79	Acceptable
A5	0.66	0.64	Cubic	2.81	Acceptable

Table 12 - Density, water absorption and porosity rate of aggregates in Phase 1.

Phase 1				
Samples	Dry density (kN/m^3)	Density in saturated and surface-dry conditions (kN/m^3)	Water absorption (%)	Porosity rate (%)
AG	27.4	27.5	0.3	0.8
A1	26.3	26.4	0.4	1.02
A2	26.4	26.5	0.2	0.57
A3	25.9	26.1	0.9	2.30
A4	26.2	26.3	0.5	1.32

Table 13 - Density, water absorption and porosity rate of aggregates in Phase 2.

Phase 2				
Samples	Dry density (kN/m^3)	Density in saturated and surface-dry conditions (kN/m^3)	Water absorption (%)	Porosity rate (%)
AG	27.2	27.3	0.3	0.8
A2	26.2	26.4	0.5	1.4
A3	26.2	26.4	0.5	1.4
A4	26.5	26.7	0.5	1.4
A5	26.3	26.4	0.4	1.1

tween 2.0 and 3% are considered good porosity rate and values that are lower than 2% are considered excellent. In Phase 1 only sample A3 was classified as a good porosity rate and the other samples were classified as excellent. In Phase 2 all the samples were classified as excellent, with values lower than 2%.

4.1.3. Artificial water/stove cycling

Table 14 shows the percentages of mass loss regarding the initial mass of the samples determined during the quantitative exam.

During each cycle it was observed whether the fragments underwent any kind of attack due to the presence of expansive clay mineral, such as disintegration, rupture, crack and spalling. The sample that presented more mass loss was that of A1, but it was not meaningful. As it was expected none of them showed presence of ex-

Table 14 - Verification of aggregate mass loss after the artificial water/stove cycling test.

Sample	Initial mass (g)	Finalmass (g) after 120 cycles	Loss mass in %
AG	470.2	468.4	0.38%
A1	317.3	315.6	0.54%
A2	350.1	348.7	0.40%
A3	526.0	524.2	0.34%
A4	497.3	496.1	0.24%
A5	573.3	571.4	0.33%

pansive minerals, not suffering, thus, degradations mentioned before.

4.1.4. Grain size analysis

When the jaw crusher was used in Phase 1, only the fragmentation of the material was performed. The samples were fragmented in varied dimensions and taken to the laboratory for classification according to ABNT (2005), using normal and intermediate sieves. All aggregate samples received the same classification process in order to have the same granulometric profile. The grain size analysis results and the limits of the granulometric zones d/D = 9.5/25 of A1 and AG samples processed in jaw crusher (Phase 1) are shown in Fig. 3. Samples had the same classification profile with a continuous granulometric distribution and next to the interval of limits established by ABNT (2005).

The samples processed by the hydrocone crusher were classified by the equipment itself after the secondary crushing. For the concrete production fractions of 19 mm were chosen, commercialized as crushed stone 1.

The results of the tests performed in laboratories and the limits of the granulometric zone d/D = 9.5/25 according to ABNT (2005) of each sample processed in hydrocone crusher are shown in Fig. 4.

The results of the samples processed and classified in the hydrocone crusher (Phase 2) fit the interval of limits (inferior and superior) established by ABNT (2005) to be used as coarse aggregate in the concrete.

4.1.5. Unit mass

In order to have the results of unit mass in loose and compacted states the samples processed in both crushers were used (Phases 1 and 2).

a) Unit mass in loose state

Tables 15 and 16 show the results of the unit mass of quartzite and gneiss aggregates in loose state with their respective void ratio in Phases 1 and 2. The results obtained of unit mass of samples processed in Phase 2 were better regarding the samples processed in Phase 1, proving once again the efficiency of the hydrocone crusher which contributed to the reduction of the void ratio of the aggregates.

b) Unit mass in compacted state

Tables 17 and 18 show the results of the unit mass of quartzite aggregates in compacted state in Phases 1 and 2,

