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High strength concrete containing natural pozzolan and silica fume

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Abstract

Various combinations of a local natural pozzolan and silica fume were used to produce workable high to very high strength mortars and concretes with a compressive strength in the range of 69–110 MPa. The mixtures were tested for workability, density, compressive strength, splitting tensile strength, and modulus of elasticity. The results of this study suggest that certain natural pozzolan–silica fume combinations can improve the compressive and splitting tensile strengths, workability, and elastic modulus of concretes, more than natural pozzolan and silica fume alone. Furthermore, the use of silica fume at 15% of the weight of cement was able to produce relatively the highest strength increase in the presence of about 15% pozzolan than without pozzolan. This study recommends the use of natural pozzolan in combination with silica fume in the production of high strength concrete, and for providing technical and economical advantages in specific local uses in the concrete industry.

Keywords: Compressive strength; High strength concrete; Natural pozzolan; Silica fume; Portland cement mortar

1. Introduction

High strength concrete has been widely used in civil engineering in recent years. This is because most of the rheological, mechanical, and durability properties of these materials are better than those of conventional concretes. High strength is made possible by reducing porosity, inhomogeneity and microcracks in concrete and the transition zone. This can be achieved by using superplasticizers and supplementary cementing materials such as fly ash, silica fume, granulated blast furnace slag, and natural pozzolan. Fortunately, most of these materials are industrial by-products and help in reducing the amount of cement required to make concrete less costly, more environmental friendly, and less energy intensive [1–8].

A definition of high strength concrete in quantitative term which is acceptable to everyone is not possible. In North American practice, high strength concrete is usually considered to be a concrete with a 28-day compressive strength of at least 42 MPa. In a recent CEB-FIP state-of-the-art report on high strength concrete, it is defined as concrete having a minimum 28-day compressive strength of 60 MPa. In many developed countries, the concrete producers arbitrarily defined the high strength concrete as the concrete having the 28-day cube strength of above 45 MPa when the normal weight aggregate is used. Clearly then, the definition of high strength concrete is relative; it depends upon both the period of time in question, and the location [1–3,8,9].

The use of high strength concrete results in many advantages, such as reduction in beam and column sizes and increase in the building height with many stories. In pre-stressed concrete construction, a greater span–depth ratio for beams may be achieved with the use of high strength concrete. In marine structures, the low permeability characteristics of high strength concrete reduce the risk of corrosion of steel reinforcement and improve the durability of concrete structures. In addition, high strength concrete can perform much better in extreme and adverse climatic conditions, and can reduce maintenance and repair costs [1,7,9].

The progress in the manufacturing of increasingly high strength concrete and their successful use in high rise structures over the last 20 years is well known. Most recently, concretes having the strength of around 138 MPa are being used in columns of high rise buildings and in a few European bridges. Concretes having the strength up to 800 MPa have been produced in France for special purposes [1,2,4,7].

The superior concrete properties obtained in systems in which silica fume is added in combination with

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superplasticizers is well documented [10–13]. The main objective of this study is to produce high strength concrete using local natural pozzolan and silica fume. More specifically to determine a suitable combination of natural pozzolan and silica fume that would improve the properties of the high strength concrete more than when these materials would be used separately.

2. Experimental investigation

An experimental program was designed to produce a high strength concrete with reduced cement content by adding several combinations of a local natural pozzolan and silica fume. The materials used and the experimental procedures are described in the following sections.

2.1. Materials

Locally available ordinary portland cement (ASTM Type I) and pozzolanic portland cement complying with the Jordanian specification JSS 219 were used. The natural pozzolan was a blend of certain volcanic tuffs from Tal Rimah region of northeastern Jordan and is the same material used in the production of pozzolanic portland cement. The silica fume was in powder form with an average of 93% silicon dioxide. The chemical composition and some physical characteristics of these materials are given in Table 1. The superplasticizer used was a naphthalene formaldehyde sulfonated superplasticizer with 41% solid content and a specific gravity of 1.21. The superplasticizer was incorporated in all mixes and the content was adjusted slightly for some mixes to maintain the same degree of workability. The coarse- and medium-size aggregates were crushed limestone with maximum size of 10 and 5 mm, respectively. Natural silica sand with a fineness modulus of 2.66 was used for making mortar and concrete mixes.

