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High-strength concrete with different fine aggregate

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Abstract

High-strength concrete (HSC) has undergone many developments based on the studies of influence of cement type, type and proportions of mineral admixtures, type of superplasticizer and the mineralogical composition of coarse aggregates. Most studies were carried out using natural sand with rounded and smooth grains. In practice, crushed sands from various sources are frequently used in concrete. In this paper, two aspects of the effect of crushed sands on HSCs are presented. First, the performance of crushed sands in relation to natural sand using a low water/cement (w/c) ratio and fixed coarse aggregate and cement content is analyzed. Results show that concrete with crushed sand requires an increase of superplasticizer to obtain the same slump. It also presents a higher strength than the corresponding natural sand concrete at all test ages, while its elastic modulus is lower at 28 days and is the same after that. Studies on the development of hydration and mortar phase of concrete show that the increase of strength can be attributed to the improvement of paste–fine aggregate transition zone. Second, the influence of the mineralogical source of the crushed sands was studied using three different types of crushed sands (granite, limestone and dolomite) with similar grading. Two mixtures containing 450 and 485 kg/m^3 cement and low w/c ratio are analyzed. Results show the adverse effects of shape and texture on workability of concrete, but the compressive strength of concrete is improved. Granite crushed sand appears as the most advantageous sand for this purpose.

Keywords: Aggregate; Petrography; High-performance concrete; Mechanical properties; Crushed sand

1. Introduction

Crushed sand is produced by crushing a large parent mass of rock. Thus, many aggregate properties depend on the properties of the parent rock (e.g., chemical and mineralogical composition, petrographic classification, specific gravity, hardness, strength, physical and chemical stability, pore structure and color). Some properties such as shape and size of particles and surface texture of crushed sands are not seen in the parent rock, while others properties such as absorption can change due to the crushing. The shape depends on the nature and the degree of stratification of rock deposit, the type of crushing plant used and the size reduction ratio. All these properties have an important influence on the quality of fresh and hardened concrete [1].

Concrete codes and standards specify the fine aggregate requirements necessary to obtain homogeneous, workable and durable concrete of adequate strength. The use of crushed sand is generally limited due to the high cement paste volume needed to obtain an adequate workability of concrete [2–4]. The amount of additional paste content depends on shape, texture, grading and dust content of the crushed sand.

Mechanical and durability properties of concrete containing crushed sand depend on paste composition, paste volume, the physical characteristics of the sand particles and the nature of the paste–aggregate interface. The increase of water demand of concrete mixtures produced by the adverse effects of shape and texture of crushed sand can be mitigated using a high-range water-reducing admixture as reported in a previous paper [5]. Several studies [6–9] on high-strength concrete (HSC) have been developed with the objective of studying the influence of coarse aggregate from different mineralogical sources. However, few studies have been conducted on the influence of different crushed sands [10] and the codes only include brief requirements for fine aggregates [3].

The effect of shape and surface texture of fine aggregates on mechanical properties is often not a factor in conven-

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tional concretes (30–40 MPa), although these properties may cause an increase in the water demand. For these concretes, the hydrated cement paste and the transition zone around the aggregate are relatively weak. Consequently, the water/cement (w/c) ratio controls the mechanical properties of concrete for the same degree of hydration.

Around the world, many aggregate quarries produce crushed sand from different mineralogical sources. In localities near the quarries, this fine aggregate is commonly used in concrete when good-quality natural sand is no longer available.

The main objective of this research is to provide information about the effects of shape and texture of fine aggregate on fresh and hardened properties of HSC. In this paper, two aspects are analyzed: the performance of crushed sands in relation to natural sand, and the influence of the mineralogical source of the crushed sands.

Table 1
Gradation and physical characteristics of fine aggregates

	Cumulative percentage retained			
	Siliceous (NS)	Granite (GS)	Limestone (LS)	Dolomite (DS)
9.5 mm (3/8 in.)	0	0	1	0
4.75 mm (no. 4)	1	0	6	3
2.36 mm (no. 8)	12	28	38	39
1.18 mm (no. 16)	51	56	61	63
600 μm (no. 30)	74	69	75	73
300 μm (no. 50)	96	78	81	78
150 μm (no. 100)	100	84	86	82
Dust content (< 75 μm)	0	10.7	10.6	13.3
Fineness modulus	3.34	3.15	3.48	3.38
Relative density	2.64	2.69	2.68	2.77
Rodded voids (%)	33	32	34	38
Shape	Rounded	Angular	Angular	Elongated
Surface texture	Smooth	Crystalline	Rough	Rough

2. Experimental methods

2.1. Materials

A high-early-strength Portland cement (ASTM Type III; 438 m^2/kg Blaine fineness) was used. Coarse aggregate was crushed granite stone with a maximum size of 16 mm. A sulfonate melamine formaldehyde condensate superplasticizer, without chlorides, was incorporated in the concrete mixtures. In this work, silica fume was not used because it is very effective in enhancing the interfacial transition zone and it could, thus, camouflage the effects of shape and surface texture of the crushed sand.