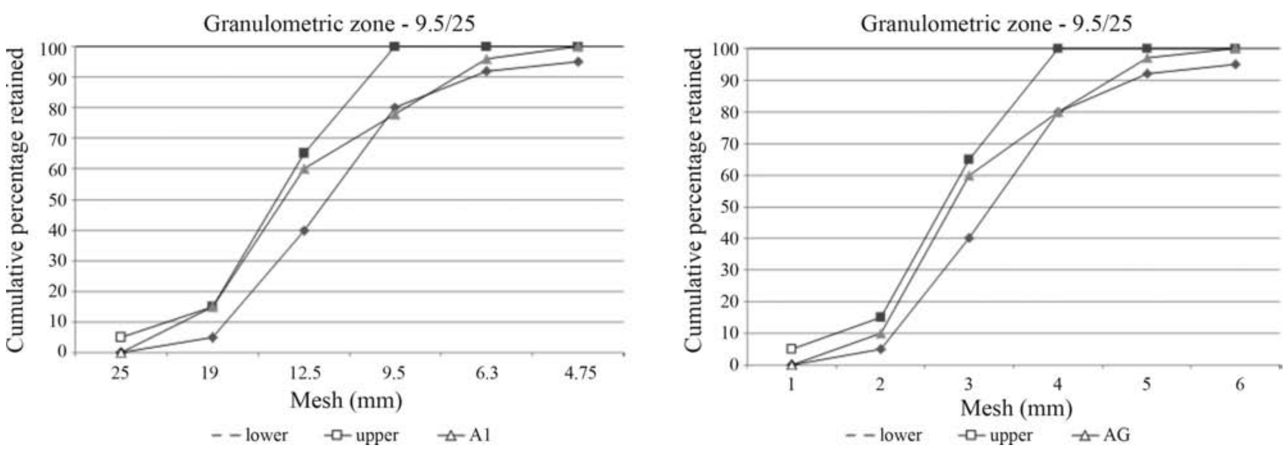

Figure 3 - Grain size analysis of quartzite samples A1 (a) and Gneisses - AG (b) processed in Phase 1, in granulometric zone 9.5/25.

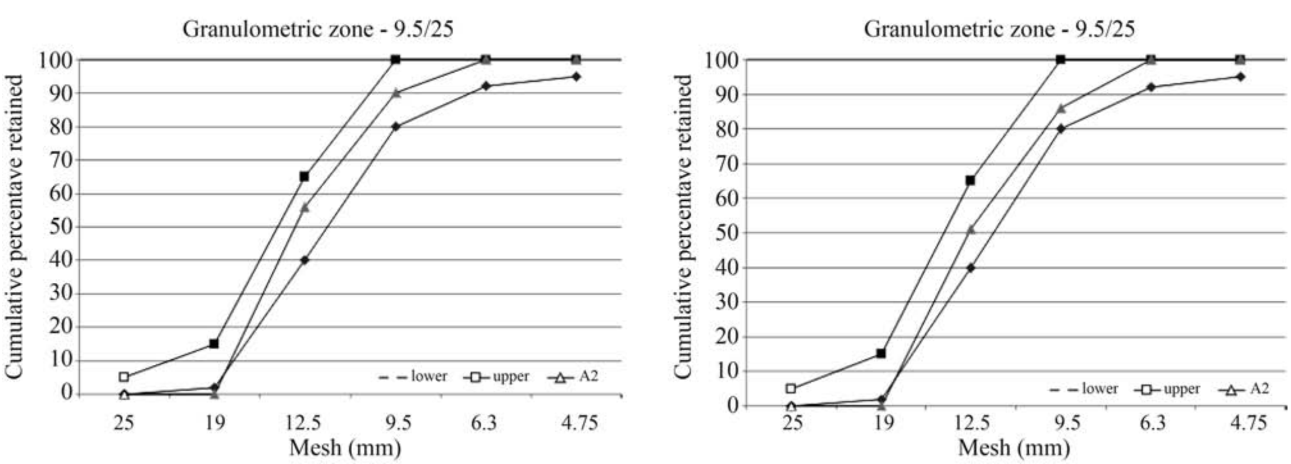

Figure 4 - Grain size analysis of quartzite samples A2 (a) and AG (b) processed in Phase 2, in granulometric zone 9.5/25.

Table 15 - Results of the unit mass of aggregates in loose state in Phase 1.

Phase 1		
Sample	Unit mass in loose state (kN/m^3)	Void ratio
AG	14.80	46.00%
A1	13.63	48.20%
A2	13.69	48.10%
A3	13.61	48.10%
A4	13.63	48.00%

Table 16 - Results of the unit mass of aggregates in loose state in Phase 2.

Phase 2		
Sample	Unit mass in loose state (kN/m^3)	Void ratio
AG	14.53	46.60%
A2	14.82	43.90%
A3	14.47	44.80%
A4	14.25	45.60%
A5	14.55	44.70%

respectively. Values very close to the unit mass in compacted state were found among the samples processed in the different crushers. As expected, the samples processed in Phase 1 with the jaw crusher presented inferior values to the ones processed in Phase 2 with the hydrocone crusher.

4.1.6. Powdery material content

ABNT (2005) determines that the maximum quantity of powdery materials that the coarse aggregate to use in concrete may have is 1%. According to Table 19, of all the five crushed samples, only the AG sample presents unfavorable condition. But ABNT NBR 7211:2005 allows a tolerance to the rocks with water absorption rate inferior to 1%, determined according to ABNT (2001). Thus, the limit of fine material (powdery) becomes 2%. This applies to AG sample, which has an absorption rate of 0.3%.

4.1.7 .“ Los Angeles ” abrasion

ABNT (2005) establishes that the abrasive wearing off underwent by the aggregate according to ABNT (2000) must be inferior to 50% in mass. Figure 5 shows that samples in Phases 1 and 2 presented satisfactory behavior of the aggregate wearing off to abrasion.

4.1.8. Crushing

It is possible to verify in Fig. 6(a) that the results of the crushing strength of samples A2 and A4, in Phase 1, were classified as excellent, with loss percentages lower than 20%. The samples of quartzite A1 and A3 fit the interval of 20% and 25%, therefore they were classified as having a good index to use as aggregate in the civil construction, according to Verhoef e Van De Wall (1998 *apud* Gomes, 2001).