2.2. Mix proportions

The objective was to produce high to very high strength and workable structural concretes using local natural pozzolan and silica fume. Accordingly, trial mortar mixes using different mix proportions and several combinations of natural pozzolan and silica fume were initially performed. Two high strength mortar mixes were optimized and used in the current study. One mix contained 15% silica fume and different proportions of natural pozzolan (0%, 5%, 10%, 15%, 20%, and 25%) by weight of cement. The other mix contained 15% natural pozzolan and different proportions of silica fume (0%, 5%, 10%, 15%, 20%, and 25%) by weight of cement. The details of these mixes are given in Tables 2 and 3, respectively. The superplasticizer was incorporated in all mixes and the content was adjusted slightly for each mix to provide efficient dispersion of the cementitious particles and to maintain similar consistency. It is expected that the results and conclusions obtained here on mortars will be transferred to concretes.

All the optimized concrete mixes were prepared with superplasticizers at a dosage of approximately 1.5 l per 100 kg of the total cementitious materials. The concretes made were of similar workability and water to cementitious (including cement, natural pozzolan and silica fume) materials ratio. They consisted of approximately 400 kg/m^3 of pozzolanic cement containing 15% natural pozzolan, as a partial cement replacement, with addition of 20, 40, 60, and 80 kg/m^3 of silica fume, as an additive, (5%, 10%, 15%, and 20%) by weight of cement. It should be noted that despite the deviation in the way silica fume is used, this is still counted as a part of the cement when calculating the water to binder ratio. Two reference concretes of the same workability (without silica fume) were prepared. The first reference mix had the same cement content (400 kg/m^3) and similar workability as the silica fume concrete. Its water to cementitious

Table 1
Characteristics of cements, natural pozzolan, and silica fume

Oxide (%)	Natural pozzolan	Silica fume	Type I cement	Pozzolanic cement
SiO_2	40.8	93	20.9	22.3
Al_2O_3	12.8	0.4	5.6	6.0
Fe_2O_3	10.5	1.2	3.1	4.0
CaO	11.8	0.2	62.7	55.8
MgO	9.10	1.2	2.2	4.8
Na_2O	2.30	0.1	0.2	0.4
K_2O	1.10	1.1	0.8	0.8
SO_3	0.10	0.3	2.9	2.7
Loss on ignition (%)	9.30	0.75	1.30	2.48
Specific gravity	2.68	2.10	3.15	3.12
Specific surface (m^2/kg)	600	20 000	300	434

Table 2
Compressive strength of mortars containing 15% silica fume, and 0%, 5%, 10%, 15%, 20%, and 25% natural pozzolan by weight of cement

Mix no.	Mix proportions (by weight of cement)		Compressive strength (MPa)		
	Constituent	Proportion	3 days	7 days	28 days
1	Cement	1.00	60	71.5	87
	Silica sand	0.60			
	Silica fume	0.15			
	Pozzolan	0.00			
	Water	0.35			
	Superplasticizer	0.03			
2	Cement	1.00	57.5	71	89.5
	Silica sand	0.60			
	Silica fume	0.15			
	Pozzolan	0.05			
	Water	0.35			
	Superplasticizer	0.03			
3	Cement	1.00	58	73.5	87
	Silica sand	0.60			
	Silica fume	0.15			
	Pozzolan	0.10			
	Water	0.35			
	Superplasticizer	0.03			
4	Cement	1.00	65.5	75	110
	Silica sand	0.60			
	Silica fume	0.15			
	Pozzolan	0.15			
	Water	0.35			
	Superplasticizer	0.03			
5	Cement	1.00	63.5	74.5	94
	Silica sand	0.60			
	Silica fume	0.15			
	Pozzolan	0.20			
	Water	0.35			
	Superplasticizer	0.03			
6	Cement	1.00	58.5	74	91
	Silica sand	0.60			
	Silica fume	0.15			
	Pozzolan	0.25			
	Water	0.35			
	Superplasticizer	0.03			

materials ratio was 0.40, which is higher than the silica fume concrete, thus reflecting the water reducing effects of the silica fume when added in combination with a superplasticizer. The second reference mix was designed to have the same water to cementitious materials ratio and similar workability as the silica fume concretes. This was achieved by increasing the cement content to levels of 400–443 kg/m^3. The compositions of the concretes and the designation of the mixes are given in Table 4.