Four fine aggregates from different mineralogical sources, but of similar fineness modulus, were used. Natural siliceous river sand (NS) having rounded and smooth particles was used as a reference sand. Crushed sands were selected with different petrographic characteristics (granite, limestone and dolomite) but similar grading curves. Table 1 gives the gradation and physical characteristics of the fine aggregates. In all crushed sands, dust content is higher than the limit proposed (7%) by the ASTM C 33 Standard, but lower than that proposed by the BS 882 Standard (16%). The surface texture and particle shape can be observed in Fig. 1 and their classifications according to BS 812 are also reported in Table 1.

2.2. Mixture proportions

Eight concrete mixtures were designed and identified by the mineralogical source of fine aggregate and the cement content. Table 2 shows the mixture proportions and measured slump.

Two concrete mixtures were prepared to study the influence of crushed sand compared with natural sand. These mixtures were designed with a w/c of 0.30, a very large cement content (530 kg/m^3) and similar slump. The effects of shape and texture of fine aggregate were evaluated by comparing the fresh and hardened properties of granite sand concrete (G-530) with the corresponding properties of natural sand concrete (S-530).

To evaluate the influence of mineralogical source of crushed sand, six concrete mixtures were designed using 450 and 485 kg/m^3 cement content and similar w/c ratio. Coarse aggregate content was kept constant in all mixtures.

2.3. Testing

Compressive strength and elastic modulus tests were carried out on 100 × 200 mm cylinders. For splitting tensile strength tests, 150 × 300 mm cylinders were used. To evaluate flexural and compressive strengths of the matrix of concrete, mortar was obtained from fresh concrete by sieving through a 4.75-mm sieve (No. 4) and prisms of 40 × 40 × 160 mm were cast. After 24 h, concrete and mortar specimens were removed from the mold and cured in lime-saturated water until the age of test. After compressive strength testing, fragments of mortar prisms were used to determine the nonevaporable water according to the procedure proposed by Powers [11]. This value was used to estimate the degree of hydration assuming that the w/c needed for full hydration of cement was 0.23 and the sand distribution was uniform. Corrections due to the loss by ignition of limestone and dolomite sand were also made. Subsequently, the gel–space ratio was computed for each mixture and test age.

3. Results and discussion

3.1. Fresh concrete properties

For S-530 and G-530 concretes, a very similar fresh behavior (slump, good finish and visual aspect) was

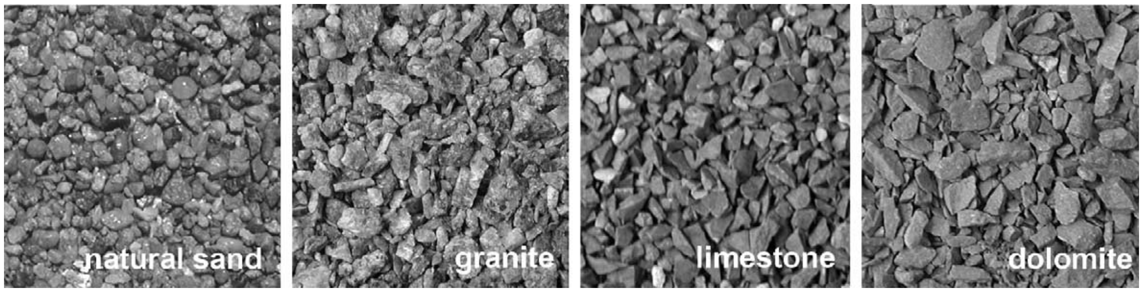

Fig. 1. Photographs of used sands.

observed. In these concretes, the inclusion of superplasticizer permits the reduction of water demand for achieving a high-slump range (180 and 170 mm, respectively). However, a higher dosage of superplasticizer was needed in concrete with granite sand to overcome the adverse effect of shape and texture of grains.