Figure 6(b) presents the results of crushing strength of aggregates in Phase 2. AG and A1 samples were classified as excellent with loss percentages lower than 20%. A3, A4, and A5 quartzite samples fit the interval of 20 and 25%, therefore they were considered good for use.

Table 17 - Unit mass of quartzite aggregates in compacted state - Phase 1.

Phase 1	
Sample	Unit mass in compacted state (kN/m^3)
A2	15.17
A3	15.11
A4	15.03
A5	15.20

Table 18 - Unit mass of quartzite aggregates in compacted state - Phase 2.

Phase 2	
Sample	Unit mass in compacted state (kN/m^3)
A1	17.18
A2	17.20
A3	17.32
A4	17.14

Table 19 - Results of the powdery material content.

Samples	Initial mass (g)	Final mass (g)	Powdery material (%)
AG	3000.3	2967.0	1.11
A1	3000.0	2982.9	0.57
A2	3000.0	2986.2	0.46
A3	3000.2	2982.1	0.60
A4	3000.3	2970.6	0.99
A5	3000.1	2983.7	0.55

4.1.9. Potential alkali reactivity of aggregates

It was produced two traces of mortar for each of the four quartzite samples (A1, A2, A3 e A4). For each trace three bars of mortar were casted, totalizing 24 bars and the expansion was measured periodically according to the accelerated test of ASTM (2007). The first trace was produced using CP II-Z-32 cement and the second trace was produced using the CP V-ARI cement. The chemical analy-

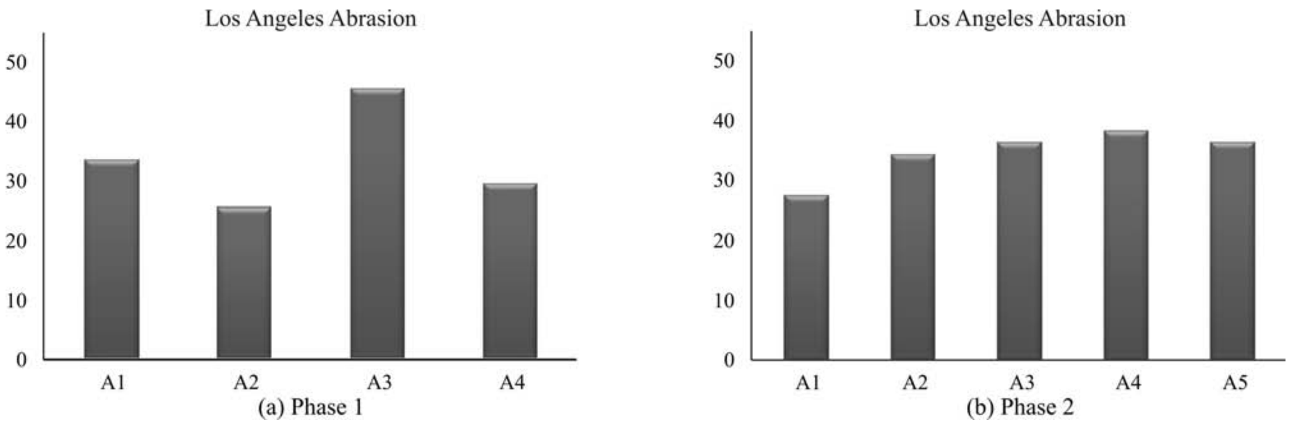

Figure 5 - Indices of "Los Angeles" abrasion.

sis of these two kinds of cement emphasizing the alkali content is described in Table 20. The equivalent alkaline presents values practically identical in both cements.

Figure 7 shows the growing behavior of mortar bar expansion up to 30 days, and Table 21 contains the values of expansion within 16 and 30 days for each kind of cement.

According to the limits of ASTM (2007) at 16 days, A1, A2, and A3 samples produced with CP II-Z-32 cement, indicated an innocuous behavior, with expansions lower than 0.10%, whereas A4 sample obtained average expansion of 0.116% indicating the possibility of deleterious manifestation. On the 30th day of testing, it was proved the potentially deleterious behavior in A4 sample, indicating expansions higher than 0.2%.

All the mortar bars produced with the CP V-ARI cement analyzed on the 16th day indicated an innocuous behavior with expansions lower than 0.10%, however, on the 30th day of testing, it was confirmed a potentially deleterious behavior in A2 sample, indicating expansions higher than 0.2%. Results indicated the possibility of the presence of aggregates with both behavior - innocuous and deleterious, in samples A1, A3, and A4. Sample A3 presented the lowest rate of expansion, but within the range of deleterious potentiality.

