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High-performance concrete with recycled stone slurry

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Abstract

Presently large amounts of slurry are generated in natural stone processing plants with an important impact on the environment and humans. This paper describes this impact and presents test results showing the feasibility of using this industrial by-product in high-performance concrete production as a substitute of fine aggregates. Test results show that this industrial by-product is capable of improving hardened concrete performance up to 16%, enhancing fresh concrete behaviour and can be used in architectural concrete mixtures containing white cement.

Keywords: High-performance concrete; Architectural concrete; Stone slurry; Stone dust; Microfiller

1. Introduction

Dimension stone industry generates different types of waste: solid waste and stone slurry. Whereas solid waste is resultant from rejects at the mine sites or at the processing units, stone slurry is a semi-liquid substance consisting of particles originated from the sawing and polishing processes and water used to cool and lubricate the sawing and polishing machines.

Stone slurry generated during processing corresponds to around 40% of the dimension stone industry final product. This is relevant because dimension stone industry presents an annual output of 68 million tons of processed product.[1] Therefore, scientific and industrial community must commit towards more sustainable practices.

There are several reuse and recycling solutions for this industrial by-product, both at an experimental phase and already in practical applications [2]. However, dimension stone industry waste management present strategy is to discharge the waste in landfills, regardless of the potential use these by-products may present for other industries.

When stone slurry is disposed in landfills, its water content is drastically reduced and the stone dust resulting from this presents several environmental impacts [2].

To analyze the applications of this stone dust in the construction industry, an experimental program was undertaken at Technical University of Lisbon – IST (Portugal) with the support of the Portuguese dimension stone industry, to evaluate

Table 1
Properties of coarse and fine aggregates

Property	FA1	FA2	CA1
Water absorption (%)	0.4 NP954	1.0 NP954	1.9 NP581
Dry specific density (kg/m^3)	2594 NP954	2526 NP954	2576 NP581
Saturated surface dry specific density (kg/m^3)	2604 NP954	2551 NP954	2628 NP581
Bulk density (kg/m^3)	1498 NP955	1537 NP955	1389 NP955
Microfines content (%)	0.5 NP86	1.7 NP86	3.0 NP86
Maximum size (mm)	0.595 NP1379	2.38 NP1379	9.51 NP1379
Fineness modulus	1.4 NP1379	3.2 NP1379	5.7 NP1379

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[1] Countries that produce more than 1 million tons/year of dimension stones are China, Italy, India, Portugal, Brazil, Turkey, USA, Greece, South Africa and France [1].

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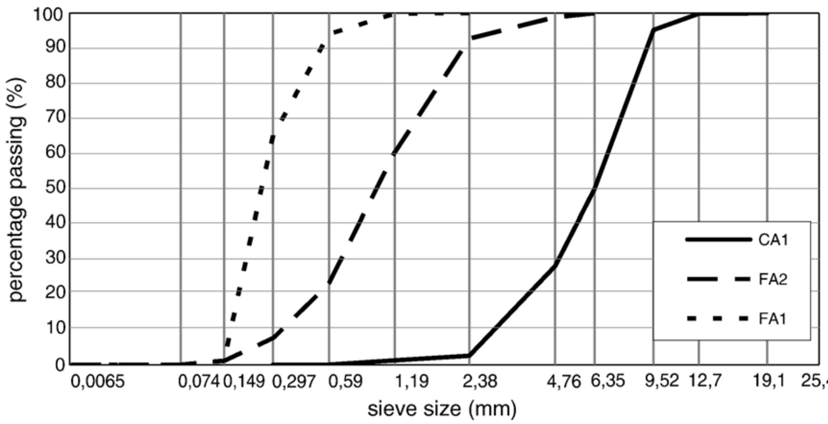

Fig. 1. Grading curve of aggregates.

the influence of this waste in high-performance concrete mixtures.

The research framework implied analysis of the dimension stone industry semi-liquid waste and development of technology towards its incorporation on the concrete industry (high-performance mixtures), simultaneously reducing the pressure on the industrial stones industry (lowering sand consumption for concrete production).

This paper describes the behaviour of high-performance white cement concrete, incorporating stone dust, in terms of its fresh and hardened concrete properties.

It also shows the feasibility of using this type of concrete in aesthetic and architectural applications, due to its superior quality of wall faces, workability and colour.

2. Experimental program

2.1. General procedures

Stone slurry is naturally a potential by-product for industries that incorporate raw materials with similar composition. Among those, concrete industry presents the advantage of being capable to do so with the present available technology.

The research developed aimed at reusing the material accumulated in waste deposits (as an alternative to recycling). The reuse strategy presents the advantage of not involving further waste treatments (such as crushing), as the samples were collected directly from deposits of compressed waste slabs (particles and lumps).

After collection, the lumps were crumbled into dust in order to prevent non-resistance occurrences in the concrete matrix. This was achieved by using high contents of superplasticizer in concrete mixtures. It was concluded that previous crumbling of lumps of this stone waste (recycling) was recommended.

The stone dust chosen for these experiments was white to light coloured (originated from limestone and marble). It was expected that this dust was compatible with, or might even enhance, the characteristics of regular white cement concrete.

Eight concrete mixtures with stone dust (CMSD) were produced, replacing 0% (reference mixture), 5%, 10%, 15%, 20%, 34%, 67% and 100% of fine aggregate (sand), in terms of volume. All concrete mixtures were set with a slump of 230 ± 10 mm and a spread of 550 ± 10 mm, obtained by adjusting the water/cement ratio.