A similar behavior was observed in the other mixtures containing granite and limestone crushed sand despite the change in cement content from 530 to 485 or 450 kg/m^3. However, all mixtures displayed a considerable workability loss after 20 min.

Concretes containing crushed dolomite sand have poor fresh behavior. The D-485 mixture had the lowest slump (80 mm), while the D-450 mixture had poor cohesiveness, causing a nonworkable concrete, and was rejected. Dolomite sand contains a large proportion of elongated particles that increase the void content by 4–6% compared with limestone and granite sand. Consequently, it required an increase of at least 30 kg/m^3 cement and 11 kg/m^3 water to fill the additional voids, in order to maintain the design mixture parameters adopted.

3.2. Hardened concrete properties

3.2.1. Influence of shape and surface texture

Fig. 2 shows the development of compressive strength of natural and crushed sand concrete. It can be observed that G-530 concrete has a higher strength (10% at 1 year) than the corresponding S-530 concrete at all test ages. If both concretes have the same quality of paste (w/c ratio and degree of hydration), and if the coarse aggregate interface remains constant in quality and quantity and there is no chemical interaction between cement and sand particles, then the increase in compressive strength of G-530 concrete could be related to the strong paste–fine aggregate interface and the intrinsic strength of granite particles.

For these concretes, the weak link is at the physical interface. Goble and Cohen [12] have concluded that the sand surface area has a significant influence on the mechanical properties of Portland cement mortar. Assuming that the interface has a constant thickness regardless of aggregate size, the volume of transition zone is 25–40 times larger in the mortar portion of the mixture, and its influence will be reflected in tensile strength. Results of flexural strength tests of the mortar fraction show that the G-530 mixture has higher strength values (11–12 MPa) than the S-530 mixture (9.4–11.4 MPa) at equivalent test ages. The improvement of the paste–fine aggregate transition zone could be attributed to the rough texture of granite sand, which increases the mechanical interlocking with the cement paste [10].

The presence of mica in granite rocks results in unfavorable condition due to the weak cleavage planes that cause the initiation of failure in the coarse aggregate [10]. Nevertheless, the good behavior of granite sand in concrete can be explained by the fact that the rock has been reduced in the crushing process, leaving the remaining particles free from flaws or weak zones.

Fig. 3 shows that G-530 and S-530 concrete have similar evolutions of degree of hydration (α) and both reach the same value at 1 year. As cement and water contents are constant, both concretes have approximately the same mass of hydration products at equivalent test ages as reported in

Table 2
Mixture proportions (kg/m^3)

Mixture	S-530	G-530	G-485	G-450	D-485	L-485	L-450	D-450
Portland cement	530	530	485	450	485	485	450	450
Water	160	160	160	160	169	168	160	175
Sand	660	660	698	727	720	702	736	724
Coarse aggregate	1030	1030	1030	1030	1030	1030	1030	1030
Superplasticizer (% by mass of cement)	0.67	0.89	0.89	0.89	0.89	0.89	0.89	0.89
w/c ratio	0.30	0.30	0.33	0.36	0.35	0.35	0.36	0.39
Slump (mm)	180	170	160	120	80	175	140	n.s.[a]

[a] No slump.

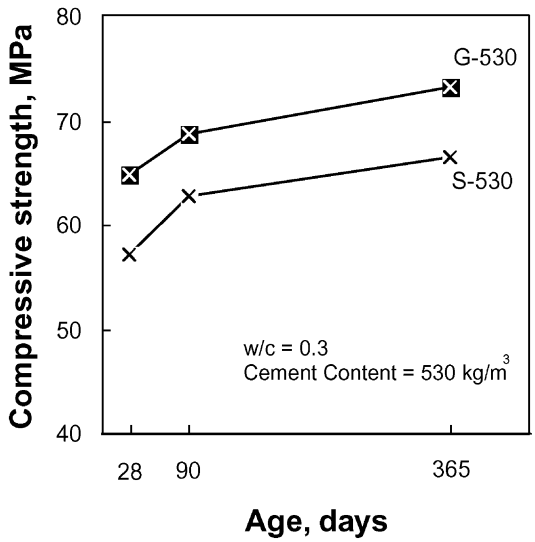

Fig. 2. Development of compressive strength of G-530 and S-530 concretes.