The results using the CP II-Z-32 presented shorter expansions in most of the mortar bars when compared to the results of the CP V-ARI. Since the alkali proportions were

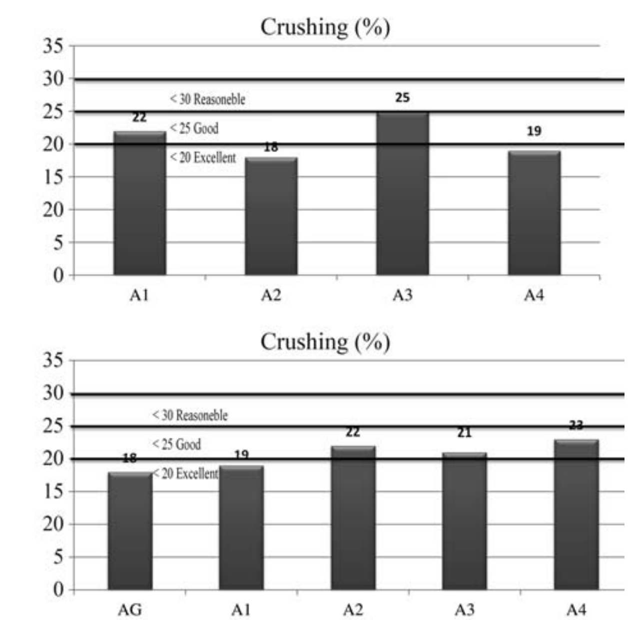

Figure 6 - Indices of crushing resistance. (a) Phase 1. (b) Phase 2.

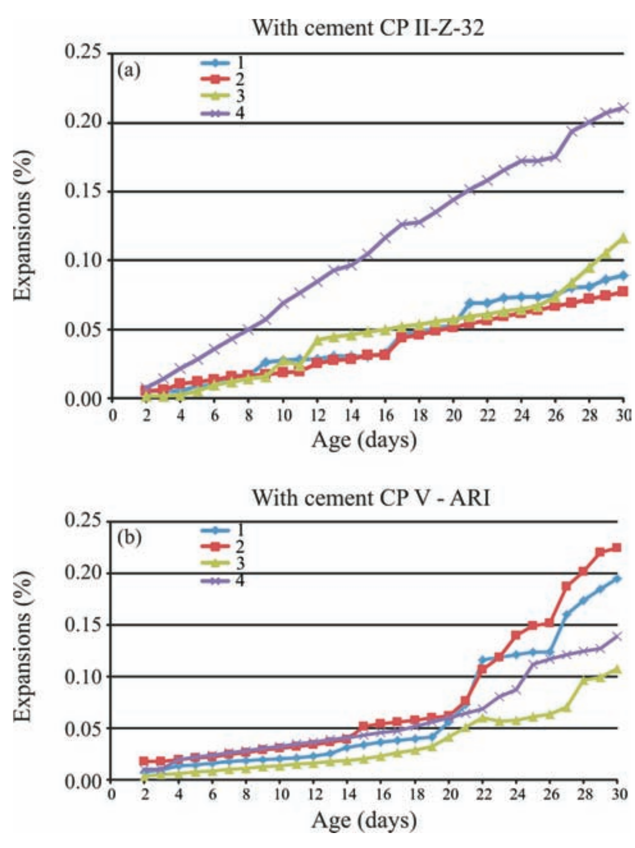

Figure 7 - Expansion of the mortar bars produced with the samples of quartzite aggregates.

Table 20 - Alkaline content of CP II Z 32 and CO V-ARI cements.

	CP II Z 32					CP V ARI				
Results in %	K_2O	Na_2O	CaO	MgO	Equivalent alkaline	K_2O	Na_2O	CaO	MgO	Equivalent alkaline
Sample 1	0.8	0.13	56.53	6.28	0.66	0.76	0.18	63.44	0.73	0.68
Sample 2	0.89	0.12	60.59	4.3	0.71	0.74	0.18	64.22	0.77	0.67
Sample 3	0.8	0.13	57.16	6.22	0.66	-	-	-	0.69	-

Equivalent alkaline = Na_2O + 0.685 K_2O.

Table 21 - Expansion of the mortar bars prepared with quartzite samples and cements CP II-Z-32 e CP V-ARI, at the age of 16 and 30 days.

Cement	Age	A1	A2	A3	A4
CP II-Z-32	16 days	0.033%	0.031%	0.050%	0.116%
	30 days	0.089%	0.077%	0.116%	0.211%
CP V-ARI	16 days	0.036%	0.054%	0.023%	0.046%
	30 days	0.194%	0.224%	0.108%	0.138%

practically identical, this difference may be attributed to the addition of pozzolana to the CP II-Z-32 cement, which accounts for the minimization of the reactions, however, in this case it was not sufficient to inhibit the expansions of A4 sample.

None of the bars tested has undergone important ruptures or fissures. Only the bars of A2 sample underwent some signs of small fissures and a trend to span.

During the casting of the mortar bars of A3 sample using the CP V-ARI cement some difficulties were checked in density increasing due to a more elevated rate of water absorption of the aggregates regarding the other samples, resulting in bigger empties in the mortar in hardened state. The irregular form of the quartzite grains accounts for this phenomenon, in this case the flat and elongated particles and angularity, which do not promote a proper compactness to concretes and mortars. The same happened in other samples, where relevant proportion of emptiness and pores in the mortar bars in the hardened state was observed.

The big quantity of empties which appeared, principally in the A3 sample specimens make that the gel coming from the reaction have more empty spaces to house, which can result in an equivocated classification of the reactive potentiality of the sample.

It was observed by Valduga *et al.* (2005) the influence of the grain form in the results of the accelerated test. The authors in this paper have verified that when the mortars are casted with more angular grains they have smaller expansions than when the aggregates have round grains, due exactly to the empties presented in those mortars, where the gel houses.

