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CRUSHED LIMESTONE SAND: AN EFFECTIVE ALTERNATIVE TO NATURAL SAND IN CONCRETE

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Due to its scarcity and the detrimental environmental effect of its extraction, leading to governmental restrictions, the good quality natural rounded siliceous sand became less available in Lebanon. This national and international issue affects the construction industry through the cost and the quality of concrete. Currently, this sand, too fine to be used alone as fine aggregate in concrete mixes, is always mixed with an appropriate percentage of crushed limestone sand to meet the standard grading. The objective of the study is to assess the feasibility of total replacement of natural rounded siliceous sand by crushed limestone sand to avoid the dependency of the construction field on the quality and availability of this material in the Lebanese context. The research program consists of proposing various concrete mixes without natural sand and verifying, following a performance-based approach, that their behaviors can be maintained, at different ages of hardened states, compared to those of the reference concrete incorporating natural sand. The resulting comparisons allow identifying the influences on compressive and flexural strengths of natural sand substitution and of the variations of granular size distribution. At this stage of the study, some preliminary conclusions about the applicability of the solution of natural sand total substitution are proposed.

Keywords: Fine aggregates, Rounded siliceous sand, Mix design, Performance-based approach, Hardened properties, Compressive strength, Flexural strength.

1 INTRODUCTION

The availability of good quality natural rounded sand as a construction material is decreasing worldwide at an alarming rate and the environmental impact of its extraction is becoming more and more detrimental. In Lebanon, the extraction of natural rounded sand is now subjected to governmental restrictions, affecting thereby the cost of concrete.

In several countries, an alternative solution consists in partially or totally replacing natural rounded sand by different types of crushed sand in mortar and concrete, limiting in this way the construction extra cost and the negative environmental effects. Many studies show that this replacement can improve the strength of conventional concrete, high-performance concrete, and mortar, due to the higher bond between the rough angular crushed sand particles on one hand, and the higher interlocking between the sharp-edged crushed sand and the cement paste on the other hand (Donza *et al*. 2002, Stefanidou 2016, Yamei *and* Lihua 2017).

Most of the Lebanese natural sand used in concrete results from the fragmentation of friable sandstone. Their grains are siliceous and formed of sub-rounded quartz particles, usually coated with calcite, hematite or clay minerals (Hamad *et al*. 1996). However, this sand is too fine to meet the particle size distribution requirements specified in ASTM C33 (2016) standard. Therefore, it is always combined with an appropriate percentage of crushed limestone sand as an additional fine aggregate resource.

The objective of this paper is to verify that the mechanical properties of concrete mixes made only of crushed limestone sand are maintained compared to those of the control mix containing natural sand. Two different grades of concrete are studied in terms of compressive and flexural strengths.

2 EXPERIMENTAL PROGRAM

2.1 Materials

The chemical and physical properties of fine and coarse aggregates are listed in Tables 1 and 2. The natural sand used in this study is a sandstone siliceous sand with spherical grains, while the crushed sand is limestone sand with angular grains obtained from Lebanese limestone quarries. In addition to the difference in their chemical compositions, the two types of sand differ by their physical properties including the fines percentage, absorption, and specific gravity. Two sizes of coarse aggregates are used, 10 mm and 20 mm, provided from the same parent rock as the crushed sand. Ordinary Portland cement, having a 28 days compressive strength of 48.9 MPa, is used in all concrete mixes.

Table 1. Chemical characteristics of aggregates obtained by Inductively Coupled Plasma test.