2.3. Mixing and casting

The mortar mixes were prepared by a modified ASTM C 305 procedure [14] using a Hobart type laboratory mixer and extended mixing time, to break as much as possible the natural pozzolan and silica fume clumps that tend to occur in the dry material, and to obtain a fluid mix. The mortar mixes were poured and compacted in 50 mm cubes in accordance with a modified ASTM C 109 procedure [14].

The concrete mixes were prepared using a tilting drum mixer of 0.15 m^3 capacity. The interior of the drum was initially washed with water to prevent absorption. The coarse and medium aggregate fractions were mixed first, followed by addition of the cement, part of the sand, and water containing required amount of superplasticizer. The final mixing stage involved the addition of natural pozzolan and silica fume, and the

Table 3
Compressive strength of mortars containing 15% natural pozzolan and 0%, 5%, 10%, 15%, 20%, and 25% silica fume by weight of cement

Mix no.	Mix proportions (by weight of cement)		Compressive strength (MPa)		
	Constituent	Proportion	3 days	7 days	28 days
7	Cement	1.00	50	58	69
	Silica sand	0.60			
	Silica fume	0.00			
	Pozzolan	0.15			
	Water	0.35			
	Superplasticizer	0.02			
8	Cement	1.00	45.5	65.5	81
	Silica sand	0.60			
	Silica fume	0.05			
	Pozzolan	0.15			
	Water	0.35			
	Superplasticizer	0.02			
9	Cement	1.00	50.5	66.5	84.5
	Silica sand	0.60			
	Silica fume	0.10			
	Pozzolan	0.15			
	Water	0.35			
	Superplasticizer	0.02			
10	Cement	1.00	65.5	75	110
	Silica sand	0.60			
	Silica fume	0.15			
	Pozzolan	0.15			
	Water	0.35			
	Superplasticizer	0.03			
11	Cement	1.00	56.5	75	95
	Silica sand	0.60			
	Silica fume	0.20			
	Pozzolan	0.15			
	Water	0.35			
	Superplasticizer	0.04			
12	Cement	1.00	55.5	73.5	88.5
	Silica sand	0.60			
	Silica fume	0.25			
	Pozzolan	0.15			
	Water	0.35			
	Superplasticizer	0.04			

remaining sand. One-fourth of the superplasticizer was always retained to be added during the last 3 min of the mixing period.

The molds were oiled and placed on the vibration table at a low speed while the concrete was poured. After each mold was properly filled, the vibration speed was increased to ensure good compaction.

2.4. Curing and testing

After casting, the specimens were covered with wet burlap and stored in the laboratory at 23°C and 65% relative humidity for 24 h and then demolded and placed under water. Each specimen was labeled as to the date of casting, mix used and serial number. The specimens were then taken out of water a day before testing and dried in air. A 2000 kN capacity uniaxial compressive testing machine was used to test the specimens. The specimens were loaded at a rate of 150 kN/min. Each specimen took about 1–2 min to fail which approximately satisfies the requirements of ASTM C39 standards [15].

The compressive and splitting tensile strengths were determined after 7, 14, 28, and 56 days of water curing. The strength results included in Table 6 are the average of three specimens. The modulus of elasticity was determined from 100×200 mm cylinders after 56 days of water curing. The results included in Table 6 are the average of two specimens.

Table 4
Concrete mix quantities (kg/m^3)[a]

Mix designation	W/(C+SF+NP)	CA (10 mm)	CA (5 mm)	S	C	NP	SF	SP (L)	W
[340–15–0]	0.4	972.0	108.0	720.0	340	60	–	7	160
[383–15–0]	0.35	951.5	105.7	704.8	383	60	–	8	158
[340–15–5]	0.35	975.8	108.4	722.8	340	60	20	8	147
[340–15–10]	0.35	952.9	105.9	705.8	340	60	40	8	154
[340–15–15]	0.35	929.9	103.3	688.8	340	60	60	8	161
[340–15–20]	0.35	907.2	100.8	672.0	340	60	80	7	168

[a] CA: Coarse aggregate, S: Sand, C: Cement, NP: Natural pozzolan, SF: Silica fume, SP: Superplasticizer, W: Water [340–15–0] refers to [cement content (kg/m^3)–pozzolan content (%)–silica fume (%)].