4.2. Results of the studies carried out in the concrete specimens

4.2.1. Phase 1

4.2.1.1. Compressive strength

The results of the compressive strength obtained in 28 days in the concrete cylindrical specimens in Phase 1 are presented in Fig. 8. It is observed that the values of the strength to concrete compression produced with quartzite coarse aggregate, were smaller than the reference concrete, but they were not relevant. The maximum difference obtained was 21.88% in trace A1 in relation to AG, and the minimum difference was only 10.42% in trace A2.

Figure 9 shows a comparison between the concrete strength and the respective shape index of the coarse aggregate. The results show that, values of shape index (length x thickness ratio) lower than the limit established by ABNT (1983a), resulted in compression strengths higher than in the concretes. On the other hand, the results of the shape index which were not considered approved for the other aggregates, that is, values higher than 3.0 obtained compressive strengths lower in the concretes. The most favorable conditions of shape index approved in the tests by ABNT (1983a) are attributed to AG and A2 aggregates; the values of compressive strength of the traces produced with these two aggregates were exactly the highest and were similar.

The smallest concrete strengths produced with more lamellar grains may be attributed to the increase of the water/cement ratio in the transition zone and formation of bigger

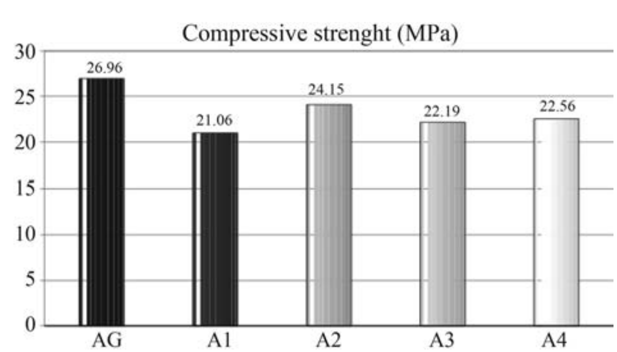

Figure 8 - Compressive strength of the concrete at 28 days of age (MPa).

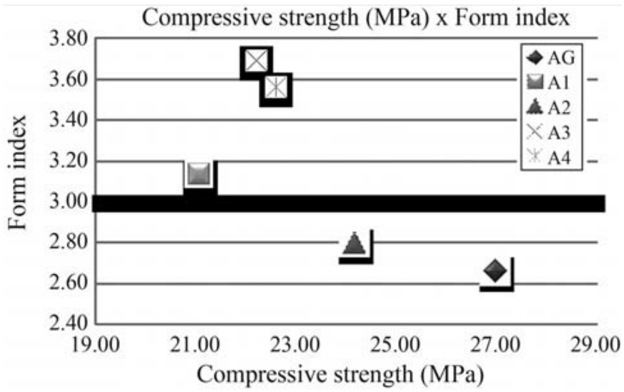

Figure 9 - Relation between the values of the aggregate shape index and the compressive strength (MPa) of the concretes.

crystalline grains reflecting in bigger porosity in aggregate interface and paste and consequently, region weakening.

After the tests of compressive strength the concretes were taken to a complete rupture so that the rupture section could be analyzed. The intention was to verify, through the visual analysis, whether the concrete rupture was happening in coarse aggregate or in cement paste. Figure 10 presents images of sections of rupture of specimens.

Analyzing the specimens produced with coarse gneiss and quartzite aggregates, it was verified that there were spoiled aggregates and also aggregates taken from the paste (paste rupture around the aggregate), which characterizes the proper aggregate adherence to the paste. It was also observed that the quantity of spoiled aggregates was smaller or approximately the same as the aggregates separated from the cement paste, indicating that the aggregate strength is also acceptable. It was also observed in all concrete traces that most of the particles were wrapped with cement paste in sections of rupture.

4.2.1.2. Tensile Strength by diametral compression

The results of tensile strength by diametral compression at the age of 28 days are presented in Fig. 11. The values presented about the tensile strength were satisfactory with no relevant difference between the samples. A1 and A3 traces obtained inferior values in relation to AG trace in 12.5% whereas A2 and A4 obtained a tensile strength increase in relation to AG trace in 6.28%.

According to Mehta &Monteiro (2008) the concrete strength, specially the flexural strength, may be affected by the aggregate texture. Rougher textures may promote the formation of a stronger physical adherence between the cement and the aggregate. The porosity rate is one of the characteristics which account for a rougher texture to the coarse aggregate.

Other factors which are dependent to classify a superficial texture, mentioned by Metha & Monteiro (2008), can be attributed to petrographic origin, hardness, grain size and exposition to friction. Fig. 12 presents a rupture section of some specimen tested on tension by diametral compression.

Studies conducted by Tasong *et al.* (1998a) verified that the strength linking the concrete interface produced with quartzite with sawn surfaces was higher when compared to basalts and limestone with the same kind of surface.