2.2. Materials

2.2.1. Aggregates

The coarse aggregate used in concrete mixtures was obtained from crushed limestone and the fine aggregates were extracted from sedimentary deposits (sand). Table 1 shows the properties of coarse aggregates (CA) and fine aggregates (FA1 and FA2),

Table 2
White cement mechanical properties

Age (days)	Bending (MPa)	Compression strength (MPa)
2	3.4	18.9
7	5.8	32.2
28	6.9	41.1

Table 3
White cement physical properties[1]

Property		Specification	Test result
Specific density			2.96 g/cm^3
	90 μm		0.1%
Sieve residue	45 μm		1.3%
	32 μm		6.7%
Specific surface area (Blaine)		NP EN 196-6	5340 cm^2/g
Average dimension of particles			9.4 μm
Water of normal consistency		NP EN 196-3	29.0%
Setting time	Initial	NP EN 196-3	95 min
	Final		170 min
Expansion (*Le Châtelier*)		NP EN 196-3	1.0 mm
Brightness *Y*		LNEC E 357	85.5%
Whiteness index		LNEC E 357	64.8%

[1]Brightness *Y* and Whiteness index are important parameters to characterize white cement [3]. White cement testing was held by the cement producer according to the Portuguese specification LNEC E 357: White cement — determination of whiteness (this specification was developed taking ASTM E 97 and ASTM E 313 into consideration).

Table 4
White cement chemical properties

Property	Existence (%)
Loss on ignition (L.O.I.)	12.20
Insoluble residue (I.R.)	0.30
SiO_2	17.50
Al_2O_3	2.15
Fe_2O_3	0.20
CaO	64.20
MgO	0.80
SO_3	2.50
K_2O	0.24
Na_2O	0.11

as well as the respective specifications used for testing. Fig. 1 presents the grading curves (determined according to NP 1379).

2.2.2. White cement

Concrete mixtures were produced with white cement type CEM II/B-L 32,5R (br[2]), characterized by the mechanical properties presented in Table 2 (determined according to NP EN 196-1), the physical properties presented in Table 3 (where no specification is quoted, the results were obtained from internal procedures of the cement producer), and the chemical properties are presented in Table 4 (cement producer results).

2.2.3. Stone dust

The stone dust was collected at an open-air dumpsite. The plant responsible for generating the collected specimens processed only marble and limestone. The *in situ* water content of the different samples ranged from 1 to 2%. When collected, the dried stone dust was composed of individual particles and lumps. The lumps resulted from the fragmentation of compacted slurry slabs obtained in the water recovering operations held at the processing plant. In order to perform testing, the collected samples were reduced to dust.

Chemical tests results are presented in Table 5. The high content of CaO confirmed that the original stones were marble and limestone. The dust was also tested (NP 85) to identify the absence of organic matter, thus confirming that it could be used in concrete mixtures.

The tested stone dust had a specific density of 2.72 g/cm^3. Laser granulometry tests were held in order to compare both grading curves of cement and dust particles (Fig. 2). The specific surface area of the dust particles was 7100 cm^2/g (calculated from the particle size distribution) and its average size was 5.0 μm (smaller than cement particles).

Due to the fact that natural fine aggregates (sand) are used directly from the exploration sites, some technical specifications impose that the clay[3] content on these materials must be limited, in order to be used on concrete mixtures. The usual procedure to guarantee the fulfilment of these specifications is to limit the quantity of material passing the sieve 74 μm [5]. Therefore, the rejection of very fine materials based solely on dimensional criteria has been common practice in the past. However, at the light of state-of-the-art concrete technology, this practice might be a mistake [6].

In fact, the dimension of dust particles was compatible with the purpose of filling up the transition zone (measuring between 10 and 50 μm [4]) and the capillary pores (which range from 50 nm to 10 μm of diameter [7]), thus acting as a microfiller.

Thus, despite the average dimension of the slurry particles was inferior to 74 μm, their chemical nature was exclusively dependent on the original material (without clay or other deleterious materials) and the test results showed that the slurry was fit to be used in concrete mixtures.

According to parallel specific testing, held by the cement producer according to Portuguese standards NP 4220 and NP EN 450, it was also concluded that the stone dust had no hydraulic or pozzolanic activity.

2.2.4. Concrete admixtures

A new generation polymer based on modified phosphonates was used, with the commercial designation of *Chrysofluid Optima 100*, compatible with potable water and acting as a high activity water reducer. The maximum dosage recommended by the producer (5 kg/100 kg of cement) was used. This plasticizer conforms to CE marking and the NF 085 certification, whose technical specifications are applied in the non-harmonized part of the NF EN 934-2.

2.3. Experimental conditions

Compressive strength testing was undertaken upon 10 cm cubic specimens at 7 and 28 days of age. Regarding splitting tensile strength and modulus of elasticity, cylinders with 30 cm of height and 15 cm of diameter were cast and tested at 35 days of age. All specimens were demoulded 48 h after casting.

10 cm cubic specimens were used (30 days after casting) to characterize properties such as bulk specific gravity, both after vacuum immersion and after drying, apparent specific gravity, and others durability-related (water absorption and voids volume). All these testing procedures were consistent with ASTM C 642-90.

Table 5
Chemical characterization of stone dust

Designation	Existence (%)
Loss on ignition (L.O.I.)	43.40
Insoluble residue (I.R.)	0.90
SiO_2	0.91
Al_2O_3	3.72
Fe_2O_3	0.40
CaO	54.29
MgO	0.30
SO_3	0.09
Cl^-	0.03

[2] "br" is used in Portuguese cements to designate white cement.

