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Mechanical behaviour of steel fiber reinforced concrete with stone powder

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ABSTRACT

Nowadays, there is an increasing interest in the development of eco-friendly materials. Thus, environmental challenges due to the necessity of reducing worldwide levels of CO_2 emissions, to limit the energy consumption and to use industrial waste are promoting an increasing effort to find viable alternatives to minimize pollution from the main productive processes. Thus, this paper addresses the results of an investigation on the influence of stone powder, residue from the production of crushed aggregates, on the mechanical performance of concrete reinforced with steel fibers. The effect of the amount of stone powder sand was evaluated using 0%, 50% and 100% natural sand replacement. Workability and mechanical properties were evaluated by compressive, elastic modulus, four-point bending and abrasion tests. Economic impact study of the composite production was also carried out. Based on the results obtained, it is possible to conclude that the use of crushed stone sand in steel fiber reinforced concrete is beneficial in terms of the workability and abrasion resistance but was some disadvantages. For instance, when 100% manufactured sand was added, the compressive and bending strength was reduced. However, the elastic modulus was not changed. It is also important to highlight that with 100% stone powder content, the compressive strength is still higher than 30MPa and the cost for producing is about of 32% cheaper.

Keywords: Stone powder, steel fiber, cement based composite, mechanical properties.

1. INTRODUCTION

In the last decades, steel fiber reinforced concrete (SFRC) has been used in many applications such as concrete pavements, overlays, patching repair of hydraulic structures, thin shells and precast products [1]. SFRC has several advantages when compared to unreinforced concrete. The presence of steel fibers enables crack bridging and a post-cracking tensile strength, which delays the development of classic failure mechanisms. When compared to the classic quasi-brittle behaviour of plain concrete structures, the SFRC exhibits increase in ductility and toughness as well as enhancement in resistance to fatigue and impact [2]. These benefits can be mobilized to construct more durable structures [3, 4].

Nowadays, there is a growing trend to use industrial wastes or by-products in the production of cementitious composite. A significant number of experimental studies have been conducted regarding the use of metal waste recycled fibers as reinforcement [5–7] and industrial wastes as admixtures or aggregate in the production of cementitious composite. The use of wastes in system of concrete elements has beneficial environmental and economic impacts, since an added commercial value is given to a sub-product industry that, in general, is considered a waste product.

The main objective of the current research is to explore the development of greener SFRC by incorporating locally available crushed stone powder instead of natural sand. Mechanical properties were evaluated by compressive, elastic modulus, bending and abrasion tests.

Abrasion resistance can be a critical design factor in certain circumstances, or in certain parts of concrete structures, i.e, highway pavements, braking and accelerating zones at toll booths on highways, approaches to urban highway tunnels [8] and some parts of hydraulic structures such as spillways, stilling basins, and bridge piles subjected to the action of water containing solid particles in suspension. Concrete erosion in hydraulic structures occurs due to cavitation, abrasion and chemical attack. Abrasion damages are created by the impact of water born silt, sand, gravel, rocks, ice, and other types of debris on the concrete surface during the operation of hydraulic structures [9]. According to HORSZCZARUK [10,11] and

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SADEGZADEH, *et al* [12], the principal factors affecting the abrasion resistance of concrete can be the environmental conditions, cement content, aggregate properties, the concrete strength, the mixture proportioning, the use of special cement and supplementary cementitious materials and the addition of fiber. Therefore, the efficiency and validity of the SFRC mixtures with addition of crushed stone sand, residue from the production of crushed aggregates, should be evaluated.

FEBRILLET, *et al* [13] investigated the compressive strength and abrasion resistance of ultrahigh-strength steel fiber-reinforced concrete. In the work, the effect of addition of steel fibers, water/binder ratio and compaction method on abrasion resistance and mechanical properties of ultrahigh-strength steel fiber-reinforced concrete were studied. It was concluded that the addition of steel fibers and using hot-press compaction for ultrahigh-strength mortar is particularly effective in improving abrasion resistance.

LI, *et al* [14] reported the compressive strength and abrasion-erosion resistance as well as bending properties of two polypropylene fiber reinforced concretes and the comparison with a steel fiber reinforced concrete. All the polypropylene and steel fibers had no great beneficial effect on the abrasion–erosion resistance of concrete.