The authors believe that the pozzolanic reactions between the quartzite Si and the CH may be the reason for the high strength in the linking. The authors suggest perform-

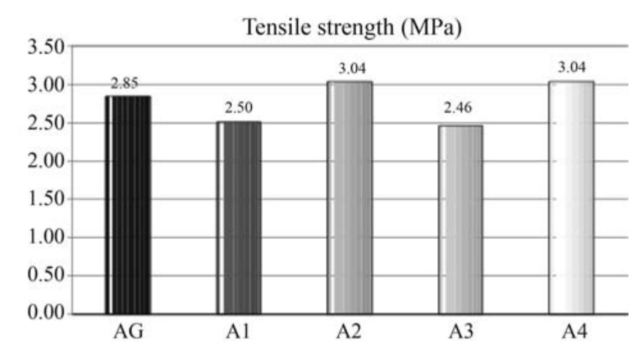

Figure 11 - Tensile strength by diametral compression of aggregates on the 28^{th} day.

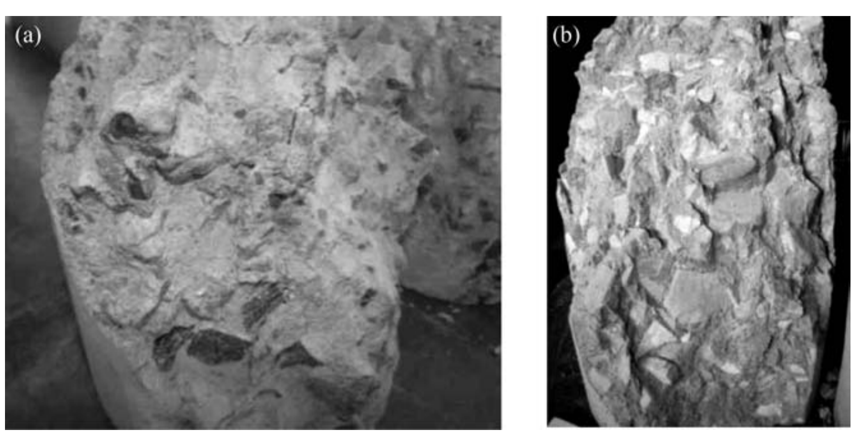

Figure 10 - Sections of rupture to the compression of concretes produced with the traces AG(a) and A1(b).

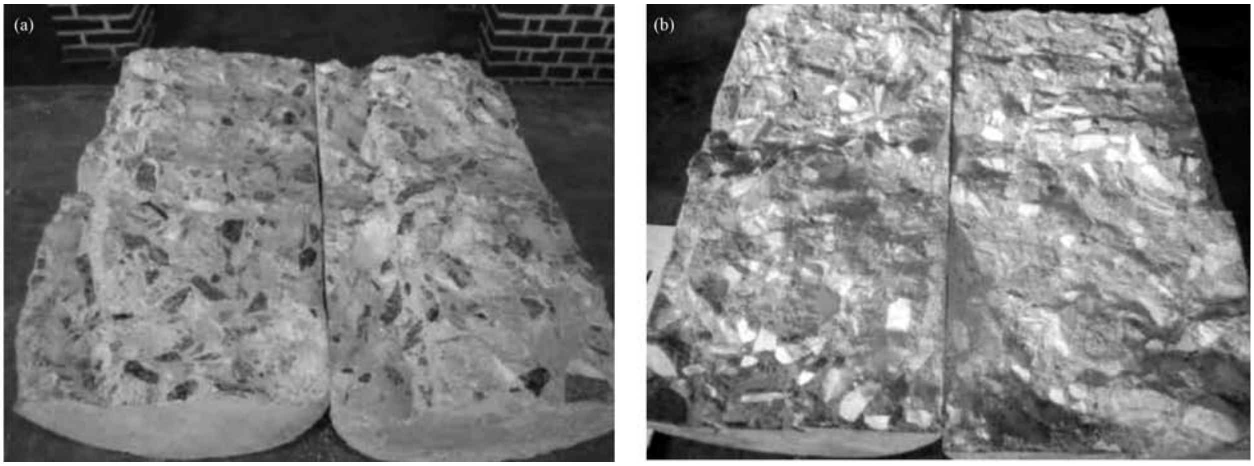

Figure 12 - Rupture sections of specimens corresponding to AG(a) and A1(b) traces.

ing not only analysis of interaction between aggregate and cement paste in the concrete transition zone, but fundamentally analysis of the behavior of the superficial aggregate texture and the kind of fissure which occurred in the transition zone, being considered interfering factors confirmed in their research.

In investigations using powder-like quartzite in cement-based solutions, Tasong *et al.* (1998b) proved that the quartzite is much more active than expected. During the test the quartzite absorbed relevant quantities of OH and Ca and released relevant quantities of Si for the solution, this point allows the indication of the formation C-S-H on the aggregate surface.

4.2.2. Phase 2

4.2.2.1. Compressive strength

Figure 13 shows the maximum values of compressive strength obtained through specimens tested at the age of 28 days.

The value differences of the concrete compressive strength were very close, showing to be on a par with the concretes produced with quartzite aggregates in relation to the reference concrete produced with gneiss aggregate. The maximum difference obtained was 13.43% in T-A3 trace in relation to AG-T and the minimum difference was only 4.16% in T-A4 trace.

It is important to point out that in Phase 1 the differences between the concretes were bigger and attributed to the irregular forms of the aggregate fragments, however in this phase these deficiencies were corrected with the help of the hydrocone crusher reflecting in better mechanic property concretes.