[3] Silicates present less than 2 μm, are characterized by low stiffness, are disintegratable, present tendency to expansion in the presence of water [4] and are susceptible of being adsorbed by the cement particles (thus interfering with the hydration reactions) [5]. For these reasons, clay is not accepted to be used in concrete mixtures.

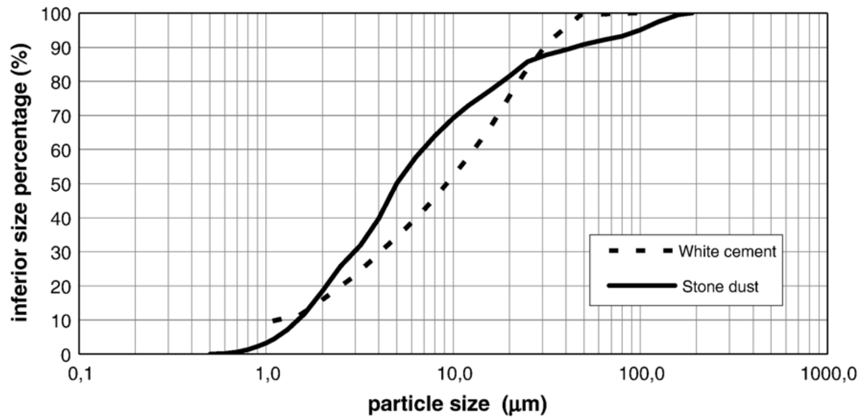

Fig. 2. Comparison of cement and dust particles size.

All specimens were demoulded 48 h after casting, cured in a moist room (20 °C) until 14 days of age, and then transferred to regular conditions (interior of the laboratory) till testing.

Concrete mixtures proportioning was designed using Faury's method, and the results are presented in Table 6 (the water/cement ratio includes the liquid phase of the admixture).

3. Results and analysis

3.1. Microfines content

Since the aim of the research implied substitution of materials with different grading (sand and dust), it was important to compute the proportions of very fine material presented in the concrete mixtures.

Table 6
CMSD mix proportions

Concrete mixture	Sand substitution (%)			CA1 (kg/m^3)	FA2 (kg/m^3)	FA1 (kg/m^3)	Cement (kg/m^3)	Dust (kg/m^3)	water / cement ratio
	FA1	FA2	Total						
CMSD0	0	0	0	1071	473	253	401	–	0.36
CMSD5	14	0	5	1080	477	219	405	38	0.33
CMSD10	29	0	10	1085	479	182	406	77	0.32
CMSD15	43	0	15	1071	473	144	401	114	0.36
CMSD20	58	0	20	1054	465	103	395	152	0.39
CMSD34	100	0	34	1037	458	–	388	256	0.44
CMSD67	100	50	67	1017	225	–	381	489	0.48
CMSD100	100	100	100	1013	–	–	379	726	0.50

Table 7 presents the microfines content in all concrete mixtures, along with the ratios dust/cement (d/c), dust/microfines (d/mf), dust/solid components (d/sc) and microfines/solid components (mf/sc).

Dust/cement, dust/solid components and microfines/solid components ratios presented linear variation because sand was substituted by the exact same volumetric amount of dust.

Concerning the total substitution of fine aggregate for stone dust (CMSD100), the quantity of dust was nearly double that of cement and represented 34% of the solid components (cement, aggregates and dust).

CMSD20 contained 586.7 kg/m^3 of microfines (cement, dust and aggregate microfines content). CMSD34, CMSD67 and CMSD100 were expected to present lower performance because their microfines content surpassed the generally accepted limit of 600 kg/m^3 [8].

Despite Faury's concrete design method does not consider microfines content, 20% of the solid components present on the reference mixture were lower than 74 μm, thus being considered as microfines. There were 54% of microfines in CMSD100.

Fig. 3 compares the optimum curves obtained by using Faury's, Bolomey's and Fuller's design methods. For test conditions, Bolomey's microfines content (13,3% — see Fig. 3) was more accurate estimating the microfines content detected in CMSD0 (18.2% — see Fig. 7).

Table 7
CMSD microfines' content and ratios

Concrete mixture	Cement (kg/m^3)	Dust (kg/m^3)	Aggregates microfines content (kg/m^3)	Microfines (kg/m^3)	Solid components (kg/m^3)	d/c	d/mf	d/sc	mf/sc
CMSD0	401.2	–	41.4	442.6	2198.4	0.00	0.00	0.00	0.20
CMSD5	404.6	38.4	41.6	484.6	2218.5	0.09	0.08	0.02	0.22
CMSD10	406.3	77.1	41.6	525.0	2229.3	0.19	0.15	0.03	0.24
CMSD15	401.2	114.2	40.9	556.3	2203.2	0.28	0.21	0.05	0.25
CMSD20	394.7	152.0	40.0	586.7	2169.1	0.39	0.26	0.07	0.27
CMSD34	388.4	255.9	38.9	683.2	2138.9	0.66	0.37	0.12	0.32
CMSD67	380.8	489.1	34.3	904.2	2111.9	1.28	0.54	0.23	0.43
CMSD100	379.3	726.4	30.4	1136.1	2118.4	1.92	0.64	0.34	0.54