Table 3. Then the values of calculated gel–space ratio are similar, indicating the same quality of cement paste. However, it can be observed in Fig. 4 that G-530 develops a higher compressive strength than the corresponding S-530 for the same gel–space ratio. Consequently, the strength improvement of concrete with granite crushed sand can be assigned mainly to the improvement of the paste–fine aggregate transition zone already stated.

Table 4 reports the results for concrete splitting tensile strength test. G-530 shows a lower strength at 28 days and it has 14% higher strength than S-530 at 1 year. On the other hand, the modulus of elasticity (*E*) of S-530 was always higher than the corresponding G-530, as shown in Fig. 5. This inverse relationship between compressive strength and *E* was reported by Giaccio and Zerbino [13]. They used coarse aggregates (natural and crushed gravel) from the same source and found that the *E* value of concrete (w/c = 0.30 and 460 kg/m^3) remained constant while the compressive strength increased in the concrete containing crushed gravel.

In a previous paper [14], a complete study on the influence of shape, texture and mineralogical composition of sand in concrete was reported. For crushed and natural sand combinations (0%, 25%, 50%, 75% and 100%) with the same grading and without dust, different concretes were made with a w/c of 0.30. Results showed no appreciable differences in compressive strength at later ages (28 and 90 days), with an increasing natural sand percentage. At 90 days, the compressive strength in all mixtures was 62 ± 2 MPa. The authors concluded that the influence of fine aggregate on compressive strength was not significant when the paste volume remains constant and crushed sand is dust-free. For each sand combination, the flexural strength does not show considerable differences, while concretes containing 75% and 100% of crushed granite sand have a lower modulus of elasticity than corresponding concretes with 100% natural sand.

Table 3
Estimated hydrated cement content (kg/m^3)

Mixture	Age (days)		
	28	90	365
S-530	294	312	322
G-530	291	297	324
G-485	287	292	305
L-485	244	268	302
D-485	230	258	296

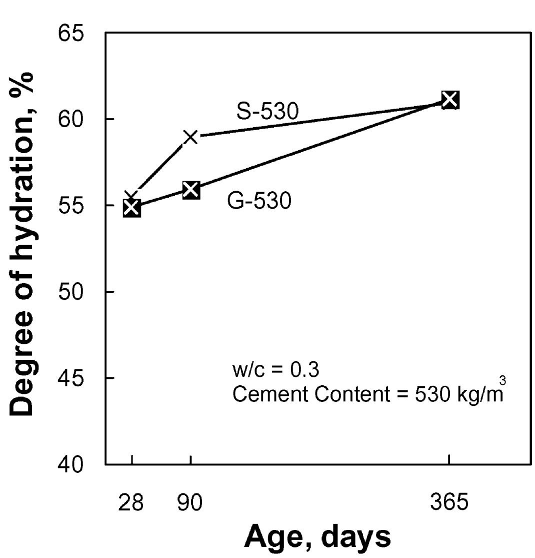

Fig. 3. Evolution of degree of hydration for G-530 and S-530 concretes.

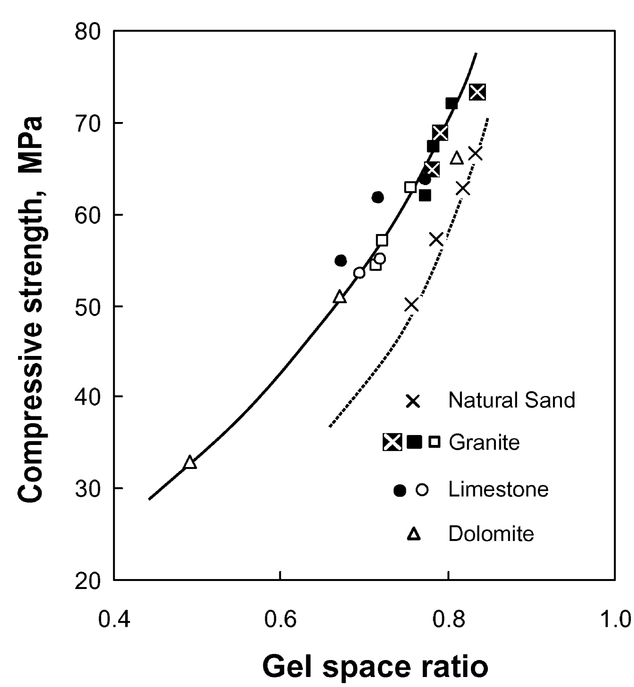

Fig. 4. Gel–space ratio vs. compressive strength of all concretes.