SADEGZADEH, *et al* [15] reported the results of a comparative investigation of the influence of three types of fiber, glass, polypropylene and steel, on properties of concrete. For each fiber type, four content were employed (1, 5, 10, and 20 kg/m³). The experimental data have clearly demonstrated that the addition of all three types of fiber brought significant improvements in the abrasion resistance, with the content being a major controlling factor.

The present study contributes the existing knowledge of SFRC by incorporating locally available manufactured sand (crushed stone powder) instead of natural sand. It is well known that commercially available natural sand, which is most commonly used as fine aggregate in the production of concrete, is relatively expensive due to excessive cost of transportation from natural sources. Also large-scale depletion of these sources creates environmental problems. Economy and sustainability objectives are better served if locally available durable aggregates can be used. Thus, this paper describes the results of an experimental investigation on the effects of manufactured sand and steel fiber on the compression, elastic modulus, bending and abrasion properties of SFRC mixtures. The effect of the amount of crushed stone powder was evaluated using 0%, 50% and 100% natural sand replacement and the effect of the steel fiber content was evaluated using 0% and 0.32% in volume basis. Overall, the recommendations of this paper will be beneficial to engineers, designers and local industries engaged in manufacturing and using cost-effective and greener SFRC mixtures for construction applications.

2. MATERIALS AND METHODS

2.1 Materials and composite manufacturing

The raw materials used to produce the mixtures were: Portland cement CP III 40-RS, with 40 MPa of compressive strength at 28 days and a density of 2.98 g/cm³; natural and manufactured (crushed stone powder) sand; coarse aggregate with a maximum diameter of 25 mm and a density of 2.78 g/cm³; a plasticizer, FK 300 Muraplast (manufactured by MC Buchemie) with 35.3% solid content and a superplasticizer, MaxiFluid 900 (manufactured by Matchen) with 17.9% solid content and density 1.10 g/cm³.

The physical characteristics of the fine aggregates are shown in Table 1 and the particle size distribution of the natural and manufactured sand and coarse aggregate can be seen in Figure 1. The steel fiber (dramix RC 80/60) used in this study is produced by Bekaert with a length of 60 mm, 0.75 mm diameter, tensile strength of 1225 MPa and density of 7.8 g/cm³.

Table 1: Physical characteristics of fine aggregates.

	NATURAL SAND	CRUSHED STONE SAND
Maximum diameter (mm)	2.36	6.30
Density (g/cm³)	2.68	2.80
Fineness modulus	2.22	2.55
Microfines content < 75 µm (%)	1.10	15.00

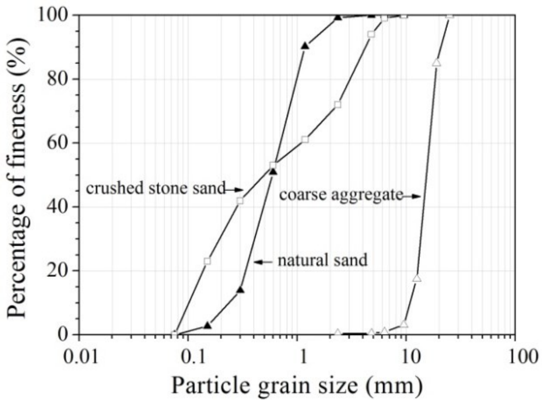

Figure 1: Particle size distribution of natural and manufactured (crushed stone powder) sand and coarse aggregate.

Three concrete SFRC mixtures containing 0.32% steel fiber and 0, 50 and 100% crushed stone powder as sand, replacement in mass basis and one mixture containing 0% steel fiber in volume basis were prepared to study the influence of different contents of the stone powder and steel fiber on the mechanical properties of the material. The mixture proportions are given in Table 2.

In all mixtures, the superplasticizer content was dosed such that all mixtures would have similar fresh properties measured by the slump test (between 100-135 mm). A slight adjustment in the superplasticizer content in each mixture was made to achieve consistent rheological properties for better fiber distribution and workability.

Table 2: Materials composition in the mixture.