3. Results and discussion

3.1. Properties of mortar

Results of an ongoing research program and previous studies [13,16–21] have suggested that the optimum performance of concretes containing supplementary cementing materials such as natural pozzolans and silica fume would be about 15% admixture level by weight of cement. In this investigation, an attempt was made to establish whether a suitable combination of a local natural pozzolan and silica fume would improve the strength of concrete more than these materials would separately. Laboratory strength tests were performed on mortars made with 15% pozzolan and 5%, 10%, 15%, 20%, and 25% silica fume, by weight of cement. Similar tests were also performed on mortars made with 15% silica fume and 5%, 10%, 15%, 20%, and 25% pozzolan. In addition to these ternary systems, binary blends, such as portland cement and natural pozzolan, as well as portland cement and silica fume, were investigated for comparison. The results of these tests are presented in Tables 2 and 3 and shown in Figs. 1 and 2.

It is observed that the addition of 15% pozzolan to the mix containing 15% silica fume resulted in an increase in 28-day compressive strength of about 26% relative to the strength of the control mix containing 15% silica fume only. Further addition of pozzolan, beyond 15%, resulted in a significant decrease in the 28-day strength of the same mix by about 17%. Similar observations can be made for the mix containing 15% pozzolan and up to 25% silica fume, where the addition of 15% silica fume resulted in an average increase in the 28-day compressive strength of 59% relative to the strength of the control mix containing 15% pozzolan only. Further addition of silica fume, beyond 15%, resulted in a significant decrease in the 28-day strength of the same mix by about 19%. It is interesting to see that among all the mortar mixes made the one containing 15% pozzolan and 15% silica fume achieved the highest strength, (about 110 MPa).

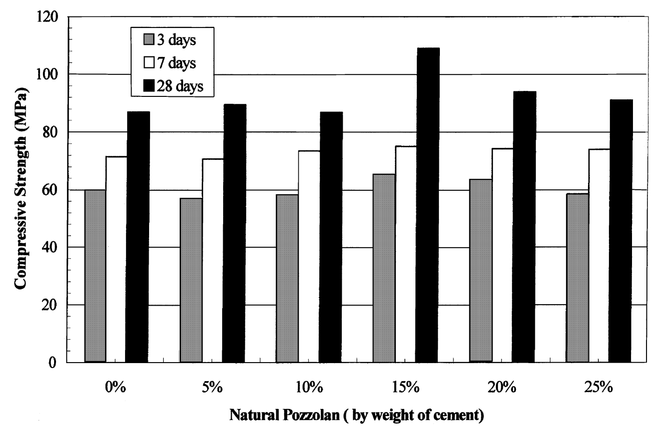

Fig. 1. Comparison of compressive strengths of mortars prepared with 15% pozzolan, and 0%, 5%, 10%, 15%, 20%, and 25% silica fume.

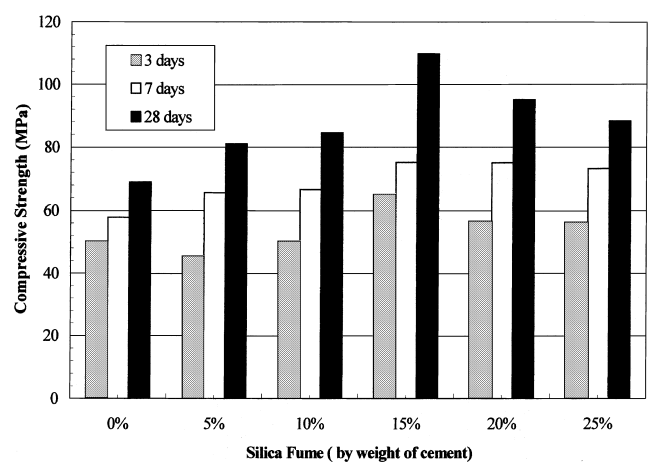

Fig. 2. Comparison of compressive strengths of mortars prepared with 15% silica fume, and 0%, 5%, 10%, 15%, 20%, and 25% pozzolan.