Table 4
Splitting tensile strength (MPa)

Mixture	Age (days)		
	28	90	365
S-530	3.36	3.44	3.59
G-530	3.27	3.45	4.08
G-485	3.84	3.94	4.54
L-485	3.90	4.03	4.09
D-485	3.62	3.81	4.39

3.2.2. *Influence of mineralogical source*

Compressive strength development for concretes containing 450 and 485 kg/m^3 cement and different crushed sands is showed in Fig. 6. Concretes with granite (G-485 and G-450), limestone (L-485 and L-450) and dolomite (D-485) crushed sands attain values between 50 and 65 MPa at 28 days.

The strength of G-485 concrete was the highest. This can be mainly attributed to the high degree of hydration (see Fig. 7) in this mixture at all ages. The higher α value produces a volume of hydrated cement in G-485 similar to that for G-530. Consequently, G-485 compressive strength is similar to G-530 strength, but cement content is 45 kg/m^3 lower. This observation indicates that in G-530, a significant part of cement remains unhydrated due to unavailable space to develop the hydration products because w/c ratio is very low. In addition, the presence of fine particles of stone dust contributes to Portland cement hydration during the early ages. Several studies [15–17] report the beneficial effect in the nucleation of hydration products and the packing of clinker grains produced by stone dust.

On the other hand, compressive strength of L-485 and D-485 concretes was lower than concretes with granite sand (G-485). This behavior could be attributed to particle strength and to the different surface textures and shapes of granite sand particles because the cement content and w/c are similar. At 28 and 90 days, the difference between the hydrated cement content of L-485 and D-485 concretes is also reflected in their strength development.

Fig. 4 also shows that the gel–space ratio for all crushed sand concretes follows a similar relation, but one different from the corresponding relation for natural sand concrete. This behavior confirms the influence of strength, texture and shape of sand particles on the compressive strength of concrete. Consequently, concretes with crushed sand have a higher strength than corresponding concrete with natural sand when the paste has a similar value of gel–space ratio.

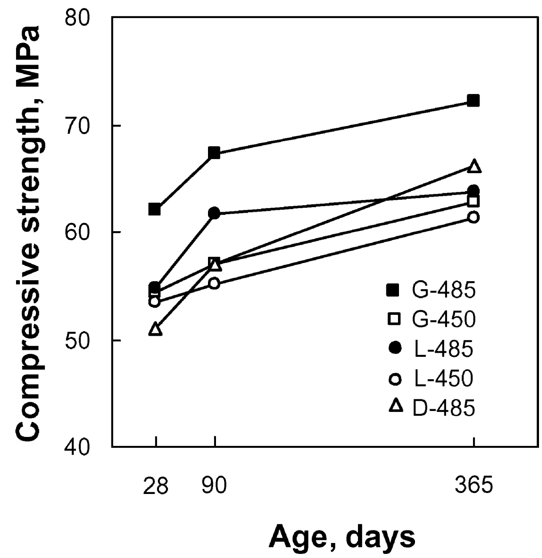

Fig. 6. Development of compressive strength of concrete with crushed sands from different sources.

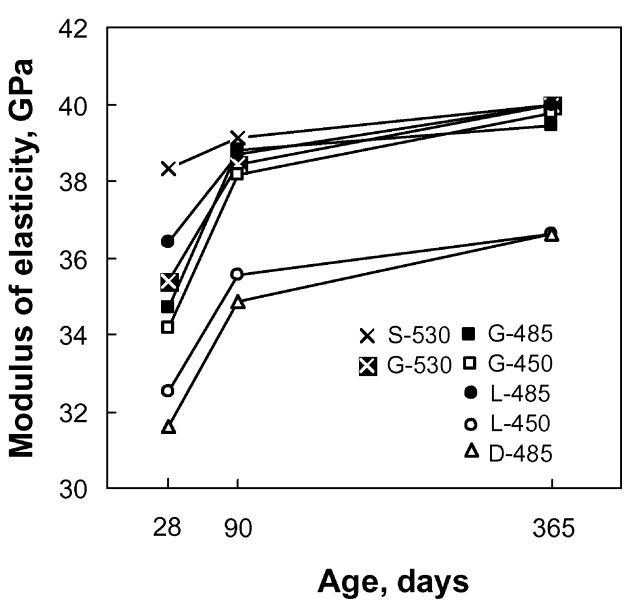

Fig. 5. Development of concrete elastic modulus.