Mass Percentage (%)	Natural Sand	Crushed Sand	Medium Aggregate (10 mm)	Coarse Aggregate (20 mm)
SiO_2	87.25	1.22	0.90	0.57
CaO	4.95	54.03	53.18	55.22
Al_2O_3	0.63	0.33	0.26	0.16
Fe_2O_3	1.93	0.26	0.14	0.10
K_2O	0.06	0.10	0.08	0.06
Na_2O	0.11	0.04	0.03	0.04
MgO	0.18	0.64	0.64	0.60
Mn_2O_3	0.018	0.004	0.003	0.003
TiO_2	0.15	0.03	0.02	0.01
SO_3	0.03	0.14	0.12	0.08
P_2O_5	0.04	0.01	0.01	0.01
Cr_2O_3	0.005	0.001	0.001	0.001
Loss on ignition (%)	4.64	43.20	44.60	43.15

Table 2. Physical characteristics of aggregates.

Properties	Natural Sand	Crushed Sand	Medium Aggregate (10 mm)	Coarse Aggregate (20 mm)
Fines < 75 µm (%)	2.3	7.2	0.8	0.3
Clay lumps & friable particles (%)	5.3	0.8	0.2	0.2
Soundness (%)	11	5	9	8
Methylene blue value (g)	1.8	0.9	-	-
Oven-Dry Specific gravity	2.62	2.55	2.66	2.67
Absorption (%)	1.10	2.60	0.60	0.50

The particles size distribution of natural sand, crushed sand, and coarse aggregates are given in Figure 1. The two types of sand, natural rounded sand, and conventional crushed sand show different gradations and they both do not respect the ASTM C33 (2016) gradation limits represented in Figure 1. Thus, the Lebanese construction market combines crushed sand and natural sand in order to fit these standard gradation limits.

The use of three different types of fine aggregates in concrete mixes is evaluated, and their particles size distribution appears in red in Figure 1.

The reference sand mix used in Lebanese concrete industry, “Control Mix Combination”, is characterized by equal mass proportions of the two types of sand, 50% natural sand and 50% crushed sand, to fit the particles size gradations defined by ASTM with a fines percentage of 4.79%.

To study the effects of the total substitution of natural sand by crushed sand and to limit the effects of gradation, an “Equivalent Crushed Sand” is constructed in the laboratory, with a particle size distribution strictly similar to the one of “Control Mix Combination”.

Finally, to study the effect of well-graded crushed sand, the third type of sand, called “Modified Crushed Sand”, is constructed from initial crushed sand by reducing its high fines percentage to 5.05% to fit the ASTM C33 (2016) gradation limits. The specific gradation of this initial crushed sand has been produced by a quarry, specifically for this research study.

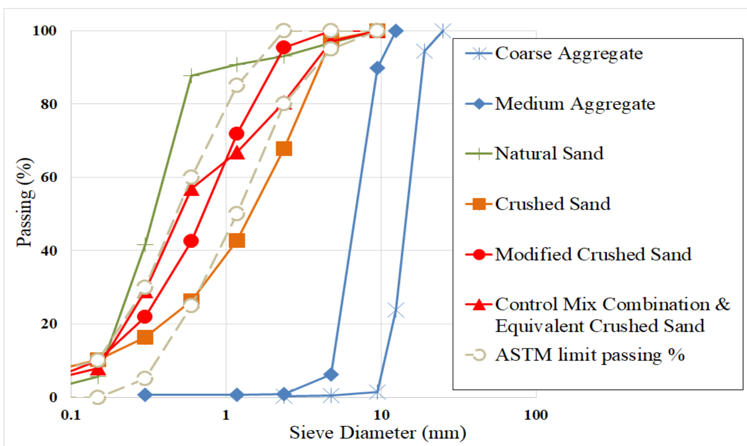

Figure 1. Particles size distribution of aggregates.

2.2 Mix Proportions

To identify the influence of natural sand substitution by crushed sand on concrete mechanical properties, three concrete mixes have been designed, mainly differing by the fine aggregate type and its size distribution:

- The Control Mix “CM” concrete corresponds to a conventional mix used in Lebanon, made of “Control Mix Combination” with equal mass proportions of natural and crushed sand.
- The Equivalent Mix “EM” concrete contains the “Equivalent Crushed Sand” as the only fine aggregate.
- The Modified Mix “MM” concrete incorporates the “Modified Crushed Sand” as the only fine aggregate.