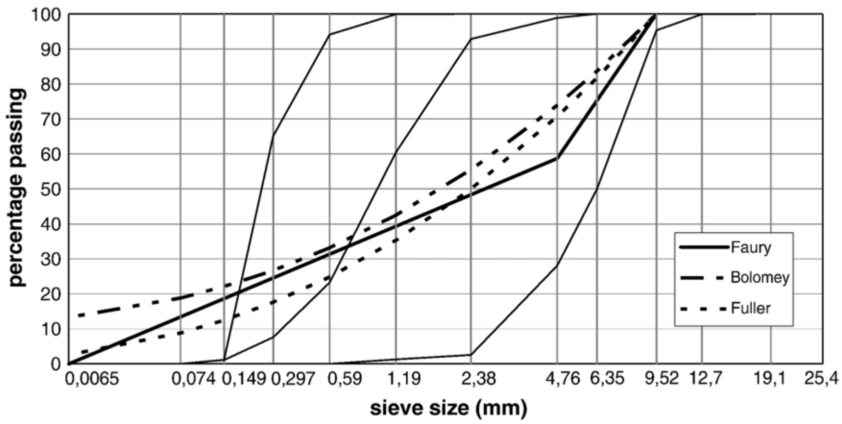

Fig. 3. Faury's, Bolomey's and Fuller's CMSD0 proportion results.

3.2. Fresh concrete

Adequate architectural white cement concrete depends on low water/cement ratios, control of the maximum dimension of the aggregate, large quantities of binder and very fine materials and admixtures [8].

The total liquid phase (water and chemical admixture liquid phase) for each concrete mixture is presented in Table 8.

According to sand substitution percentage, Fig. 4 plots the water/dust ratio variation, Fig. 5 shows the water/cement ratio variation and Fig. 6 presents the water/microfines ratio variation.[4]

Figs. 5 and 6 show distinct behaviours of water consumption concerning the incorporation of stone dust, as sand substitute, in percentages ranging from 0 to 10%, 10 to 20% or 20 to 100%.

Regarding the 0–10% range (CMSD0, CMSD5 and CMSD10):

– the water/dust ratio decreased from ∞ to 1.71;
– the water/cement ratio decreased from 0.36 to 0.32;
– the water/microfines ratio decreased from 0.32 to 0.25.

As a result of the stone dust introduction, the very fine material content increased and the water need (for constant workability) decreased, thus lowering the water/cement and water/microfines ratios.

The results indicated that dust particles had size, form and texture that benefited fresh concrete workability [6]. For these ratios of dust incorporation, higher workability prevailed over the higher specific surface area of the dust particles, comparing with the substituted sand particles.

From 0 to 10% of dust incorporation, there was lower water demand, superior behaviour of fresh concrete, better grading, efficient packing, and better aesthetic of finished concrete elements.

Concerning the 10–20% range (CMSD10, CMSD15 and CMSD20):

– the water/dust ratio decreased from 1.71 to 1.03;
– the water/cement ratio increased from 0.32 to 0.39, overtaking 0.36 (reference);
– the water/microfines ratio increased from 0.25 to 0.27, though lower than 0.32 (reference).

Comparing with the 0–10% range, there was a behaviour reversal. Variation was characterized by increasing water demand, thus higher water/cement ratio (for constant workability).

Water/microfines ratio also increased, due to a higher specific surface area. Possibly, there was also deficient grading,[5] due to the introduction of stone dust in detriment of sand (as shown in Fig. 7).

Nevertheless, it is significant that CMSD15 had the same water/cement ratio than the reference mixture (CMSD0), as this had consequences for the mechanical properties reported ahead.

Finally, within the 20–100% range:

– the water/dust ratio decreased from 1.03 to 0.26;
– the water/cement ratio increased from 0.39 to 0.50, always above 0.36 (reference);
– the water/microfines ratio decreased from 0.27 to 0.17, always below 0.32 (reference).

Even though water demand increased, the sensitivity to very high levels of sand substitution was reduced. The water/microfines ratio regained the expected tendency (decreasing).

Generally, stone dust (regardless of the incorporated amount) incorporation induced more paste, thus improving fresh concrete behaviour in terms of viscosity and showing good potential to be used in self compacting concrete mixtures.

[4] In Figs. 4, 5 and 6, "water" is considered as the total liquid phase and "microfines" as the total amount of stone dust, cement and aggregates microfines content.

[5] Discontinuous grading can be improved by introducing very fine particles, thus inducing higher performance on concrete mixtures [9]. Nevertheless, it is difficult to define designing tools to obtain proportions in such a manner that these benefits can be systematically attained. Hence, it is usually accepted that continuous grading is preferred to the unknown consequences of discontinuous grading.

Table 8
Water consumption for CMSD for constant workability

Concrete mixture	Water (l/m^3)	Admixture		Total liquid phase (l/m^3)
		Total (kg/m^3)	Liquid phase (l/m^3)	
CMSD0	128.4	20.1	14.1	142.5
CMSD5	121.4	20.2	14.1	135.5
CMSD10	117.8	20.3	14.2	132.0
CMSD15	128.4	20.1	14.1	142.5
CMSD20	142.1	19.7	13.8	155.9
CMSD34	155.4	19.4	13.6	169.0
CMSD67	171.3	19.0	13.3	184.6
CMSD100	174.5	19.0	13.3	187.8

In fact, CMSD has well known characteristics and properties of self compacting concrete mixtures [10–19], such as high powder contents, surface-active agents and better cohesion and consistency. The small particles of dust opposed the rising of free water and the descent of aggregates, reducing deleterious phenomena such as segregation and exudation. Fig. 8 shows an experiment involving concrete slabs produced with a flow table, with and without stone dust, and same workability.