INGREDIENTS	M01	M02	M03	M04
Crushed stone sand substitution ratio (%)	50.00	0.00	50.00	100.00
Fiber content (%)	0.00	0.32	0.32	0.32
Cement (kg/m³)	373.19	370.62	373.19	375.78
Natural sand (kg/m³)	423.62	841.42	423.62	0.00
Crushed stone sand (kg/m³)	423.62	0.00	423.62	853.13
Coarse aggregate (kg/m³)	997.52	990.67	997.52	1004.46
Water (kg/m³)	186.59	185.31	186.59	187.89
Plasticizer (kg/m³)	2.20	2.20	2.20	2.20
Superplasticizer (kg/m³)	0.00	0.62	0.74	1.48
Fiber (kg/m³)	0.00	25.00	25.00	25.00
Slump (mm)	100.00	100.00	133.00	130.00

To produce the mixtures the coarse aggregate, 50% water and cement were mixed for 3 minutes in a mechanical concrete mixer truck with an 8 m³ capacity. Sand, 50% water and plasticizer were added to form the basic matrix. The mixture was stirred for another 8 minutes to allow adequate flowability and viscosity, both of which are necessary for good workability and uniform fiber distribution. Fibers were dispersed carefully into the concrete mixture and it was stirred for 5 minutes more. In the last step, superplasticizer was added.

A slump test was used to quantify the deformability of the fresh mix according to NBR NM 67 [16]. Then, the specimens were cast in steel molds and demolded 24 hours after casting, always covered with damp cloths. The specimens were cured for 28 days in a curing chamber with 100% relative humidity and ambient temperature (21 ± 1ºC).

2.2 Testing procedure

All mechanical tests were performed in a testing machine with a capacity of 100 kN. Three specimens with the dimensions of 500 x 150 x 150 mm (length x width x thickness) were tested under four point bending loads at a span of 450 mm, as seen in Figure 2a. Tests were carried out according to NBR 12142 [17].

(a) (b)

Figure 2: Bending test set-up.

A compressive strength and elastic modulus test was performed according to NBR 5739 [18] and NBR 8522 [19], respectively. Tests were carried out on three cylindrical specimens of 100 × 200 mm (diameter x height). The compressive test set-up is shown in Figure 2b.

Three cylindrical samples measuring 100 mm in height and 300 mm diameter were used to evaluate the underwater abrasion resistance for each mixture at 28 days. The abrasion resistances of mixtures were evaluated according to ASTM C 1138 [20], test method for abrasion resistance of concrete (underwater method). In this test, the concrete sample is subjected to an abrasive charge consisting of 70 chrome steel balls circulating in water over the concrete surface. A paddle rotating at 1200 rpm is used to cause the circulation of this abrasive charge. The mass loss and average depth of the abrasion was measured at 12 h intervals for 72 h.

3. RESULTS AND DISCUSSION

3.1 Compression and bending tests

The compressive and bending properties of the specimens were determined experimentally at an age of 28 days. Average results with standard deviation (in parenthesis) are summarized in Table 3. The reported data are the average value from three specimens. The results of the mechanical response tests were validated by statistical testing using analysis of variance - ANOVA (probability ≤ 0.05).

The results presented in Table 3 indicate that the compressive strength was increased when fiber was added in the mixture. For example, the compressive strength of the mixture with fiber (M03) was increased 15.1% when compared with the unreinforced mixture (M01), however, the elastic modulus of the mixture was not significantly modified with the addition of fiber (M03). According to BENTUR and MINDESS [2], for the normal range of steel fiber contents (up to 2%), an increase in compressive strength ranging from nil to about 25% is expected.

Concerning the influence of manufactured sand content (M02, M03 and M04 mixtures), it was observed that it did not have influence on the compressive strength when 50% manufactured sand was added. Already, a significant reduction was noticed when 100% manufactured sand was added. The reduction on the compressive strength observed was approximately 9.4%. However, the elastic modulus of mixtures remained approximately equal.

Table 3: Compressive properties and bending strength of the mixtures (standard deviation in parenthesis).