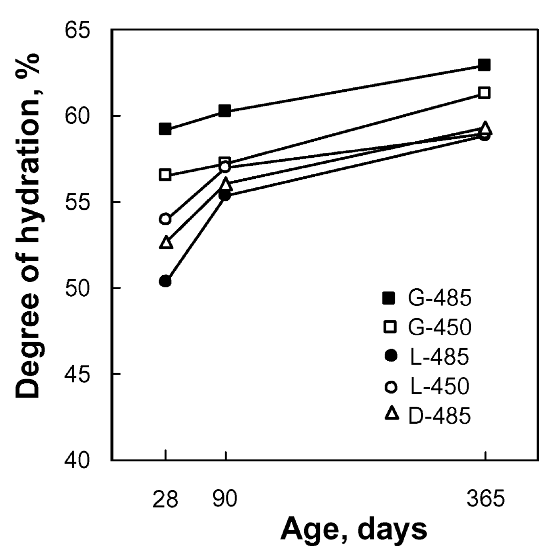

Fig. 7. Evolution of degree of hydration of concrete with crushed sands from different sources.

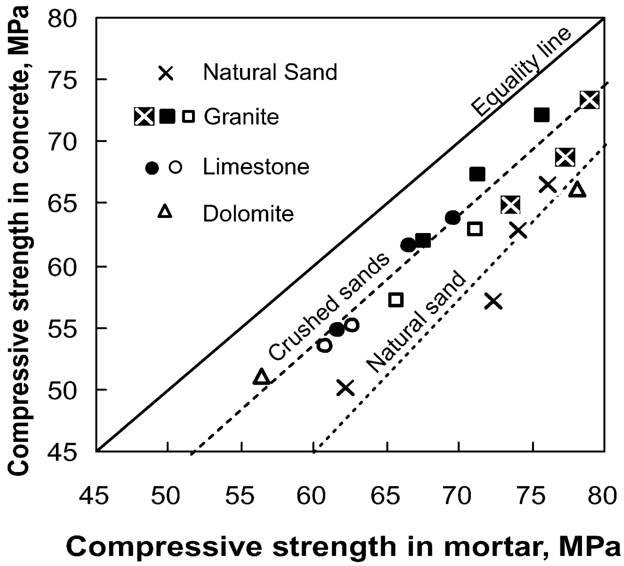

Fig. 8. Relationship between compressive strength of concrete and mortar.

Fig. 8 shows that compressive strength is directly related to mortar phase strength. However, crushed sand concretes have better performance than natural sand concretes because for equal mortar strength, their strength is higher than the corresponding natural sand concrete. This reveals the influence of the fine aggregate source on the interface sand–paste in concrete because coarse aggregate was the same for all mixtures.

It is widely assumed that concrete elastic modulus depends on the relative volume and stiffness of coarse aggregate (stiffness is closely related to aggregate source). Alexander and Milne [18] have observed a similar relationship when the source of both fine and coarse aggregates is the same. The influence of fine aggregate source on elastic modulus of concrete is also shown in Fig. 5. At early ages, the evolution of elastic modulus is closely related to texture and shape of fine aggregate, when the paste/aggregate volume ratio and coarse aggregate source are the same. However, these differences disappear and the elastic modulus tends to a value of around 40 GPa at 1 year, except for L-450 and D-485 concretes. This effect can also be observed in S-530 and G-530 concretes. In addition, granite, limestone and dolomite sand concretes with cement content of 485 kg/m^3 exhibit the same effect, but dolomite shows the lowest elastic modulus at all test ages.

Finally, the results presented above indicate that crushed sand can be used to produce a HSC with similar or better mechanical properties than corresponding concrete made with good natural sand.

4. Conclusions

The conclusions drawn from the current research may be summarized as follows.

(1) HSC having similar or better mechanical strength than concrete with natural sand can be produced using crushed sand as fine aggregate.

(2) The effect of crushed sand on fresh concrete presents some disadvantages compared with natural sand. Crushed sands require a higher dosage of admixture to overcome the adverse shape and texture of particles. For each type of sand and cement content in the mixture, the optimal doses need to be studied.

(3) The shape and texture of crushed sand particles have an important effect on the interlocking of paste and aggregate particles, leading to an improvement of strength of concrete. Granite crushed sand appears as the most advantageous for this purpose in the present study.

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