The increase in the strength of mortar and concretes due to the addition of pozzolan and silica fume can be attributed to the improved aggregate–matrix bond associated with the formation of a less porous transition zone and a better interlock between the paste and the aggregate [5,6]. The aggregate–matrix bond improvement induced by such pozzolanic materials is probably the result of a combined filler and pozzolanic effect. The filler effect leads to reduction in porosity of the transition zone and provides a dense microstructure and thus increases the strength of the system. The pozzolanic effect helps in the formation of bonds between the densely packed particles in the transition zone through the pozzolanic reaction with the calcium hydroxide liberated during the hydration of portland cement to form extra binding calcium silicate hydrates which lead to further increase in strength [5,11,13,22].

On the other hand, the observed decrease in the strength of mortar and concretes due to the addition of pozzolan and silica fume can be explained by the fact that larger increase (more than 15% each) in pozzolan and silica fume contents in concretes lead to a surplus of the small-sized fraction, which begins to move apart portland cement grains, causing unpacking of the system and thus leading to a considerable decrease in the strength of the system [6,16]. Therefore, the best packing of the mortars made was achieved at an optimum content of pozzolan and silica fume each of about 15% by weight of cement. The larger increase in strength of systems in which silica fume was varying compared to those in which pozzolan was varying is due to the higher fineness of silica fume (20 000 m^2/kg) compared to 600 m^2/kg for pozzolan as seen from Table 1.

3.2. Properties of fresh concrete

The concrete mixes were tested in the fresh state for the workability and density. The standard tests described in ASTM C 143, and C 138 [15] were carried out and the results are summarized in Table 5. According to these results, most of the concretes made had a high slump value and were workable. No wide variations in the slump values for the mixes containing increased amounts of silica fume were observed. Only the mix with 15% pozzolan and 5% silica fume was relatively stiff. The dosage level of the superplasticizer was slightly adjusted for some mixes to maintain similar workability. The concretes made did not show tendencies to segregate or bleed much, because of the high total cementitious contents including natural pozzolan and silica fume and low water to cementitious ratios. The fresh density of most of the concretes made was in the vicinity of 2300 kg/m^3 which is slightly lighter (about 4%) than normal weight concrete. The results also suggest that the mix containing 15% natural pozzolan and 15% silica fume (by weight of cement) was of optimal workability.

Table 5
Mix designation and properties of fresh concrete

Mix designation	Water/cementitious ratio	Density (kg/m^3)	Slump (mm)
[340–15–0]	0.40	2.39	50
[383–15–0]	0.35	2.31	25
[340–15–5]	0.35	2.27	5
[340–15–10]	0.35	2.23	40
[340–15–15]	0.35	2.25	65
[340–15–20]	0.35	2.26	40

3.3. Properties of hardened concrete

Many properties of concretes can be estimated from the results of better controlled and standard tests on the mortar, such results still should be verified on concrete and more realistic values should be established. With such a consideration, a typical structural concrete mix containing 15% pozzolan and varying amounts of silica fume 0%, 5%, 10%, 15%, and 20% by weight of cement was designed. The ingredients of that mix are presented in Table 4. The total cementitious content used in producing these high to very high strength concretes varied between 400 and 480 kg/m^3 which is in agreement with the cement contents used for producing normal to high strength concretes.

Compressive strength: Table 6 shows that all the concretes made in this study are high strength, as even the seven day compressive strength varied between 57 and 72 MPa. The 28-day strength varied between 64 and about 85 MPa, and the 56-day strength varied between 68 and 90 MPa. The effect of the silica fume content on the strength of concretes is shown in Fig. 3. For mixes with the same water to cementitious materials ratio of 0.35, the strength of the silica fume concretes is higher than the strength of the second reference mix designated as [383–15–0], and the difference increased with the silica fume content. As expected, the strength of the first reference mix designated as [340–15–0] which had a higher w/c, was lesser than all the other mixes at all ages, thus reflecting the water reducing effect of the silica fume when it was added in combination with the superplasticizer.

It was also observed that the relative increase in the strength of concrete became smaller at higher contents of silica fume, that is, beyond 15–20%, as shown in Fig. 3. This is in agreement with the strength results of mortar mixes as shown previously, where reductions were observed beyond 15% contents of pozzolan and silica fume. This leads to the conclusion that the mix containing 15% natural pozzolan and 15% silica fume, might be considered as an optimum mix for producing high to very high strength concrete at a lower cost.