3.3. Hardened concrete

3.3.1. Mechanical properties

Table 9 presents the results obtained for the mechanical properties and Fig. 9 plots their relative variation, when compared with CMSD0 (mixture without stone dust).

When 5% of the initial sand content was replaced by stone dust (CMSD5), 10.3% higher compressive strength after 7 days and 7.1% higher compressive strength after 28 days were detected, when compared with CMSD0. This increase can be related to the higher concentration of hydrated cement compounds within the available space for them to occupy [20]. Furthermore, by acting as microfiller, the stone dust promoted an accelerated formation of hydrated compounds, thus resulted a significant improvement of compressive strength at earlier ages (7 days).

In fact, the amount of dust present in CMSD5 enabled the very fine particles of it to act as nucleation points [20,21]. This is related to an effect of physical nature that ensures effective packing and larger dispersion of cement particles, thus fomenting better hydration conditions. Moreover, the dust particles completed the matrix interstices (transition zone and capillary pores) and reduced space for free water [22,23]. The combination of these phenomena resulted in a better bonding among the concrete components.

CMSD10, CMSD15 and CMSD20 presented a reduction of compressive strength ranging from 3.6% to 10.6% at 7 days of age and from 6.7% to 8.9% at 28 days of age (when compared to CMSD0). Lower performance of CMSD10 could seem improbable taking into account its water/cement ratio. However, for this extremely low water/cement ratio, the available space for accommodating hydrated products might have been insufficient, thus inhibiting chemical reactions.

Regarding higher contents of stone dust (substitution of more than 20% of sand), the decrease of compressive strength

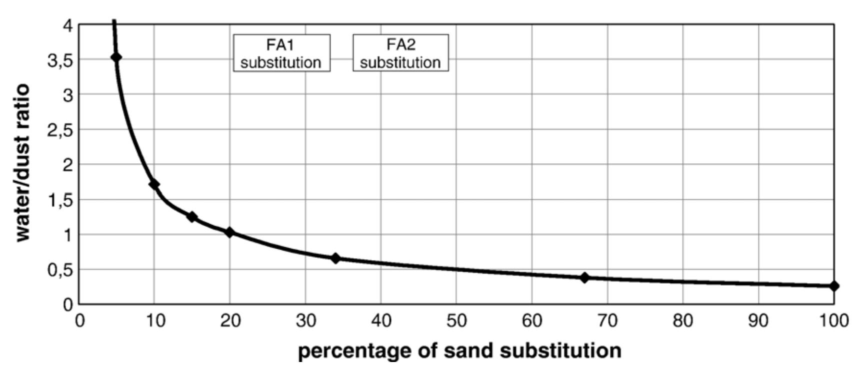

Fig. 4. Water/dust ratio variation according to the sand substitution percentage.

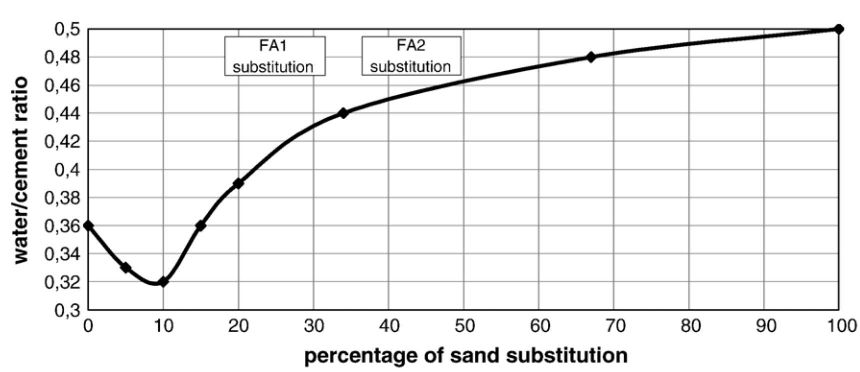

Fig. 5. Water/cement ratio variation according to the sand substitution percentage.

values was significant. The incorporation of such amounts of very fine material did not permit the microfiller effect to prevail, which, in addition to a rather inappropriate grading, caused lower results.

When substituting all the sand for stone dust (CMSD100), test results showed 50.3 MPa at 28 days and 30.1 MPa at 7 days. Whereas these results were acceptable by comparison with conventional concrete, the relative reduction amounted 40.9% for 28 days and 50.1% for 7 days. Therefore, it is possible to conclude that full substitution of fine aggregate for stone dust is not reliable when compressive strength is a critical aspect to take in consideration.

The benefits obtained in compressive strength property due to the microfiller effect induced by stone dust particles was even further important regarding the splitting tensile strength tests (relative increase of 14.3% detected for CMSD5). These are coherent results, at the light of the explanation advanced regarding the compressive strength variation of CMSD5.

As for the compressive strength case, when the substitution level of sand surpassed 20%, the tensile splitting strength was significantly reduced. Nevertheless, test results show that tensile splitting strength is less sensitive to high contents of very fine particles than compressive strength. CMSD100 presented a result of 3 MPa, correspondent to a quite acceptable reduction of 28.6% relatively to CMSD0.