After the tests of compressive strength, the concretes were taken to complete rupture so that the rupture section could be analyzed. The intention was to verify through visual analysis whether the rupture of the concretes was occurring in the coarse aggregates or in the cement paste.

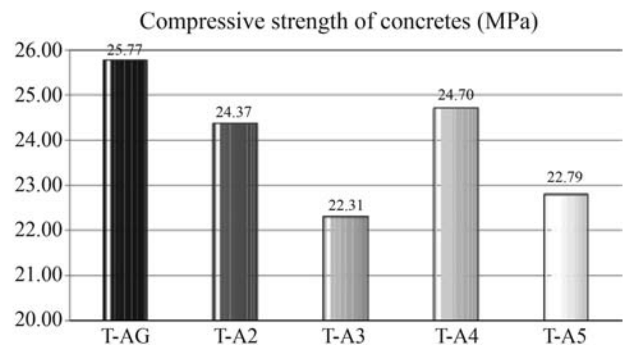

Figure 13 - Compressive strength of concretes at the age of 28 days.

Figures 14(a) and 14(b) present images of the rupture sections of the specimens.

Just like in Phase 1 it was possible to verify that there were, in the rupture region of specimens, spoiled aggregates and also aggregates taken from the paste (rupture from the paste around the aggregate), which characterizes the proper adherence of the aggregate to the paste.

It was also possible to observe that the quantity of spoiled aggregates was smaller, or approximately equal to the aggregates separated from the cement paste indicating that the aggregate strength is also acceptable. It was observed in all concrete traces that most particles were wrapped with the cement paste in rupture sections.

4.2.2.2. Tensile strength by diametral compression

Figure 15 shows the results of tensile strength by diametral compression at the age of 28 days.

The values presented of tensile strength were satisfactory, not representing relevant differences with the samples. The biggest difference was 21.43% in T-A5 trace in relation to T-AG and the smallest difference was only 5.55% in relation to T-AG trace.

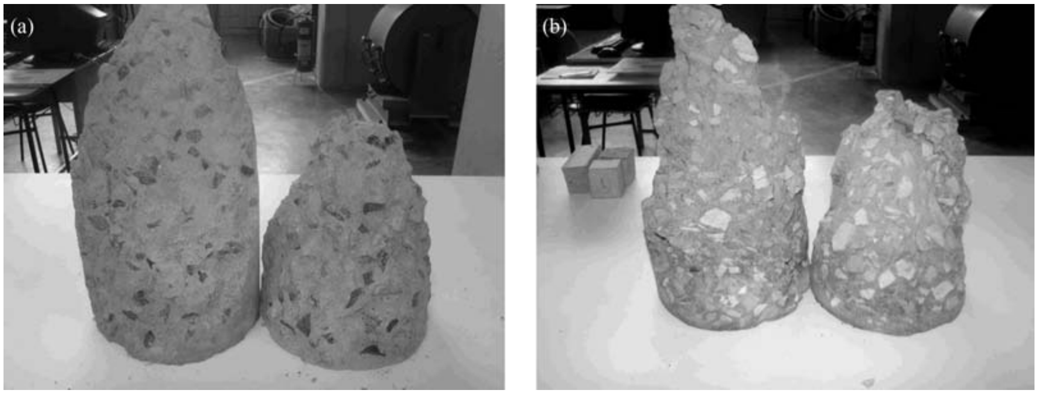

Figure 14 - Rupture sections to compression of concretes produced, corresponding to AG(a) and A4(b).

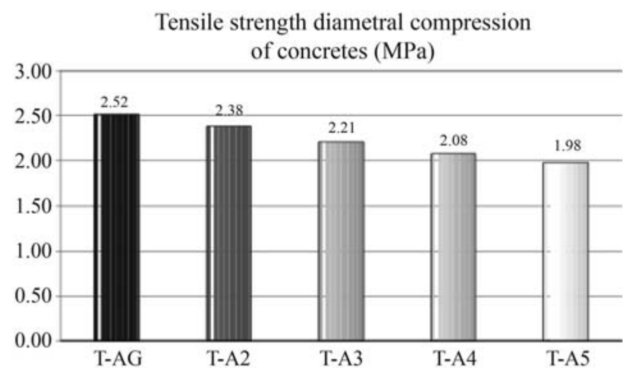

Figure 15 - Tensile strength by diametral compression of concretes at the age of 28 days.

Figure 16 presents the rupture section of the specimens tested under tension by diametral compression.

4.2.2.3. Modulus of elasticity

The results of the tests of the modulus of elasticity carried out in Phase 2 are shown in Table 22.

The biggest difference obtained was 7.67 GPa in trace T-A3 in relation to T-AG. And the smallest difference was only 5.04 GPa in trace T-A2 in relation to T-AG.

Table 22 - Results of the modulus of elasticity.

Samples	f_{cj} (MPa)	% f_{cj}	ME (GPa)
T-AG	23	20	21.58
T-A2	20	20	16.54
T-A3	20	20	13.91
T-A4	21	20	15.42
T-A5	18	20	16.09

The values (results) were very close when it comes to quartzite samples, but when they are compared to the reference trace this variation is considerable. The difference may be attributed, for example, the interaction between aggregate and binder paste in the transition zone.