Two concrete grades have been studied, with three types of fine aggregates for each one, as shown in Table 3:

- 30 MPa: a commonly used concrete grade in Lebanon, characterized by a water/cement ratio of 0.5. The proportions of medium and coarse aggregates were fixed to 427 kg/m^3 and 566 kg/m^3 respectively, for the three types of concrete. The fine aggregate combination of the Control Mix "CM" was replaced by an equivalent volume of constructed crushed sand for the other two types of mixes.
- 40 MPa: for environmental purposes and to emphasize the effects of aggregates, the amounts of cement and water were decreased, compared with C30 grade. The same principle of aggregates proportions was applied similarly to Grade C30 but with higher values, and the water/cement ratio is reduced to 0.4 to reach such a compressive strength grade.

To have a representative industrial workable concrete, the slump value was fixed to 20 cm. Thus, for each mix, the dosage of high-range water-reducing admixture was adapted to reach this slump value.

Table 3. Mix design proportions (kg/m^3) for the six concrete mixes.

Mix Type	Cement (C)	Effective Water (W)	W/C	Admixture	Natural Sand	Crushed Sand	Equivalent Crushed Sand	Modified Crushed Sand	Medium Aggregate (10 mm)	Coarse Aggregate (20 mm)
CM-30	350	175	0.5	2.47	406	406	0	0	427	566
EM-30	350	175	0.5	1.01	0	0	802	0	427	566
MM-30	350	175	0.5	0	0	0	0	802	427	566
CM-40	300	120	0.4	10.38	448	448	0	0	471	624
EM-40	300	120	0.4	6.90	0	0	884	0	471	624
MM-40	300	120	0.4	5.99	0	0	0	884	471	624

2.3 Experimental Methods

For each concrete mix, compressive and flexural strengths were assessed. The compressive test has been performed on 15x30 cm cylinders at three different ages: three, seven, and 28 days, according to ASTM C39 (2017) procedure, by applying a compressive axial load at 0.25±0.05 MPa/second. The cylinders were previously cast by rodding three layers of concrete in 15x30 cm molds, in accordance with ASTM C192 (2016). Flexural strength was assessed at 28 days from third-point loading test led on a 10x10x50 cm prism, following ASTM C78 (2016) procedure with a loading rate of 0.0667 kN/second. The prisms were prepared by rodding two layers of concrete in molds, with accordance to ASTM C192 (2016). For both tests, the specimens were de-molded after 24h and cured in water tanks at 23±2 ºC until the age of testing.

3 RESULTS AND DISCUSSION

The average value and the standard deviation of the compressive strength at each age and the flexural strength at 28 days, were calculated from tests conducted on three specimens for each concrete mix and for both concrete grades. These values are tabulated in Table 4.

Table 4. Compressive and flexural strengths values for the three mixes of each grade at different ages.

		Compressive Strength (MPa)						Flexural Strength (MPa)	
		3 Days		7 Days		28 Days		28 Days	
Grade	Mix	Average Value	Standard Deviation	Average Value	Standard Deviation	Average Value	Standard Deviation	Average Value	Standard Deviation
C30 (30 MPa)	CM-30	17.8	0.52	24.7	1.11	35.1	0.34	5.05	0.17
	EM-30	17.5	0.30	24.6	0.39	35.8	1.05	5.44	0.68
	MM-30	17.5	0.87	24.2	1.74	33.5	0.86	5.59	0.88
C40 (40 MPa)	CM-40	27.4	0.02	39.1	1.41	47.8	0.22	5.96	0.39
	EM-40	28.4	1.29	39.2	2.04	49.5	1.07	5.71	0.41
	MM-40	26.7	0.22	39.0	1.73	46.1	0.10	6.35	0.17