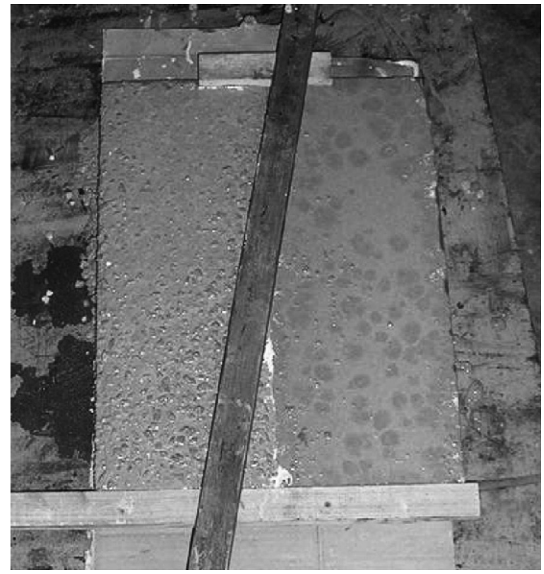

Fig. 8. Fresh concrete slabs incorporating 255 kg/m3 of stone dust, on the left (no exudation), and no dust on the right (with superficial signs of exudation).

Test results also showed that CMSD5 had the better behaviour in terms of modulus of elasticity (6.2% higher than CMSD0) and that all mixtures containing less than 20% of stone

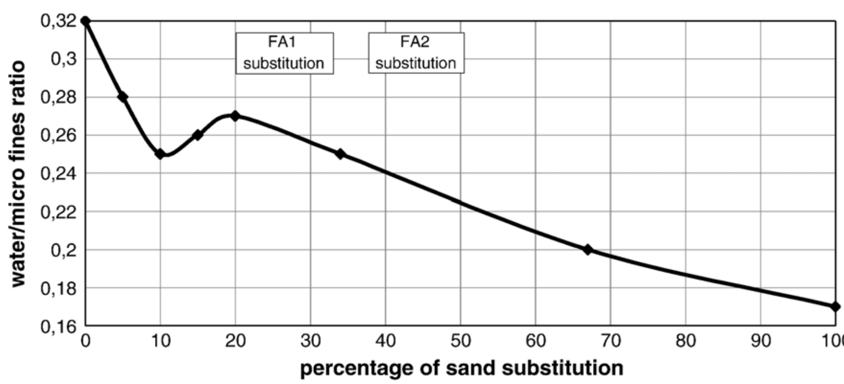

Fig. 6. Water/microfines ratio variation according to the sand substitution percentage.

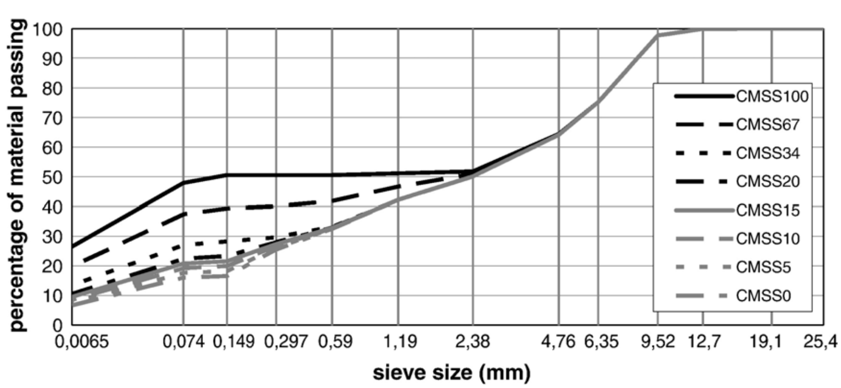

Fig. 7. Grading variation due to substitution of fine aggregate for stone dust.

Table 9
Mechanical properties test results

Concrete mixture	Compressive strength 7 days (MPa)	Compressive strength 28 days (MPa)	Spitting tensile strength (MPa)	Modulus of elasticity (GPa)
CMSD0	60.3	85.1	4.2	40.5
CMSD5	66.5	91.1	4.8	43
CMSD10	55.3	79.4	4.2	41.4
CMSD15	58.1	79.5	4.3	38.8
CMSD20	53.9	77.5	4.0	36.9
CMSD34	41.1	60.8	3.3	33.5
CMSD67	36.4	58.2	3.2	30.7
CMSD100	30.1	50.3	3.0	26.7

Table 10
Physical properties test results

Concrete mixture	Apparent specific gravity (kg/m^3)	Bulk specific gravity — dry (kg/m^3)	Bulk specific gravity — after vacuum immersion (kg/m^3)
CMSD0	2595.4	2434.5	2334.2
CMSD5	2571.7	2440.0	2356.3
CMSD10	2593.0	2449.2	2359.0
CMSD15	2565.3	2422.1	2330.7
CMSD20	2575.3	2404.4	2296.0
CMSD34	2564.5	2371.1	2247.5
CMSD67	2574.8	2348.3	2204.5
CMSD100	2572.9	2322.7	2163.6

dust obtained acceptable results. CMSD10 also presented a slight behaviour improvement of 2.2%. In the extreme case of dust incorporation (CMSD100), the average of test results for the modulus of elasticity was 26.7 GPa (34.1% less than the reference concrete mixture CMSD0).

It is known that cement paste modulus of elasticity is generally half the modulus of elasticity of aggregates [23]. Therefore, when introducing stone dust (very fine particles, with slight inferior size than cement particles), the paste could be considered as increased, thus promoting a negative effect on the modulus of elasticity of the hardened concrete's. This fact, in addition to the higher water/cement ratio, could explain the lower modulus of elasticity attained for more than 15% substitution (inclusively).

3.3.2. Physical properties

Test results concerning physical properties are presented in Table 10 and its variation in Fig. 10. Bulk specific gravity – both after vacuum immersion and dry – evolved according to water/cement ratio variation.