It is important to point out that microscopic studies can help interpret these differences of modulus of elasticity and that specific dosage studies can make the performance of the concrete modulus of elasticity better, through variations of the a/c ratio, reduction, coarse aggregate content, among others.

5. Conclusion

Two distinct lithological kinds of waste from quartzite mines in the region were identified: Type 1- which is

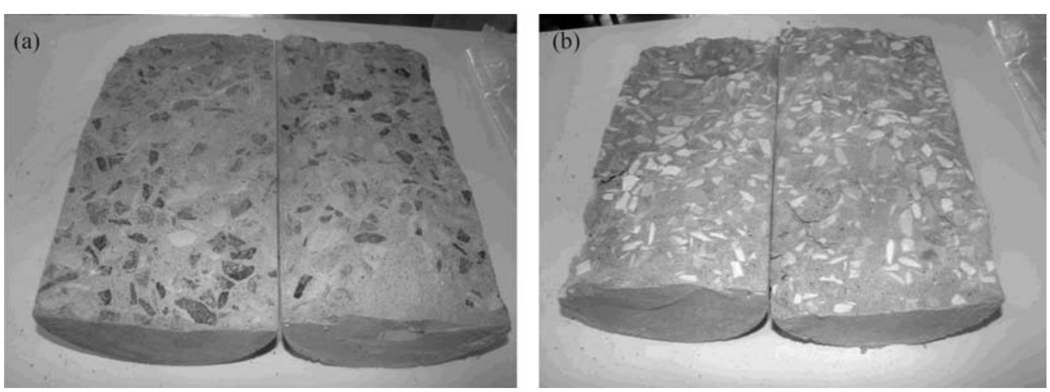

Figure 16 - Rupture sections of the specimens corresponding to the sample traces AG(a) and A5(b).

constituted by the remaining foliate quartzite, mica - which is effectively used as “coating stone”; and Type 2, which is a silicified quartzite, with low mica content, non-foliated and that after the extraction, it is completely discharged. Type 2 due to its physical, mineralogical, and mechanical characteristics was selected in this study.

The results to characterize the quartzite aggregates, in general, were quite satisfactory compared to the conventional gneissic aggregate, to the rates presented by Verhoef e Van De Wall (1998 *apud* Gomes, 2001) and to the parameters established by ABNT (2005).

The deficiencies of shape index found in aggregates in Phase 1 using the jaw crusher according to ABNT (1983a) were corrected in Phase 2 using the hydrocone crusher.

Regarding the alkali-aggregate reactivity done by ASTM (2007) accelerated test, the deleterious potentiality was verified both, with CP II-Z-32 and CP V-ARI cements. In this case it is recommended the use of low-content alkali and with addictions such as the CP III (High-Furnace Portland Cement) and the CP IV (Pozzolanic Portland Cement) and preventive methods of the reaction such as the water-proofing structure, for instance. However, further studies using different methods should be carried out for a final conclusion of the quartzite reactivity.

The results of the properties in hardened state were also satisfactory. The differences obtained in Phase 1 after the compressive strength test (maximum 21.88% in A1 and minimum 10.42% in A2 in relation to AG) were attributed to the irregular forms of the grains affecting directly the concrete strength. The bigger the proportion of flat and elongated particles, the bigger the trend for accumulation of water film along the aggregate surface will be, weakening the transition zone in the aggregate-paste interface.

In Phase 2, the differences obtained after the compression test (maximum 13.43% in T-A3 trace and minimum 4.16% in A4 trace in relation to the T-AG concrete) showed the efficacy of the hydrocone crusher demonstrating that the results between the quartzite and gneiss concretes were very close.

The results of the modulus of elasticity, carried out in Phase 2 presented considerable variations between the quartzite and gneiss traces, however, they were next to the conventional interval of the concretes to use in structures which is 16 GPa to 35 GPa. Thus, alternative dosage studies varying the characteristics of concretes and analyses of the internal microstructure of these concretes are recommended for a better interpretation of these differences.

In Phase 1 it was observed visually that not all the aggregate grains presented a formation of a cement paste layer on its surface. The arrangement of the aggregate particles inside the concrete is also an interfering factor, due to the flat and elongated forms of some grains, which make it difficult the compactness and homogeneousness of the material. In Phase 2 the grains presented greater adherence to the cement paste, confirming the efficacy of the quartzite aggregates when processed in proper crusher.

In a last analysis, the studies carried out in this paper indicated that the quartzite residues coming from mines in the Southwestern Minas Gerais presented satisfactory behavior for the use as a coarse aggregate in the concrete.

With further research and also the support of institutions that contribute to the moving of regional economy, the commercialization of this product will be feasible and it will also contribute to solve social, economical, and environmental problems which reach the mining sector of the Southwest of the state, especially when it comes to quartzite.

6. Recommendations

As recommendations for future studies, it is suggested:

- Study concretes with different consistency and strength;
- Carry out studies of potential alkali reactivity of aggregates, using alternative methods, other kinds of cement and check the interference of the grain form on the empty index of mortars;
- Analyze the microstructure of concretes to check the aggregate interface and binder paste, principally in more advanced ages.

Acknowledgments

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