The increase in strength in systems of concretes containing natural pozzolan and silica fume can be explained in a way similar to the strength increase in mortar mixes. Furthermore, these pozzolanic materials play an important role in improving the aggregate–paste bond through the densification of the transition zone

Table 6
Properties of hardened concrete[a]

Mix designation	Compressive strength (MPa)				Splitting tensile strength (MPa)				Elastic modulus (GPa)	f_{sp}/f_c
	7 days	14 days	28 days	56 days	7 days	14 days	28 days	56 days	56 days	
[340–15–0]	57	59	64	68	3.80	4.45	5.05	4.25	38.5	7.9
[383–15–0]	63	66	72.5	77	4.70	5.40	4.10	4.25	47.2	5.6
[340–15–5]	67	74.5	78	86	4.25	5.20	5.15	4.80	43.8	6.6
[340–15–10]	68.5	75.5	78.5	86	4.25	4.80	5.85	3.25	42.3	7.4
[340–15–15]	69.5	77	82	89.5	4.85	5.70	5.40	5.25	38.6	6.6
[340–15–20]	72.5	79.5	85	90.5	5.10	5.75	5.75	4.40	36.2	6.8

[a] f_{sp}: Splitting tensile strength at 28 days, f_c: Compressive strength at 28 days.

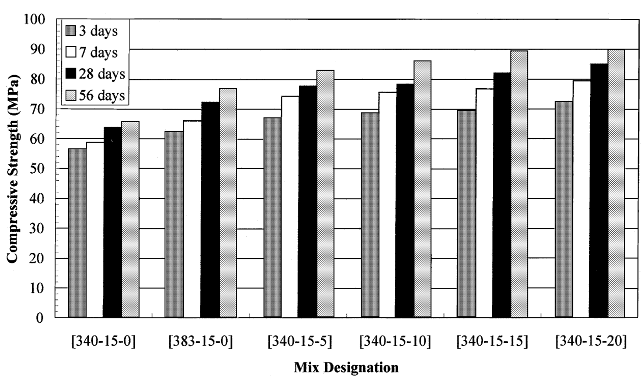

Fig. 3. Comparison of compressive strengths of concretes prepared with 15% pozzolan, and 0%, 5%, 10%, 15%, and 20% silica fume.

and formation of more calcium silicate hydrates [5,13,17].

Modulus of elasticity: The modulus of elasticity is related to the compressive strength of concrete. However, due to the presence of non-linear relationship between them [3,7], the increase in the modulus of elasticity is not proportional to the increase in compressive strength as noted in Table 6. The modulus values presented in Table 6 indicate that the rate of increase in the modulus is lower than the rate of increase in the compressive strength. The average modulus of elasticity for the optimized concretes was about 40 GPa.

Splitting tensile strength: Unlike compressive strength, the tensile strength of high strength concrete with varying amounts of natural pozzolan and silica fume showed inconsistency in the results as noted in Table 6. The average value of the 28-day tensile strength for the concretes made was about 5.20 MPa, which corresponds to 6.8% of the compressive strength for the same concretes. Table 6 shows that the average ratio between the tensile strength (f_{sp}) to cube compressive strength (f_c) of concrete at 28 days was lower than the range (of about 9–10%) for medium strength concrete reported previously [3,9,17]. This indicates that the higher the compressive strength of concrete the lower the ratio, which is consistent with data published by other investigators [9,13,17]. The ratio of the splitting tensile strength and the cube compressive strength for the two highest strength concretes obtained in this study is [6.6% and 6.8%], respectively.

4. Conclusions

Based on the results of this study, it can be concluded that certain natural pozzolan–silica fume combinations can improve the strength of mortars more than natural pozzolan or silica fume alone. Considerably, a higher 28-day compressive strength of about 110 MPa was achieved at 15% admixing level by weight of cement. The increase in strength can be attributed to the improved aggregate-matrix bond resulting from the formation of a less porous transition zone in the silica fume concrete.

The natural pozzolan and silica fume combinations can be used to produce high to very high strength concretes in the range of 69–85 MPa 28-day compressive strength, with medium workability, using total cementitious contents between 400 and 460 kg/m^3. These concretes also exhibited a 28-day splitting tensile strength of the order of 6.5% of their compressive strength and showed relatively high values of modulus of elasticity.

Therefore, high to very high strength mortars and concretes with 15% natural pozzolan and 15% silica fume by weight of cement can be produced and marketed to provide technical and economical advantages in specific local uses.

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