CMSD10 presented the highest values for mixtures incorporating stone dust. Increasing bulk specific gravity within the 0–10% range can be explained by water/cement ratio reduction and better packing, induced by superior fresh concrete behaviour.

For more than 10% sand substitution, the water/cement ratio was higher and, consequently, there was higher loss of free water and voids volume and lower specific gravity.

3.3.3. Properties related to durability

Table 11 and Fig. 11 present the test results in terms of voids volume and water absorption, calculated according to ASTM C 642-90, and provides an insight on these concrete mixtures durability properties.

According to the water/cement ratio variation (Fig. 5), hardened concrete properties related with durability were expected to be higher up to a 15% stone dust substituting sand ratio.

Tests showed a 16% reduction in voids volume and water absorption for CMSD5, indicating that the stone dust particles secured a more effective dispersion of cement particles, thus enhancing hydration chemical reactions (microfiller effect within the concrete matrix).

Furthermore, stone dust particle dimensions were within the usual range of the transition zone and promoted higher density of hydrated compounds and inferior free space for excess water to accommodate.

The volume of permeable pore spaces (voids volume) and the water absorption (in vacuum immersion) test results revealed the extent of the communicability between separate pores, their distribution, display and diameter

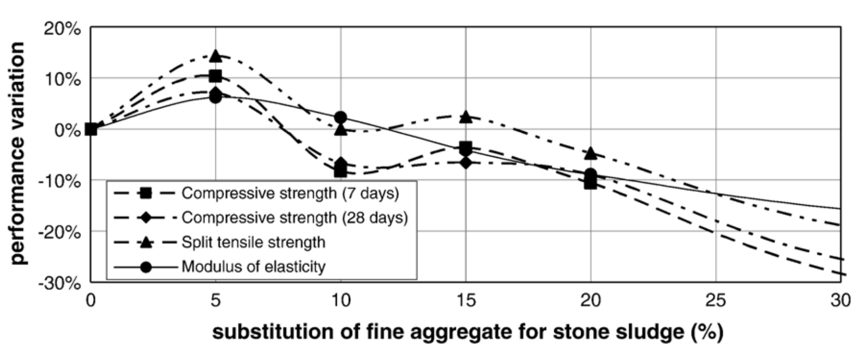

Fig. 9. Variation of mechanical properties for low contents of stone dust.

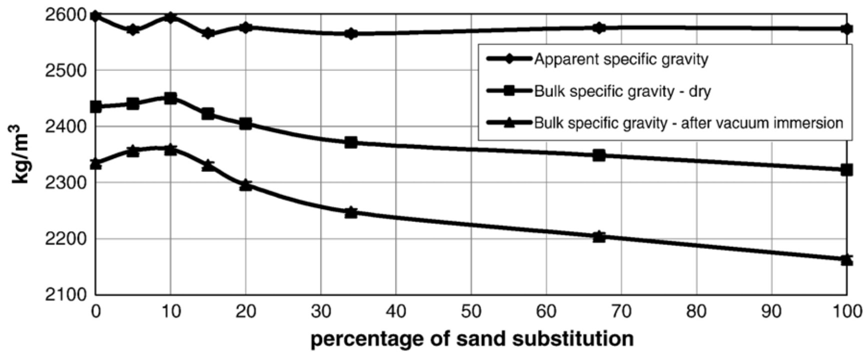

Fig. 10. Variation of hardened concrete physical properties.

[22] — which is directly related with hardened concrete durability.

CMSD5, CMSD10 and CMSD15 presented lower voids volume and water absorption, resulting from dust particles being approximately the same size as capillary pores, thus interrupting connections within the pores structure.[6] This reduced penetration of degrading agents within concrete, as more pores became inaccessible.

Inferior durability-related performance was detected only for sand replacement ratios over 15%. CMSD100 showed 59% higher voids volume and 72% higher water absorption. Regardless of lower performance as compared with CMSD0, CMSD100 results were 7.5% for water absorption and 15.9% for voids volume.

Taking into account CMSD10's water/cement and water/microfines lowest values, this concrete mixture was expected to present the lowest voids volume. However, as shown in Fig. 12, this was not the case. CMSD10 voids volume was higher than the ones obtained for CMSD5 and similar to CMSD15's.

The reason for this was that CMSD10 had the lowest water/cement ratio (0.32) and the highest specific gravity. Under these conditions, it is feasible that there was insufficient volume to accommodate all the hydration products[7] and that hydration within the capillary pores [20] was restricted due to the lack of water to enable chemical reactions.[8]

Hypothetically, if water/cement ratio was not so low for CMSD10, to the point of causing negative effects on cement hydration, an even higher performance could have been achieved.

It was shown that stone dust improves concrete properties related to durability. Comparing CMSD15 to CMSD0, which had the same water/cement ratio, slump and water/microfines ratio, the voids volume was 8% lower in the first case. This shows that lower water/cement ratio is not the only factor that explains improvements and that there were benefits related with the physical effect of the particles of stone dust (microfiller effect).

4. Architectural application of CMSD

Tests also showed that stone dust provides different colouration to concrete according to the nature of the original material from which the dust is generated and, hence, it can be used as a pigment in concrete mixtures for architectural purposes.

White to light coloured concrete was made using marble and limestone dust. Series of 50×20×2 (cm) concrete slabs were produced, containing different types of cement and different amounts of dust, demonstrating the feasibility of using this materials in façade's coatings and other applications of architectural concrete.