Figure 2 presents the evolutions of the compressive strengths of the three concrete mixes for each concrete grade. For Grade C30, the compressive strengths of the three concrete mixes are similar at three and seven days, considering the standard deviation. At 28 days, the values are also relatively close. However, the MM presents slightly lower values (< 7% lower) compared to the other two mixes, although the size distribution of modified crushed sand is the one that fits better the ASTM limits. Overall, for this concrete grade, the compressive strength values and the gain of strength kinetics seem not strongly affected by the natural sand substitution. For Grade C40, the compressive strengths are also equivalent whatever the concrete age. Their kinetics of hydration are thus not affected by the type of fine aggregates. A little difference (3% - 7%) is observed at three and 28 days, with the highest values for the EM. As for Grade C30, the lowest value is obtained for MM at three and 28 days. The well-graded crushed sand does not improve the compressive strength.

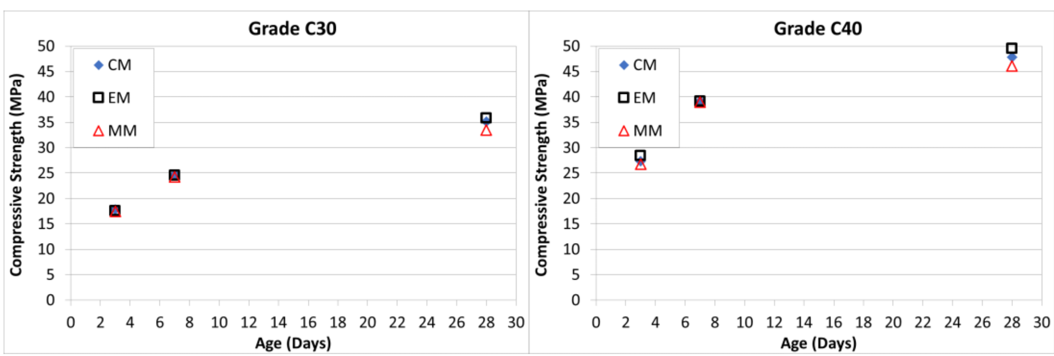

Figure 2. Compressive strength results for CM, EM, and MM concretes for Grade C30 and Grade C40.

The flexural strength values of the three mixes for both grades, presented in Table 4, are quite similar. However, for the two grades, the MM mix values are slightly higher than the values of the other two mixes (10% higher values compared to CM). This comparison shows that flexural strength can be maintained by totally replacing the natural sand by crushed sand in concrete and can be even improved with the well-graded crushed sand.

For the same slump and water to cement ratio, the compressive and flexural strengths are not significantly influenced by the type of fine aggregates, differing by their particle shape, physical properties, mineralogy, and particle size distribution. This comparison confirms that the total substitution of natural sand by crushed sand, respecting the ASTM C33 (2016) grading requirements, is a relevant solution.

4 CONCLUSION

To avoid the dependency of the construction field on the natural sand quality and availability in the Lebanese market and to reduce the negative environmental effects of its extraction, this research studied the influence of the total replacement of natural siliceous sand by crushed limestone sand on the compressive and flexural strengths. Two concrete grades were studied and, for each one, three mixes have been designed having the same slump and water to cement ratio and mainly differing by their type of fine aggregates and the amount of superplasticizer. The control mix is made of equal mass proportions of natural sand and crushed sand. The Equivalent Mix only contains crushed sand with the same particles size distribution as the combination of fine aggregates in the control mix. The Modified Mix is made of crushed sand with a well-graded size distribution.

Although natural sand and crushed sand are distinguished by their mineralogy, particle shape, physical properties, and particle size distribution, the compressive and flexural strengths of grades C30 and C40 concrete, are not affected by the total substitution of natural sand by limestone crushed sand. Consequently, this crushed sand, respecting the ASTM C33 (2016) grading requirements, can be considered as an effective alternative to natural rounded sand in concrete.

However, in order to have a global conclusion covering the concrete performance at different ages, this study will be extended to evaluate the fresh state characteristics, additional mechanical properties and durability properties of concrete.

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