MIXTURE	ELASTIC MODULUS (GPa)	COMPRESSIVE STRENGTH (MPa)	BENDING STRENGTH (MPa)
M01	23.60 (0.50)	31.60 (1.44)	4.25 (0.04)
M02	25.20 (0.40)	37.10 (1.32)	4.87 (0.05)
M03	24.60 (0.45)	36.36 (1.14)	4.81 (0.05)
M04	24.50 (0.60)	33.60 (1.07)	4.30 (0.04)

As seen in Table 3, the bending strength of the concrete is also slight altered when fiber is added. The bending strength of the M03 mixture increased 13.2%, when compared with the unreinforced mixture (M01), but the strength increment was almost nil (> 2%) when 100% manufactured sand (M04) was added.

This finding is consistent with the work of MUNDRA, *et al* [21], in which indicate that partial replacement greater than 50% natural sand with crushed stone sand, leads to decrease in compressive strength of concrete. According BEIXING, *et al* [22], the compressive and flexural strength of concrete can be increased with use of microfines (particles smaller than 75 µm) in the mixture; however, the effect is reduced when significant quantities of particles smaller than 75 µm exceed 10%.

Although the compressive and bending strength of the mixture with 100% manufactured sand (M04) was reduced, its cost is cheaper than the mixture with 50% manufactured sand (M03), i.e, considering that the cost of the fine aggregate and superplasticizer in M03 and M04 mixtures is equal to \$10.90 and \$7.36 per m^3, respectively, the production cost of the M04 mixture is 32.4% cheaper than the M03 mixture. The prices presented are per m^3 of concrete and the cost of the natural sand (\$17.10/ton), manufactured sand (\$5.24/ton) and superplasticizer (\$2.10/kg) is of December, 2015 (1.0 U.S. dollars was equal to 3.80 Brazilian real). A significant reduction in the cost of concrete with manufactured sand also was reported in the study conducted by ILANGOVAN [23].

3.2 Abrasion tests

Table 4 summarizes the results of the abrasion test at 28 days. The reported results of mass loss and damage depth are average values of two specimens. The damage depth was obtained dividing the volume difference (before and after damage) by the area of specimen. In this test was not measured the abrasion resistance of unreinforced mixture.

Table 4: Mass loss and depth of abrasion of the mixtures (standard deviation in parenthesis).

MIXTURE	MASS LOSS (%)	DEPTH OF DAMAGE (mm)
M02	2.25 (0.02)	2.25 (0.02)
M03	1.91 (0.39)	1.91 (0.39)
M04	1.86 (0.00)	1.86 (0.00)

It can be seen from Table 4 that the mass loss and average depth of damage of concrete mixtures containing 100% manufactured sand (M04) is 17.7% smaller than that of the M02 mixture made with 0% manufactured sand. It indicates that addition of 100% manufactured sand in steel fiber reinforced concrete significantly improved the abrasion properties of composite. As shown in Figure 3, the surface of M03 specimen was more damaged than M04 specimen. In fact, the use of manufactured sand with high content of particles smaller than 75 µm (microfines) as part of the fine aggregate resulted in improved abrasion resistance. The variation in abrasion resistance of the material is related to the volume and abrasion resistance of the paste, as the coarse aggregate sources and fiber content were held constant. According to BEIXING, *et al* [22] the microfines play a further role in enhancing abrasion loss, which is likely related to their hardness and their bonding within the paste. The improvement in abrasion resistance when microfines are used is in agreement with the findings of earlier studies [24, 25].

M03 M04

Figure 3: Surface of the typical specimens after abrasion tests.

4. CONCLUSIONS

In this work, a study of the influence of the crushed stone sand, residue from the production of crushed aggregates, on the mechanical performance of concrete reinforced with steel fibers was presented. It was concluded that crushed stone sand may be an alternative to the natural sand.

The crushed stone sand was found to influence the mechanical behaviour of the steel fiber reinforced concrete. The total substitution of natural sand for sand manufactured from a crushed stone was found to decrease the compressive and bending strength but to increase significantly abrasion resistance. However, the elastic modulus of the mixtures remained approximately equal.

The results presented also indicate that the compressive strength was slightly increased when fiber was added in the mixture, however, the elastic modulus of the mixture was not significantly modified.

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