Fig. 13 shows, from left to right, concrete slabs of different white/grey tonalities produced with: regular Portland cement and no stone dust; regular Portland cement and

Table 11
Test results for properties related with durability

Concrete mixture	Voids volume (%)	Water absorbtion (%)
CMSD0	4,3	10,0
CMSD5	3,6	8,4
CMSD10	3,8	9,0
CMSD15	3,9	9,2
CMSD20	4,72	10,9
CMSD34	5,5	12,4
CMSD67	6,5	14,4
CMSD100	7,4	15,9

[6] It is well known that there are durability benefits for concrete if its matrix voids are completed, if the pores display is refined and if barriers are created in order to diminish communicability among them.

[7] Cement hydrated products volume is considered to be twice the one of non-hydrated cement particles [20].

[8] Even though the water/cement ratio which defines this limit varies according to specific concrete components proportioning and nature, several researchers confirm similar phenomena for this range of values [24,25] and the microfiller effect induced by particles with similar size of the marble or limestone dust [23,26–31].

256 kg/m^3 of dust; white cement and no stone dust (CMSD 0); white cement and 256 kg/m^3 of dust (CMSD 34).

5. Conclusions

Dimension stone industry is responsible for generating about 1 ton of stone slurry (semi-liquid natural stone waste) per 2.5 ton of final product. Besides depleting mineral resources, it causes serious environmental impact regarding water, air, soil, landscape visual aggression, biodiversity and human communities [2].

With the support of the Portuguese dimension stone and concrete industries, a research was undertaken at Technical University of Lisbon – IST (Portugal) aiming to evaluate the feasibility of incorporating stone slurry in high-performance concrete mixtures.

The results showed that the substitution of 5% of the sand content by stone slurry induced higher compressive strength, higher splitting tensile strength, higher modulus of elasticity and improvement of properties related to durability. The feasibility of incorporating up to 20% stone slurry in detriment of the respective amount of fine aggregate without prejudicing mechanical properties in a serious manner was also determined.

It was shown that the behaviour of fresh high-performance concrete is enhanced due to the presence of the stone slurry particles and that the performance of hardened concrete can benefit up to 16%.

Furthermore, tests concerning the use of this type of mixtures for architectural purposes revealed that there is a great potential for stone slurry to be used in concrete elements with aesthetics demands, namely related to non-protected white concrete.

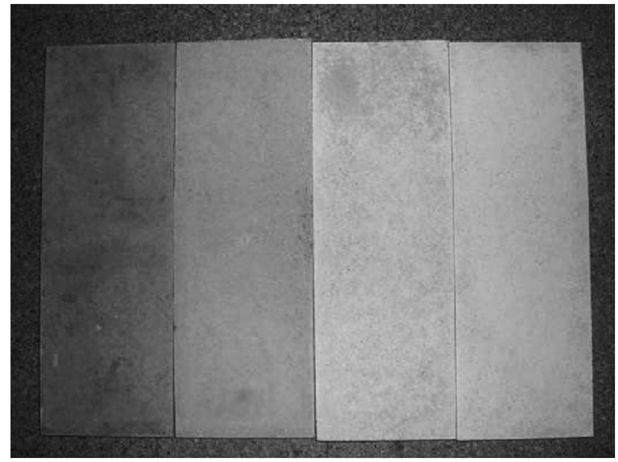

Fig. 13. Colour change of concrete slabs produced with different types of cement and different amounts of stone dust.

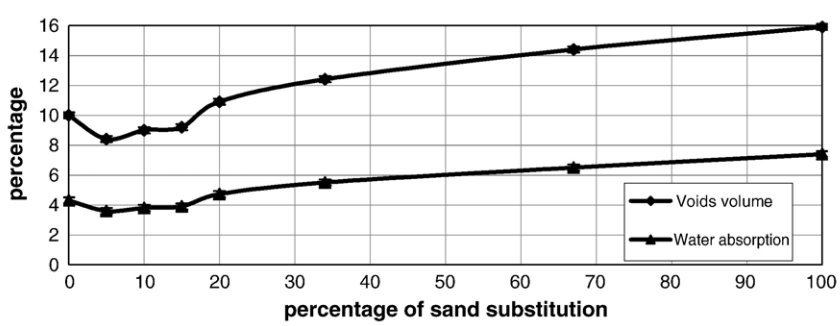

Fig. 11. Variation of hardened concrete properties related with durability.

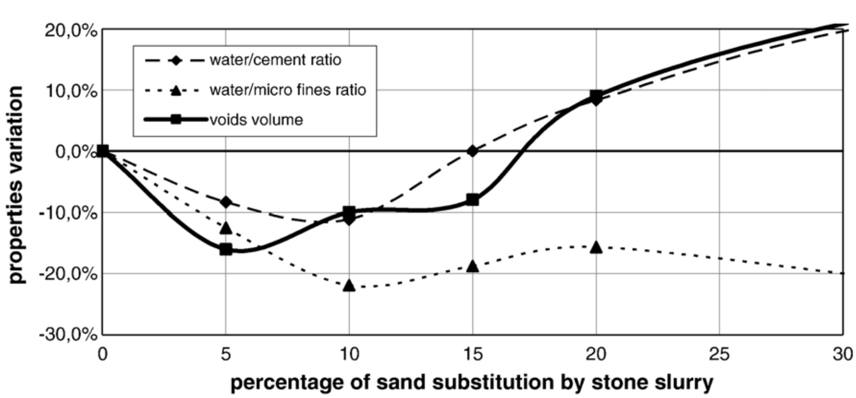

Fig. 12. Variation of voids volume for low contents of stone dust.

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