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Effect of silica fume on the mechanical properties of low quality coarse aggregate concrete

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Abstract

This paper reports results of a study conducted to evaluate the effect of silica fume on the compressive strength and split tensile strength and modulus of elasticity of low quality coarse aggregate concrete. Concrete specimens were prepared with four types of low quality aggregates, namely calcareous, dolomitic and quartzitic limestone and steel slag. Results indicate that the type of coarse aggregate influenced the compressive strength and split tensile strength and modulus of elasticity of both plain and silica fume cement concretes. Both the compressive and split tensile strengths of steel-slag aggregate concrete were more than those of limestone aggregate concretes. Incorporation of silica fume enhanced the compressive strength and split tensile strength of all concretes, especially that of the low quality limestone aggregates.

1. Introduction

In recent years, high-strength concrete (HSC) has gained broad acceptance among engineers and contractors. Many new high-rise reinforced concrete buildings have employed concrete with a compressive strength of more than 100 MPa. With the increasing use of HSC considerable research work has been carried out on its mechanical properties.

In conventional concrete (compressive strength < 40 MPa), the properties of coarse aggregates seldom become strength-limiting as the weakest components in this type of concrete mixtures are the quality of hardened cement paste and the transition zone between the cement paste and the coarse aggregates, rather than the coarse aggregates themselves [1–5]. However, the quality of coarse aggregate is an important factor that affects the behavior of HSC and high-performance concrete.

The importance of the mineralogical characteristics of coarse aggregate on the properties of concrete has been pointed out by Baalbaki et al. [6] and Giaccio et al. [7]. The effect of the coarse aggregates on the elastic properties of HPC was studied by Aitcin [8] and Aitcin and Mehta [9]. They observed significant differences in the elastic modulus and hysteresis loop in the case of HPCs prepared with different coarse aggregates, but with similar water to cement ratio. Aitcin et al. [10] investigated the effect of three different coarse aggregates in superplasticized concrete mixtures with identical materials and properties (w/c: 0.24). They found that for calcareous limestone aggregate (85% calcite), dolomitic limestone aggregate (80% dolomite), and quartzitic-gravel aggregate containing schist, the 91-day compressive strengths were 93, 103, and 83 MPa, respectively. Moreover, they concluded that the aggregate-cement paste bond was stronger in the limestone aggregate concrete than in the gravel aggregate concrete due to the interfacial reaction effect. Zhang and Gjorv [11] investigated the effect of four coarse aggregate types, available in North California, on the compressive strength and elastic behavior of a very high-strength concrete mixture. Based on their study, some significant differences in the elastic moduli and hysteresis loop were noted. A formula was derived by Chang and Su [12] from the theory of granular mechanics to estimate the compressive strength of a coarse aggregate particle to be used in HSC. This study [12] showed that there is good

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correlation between the compressive strength of aggregates and some of the engineering properties of concrete.

Setunge et al. [13] evaluated the ultimate strength of confined very high-strength concrete under triaxial loading. Several mixes were used with strengths ranging from normal to very high, including different parameters in the mixes, such as silica fume, and the type of crushed coarse aggregate. A two parameter empirical expression for the failure envelope was derived for normal and high-strength concretes both with and without silica fume. Also, a simple lower bound expression for the ultimate strength of concrete under confinement was developed for any grade of concrete.

During the last decade, considerable attention has been given to the use of silica fume as a partial replacement of cement to produce high-strength concrete. Silica fume cement concrete was found to be extremely strong, impermeable, and very durable against freezing–thawing damage and salt water attack and was also highly abrasion resistant. Khatri and Sirivivatnanon [14] indicated that the addition of silica fume to Portland cement concrete marginally decreased the workability of concrete but significantly improved its mechanical properties. The compressive strength improved at all ages and the strain due to creep was lowered. However, the early age drying shrinkage of concrete was observed to increase with the addition of silica fume and the long-term drying shrinkage of silica fume cement concrete was lower than that of plain cement concrete.

In summary, the review of literature presented earlier indicates that the production of a HSC may be hampered if the aggregates are weak even though low water–cement ratio and high cement content are used. Weak and marginal aggregates are widespread in many parts of the world and there is a concern as to the production of HSC in those regions. Incorporation of silica fume is one of the methods of enhancing the strength of concrete, particularly when the aggregates are of low quality. Such a measure is of importance in areas where high-quality aggregates are not available.

This study was conducted to evaluate the mechanical properties of concrete prepared with four types of low quality coarse aggregates, namely calcareous, dolomitic, and quartzitic limestone and steel slag. In order to evaluate the influence of silica fume cement in enhancing the strength of concrete prepared with the aforesaid low quality aggregates specimens were prepared with silica fume partially replacing 10% and 15% of the cement.

2. Experimental program

2.1. Materials

Type I cement complying to ASTM C 150 requirements was used in the preparation of concrete specimens. A high-quality commercial grade silica fume was used for preparing the silica fume cement concrete specimens. The chemical composition of cement and silica fume is given in Table 1. The concrete specimens were prepared with 0%, 10% and 15% silica fume, utilized as a proportion of the total cementitious materials content.

Table 1
Chemical composition of portland cement and silica fume

Constituent (wt%)	Type I cement	Silica fume
SiO_2	19.92	92.50
Al_2O_3	6.54	0.72
Fe_2O_3	2.09	0.96
CaO	64.70	0.48
MgO	1.84	1.78
SO_3	2.61	–
K_2O	0.56	0.84
Na_2O	0.28	0.50
L.O.I.	0.73	1.55
C_3S	55.90	–
C_2S	19.00	–
C_3A	7.50	–
C_4AF	9.80	–

The fine aggregate was dune sand with a bulk specific gravity of 2.54 g/cm^3 and water absorption of 0.65%.

The following four types of coarse aggregates were utilized in the preparation of concrete specimens:

(1) dolomitic limestone,
(2) calcareous limestone,
(3) quartzitic limestone,
(4) steel slag.

The physical properties of the selected coarse aggregates and their grading are shown in Table 2.

2.2. Mix proportions

The concrete specimens were prepared with effective water to cementitious materials ratio of 0.35 and a coarse aggregate to fine aggregate ratio of 1.63. A total cementitious materials content of 450 kg/m^3 was maintained invariant in all the concrete mixtures. The concrete mixtures were designed for a constant workability of 50–75 mm slump. Suitable dosages of a naphthalene-based superplasticizer were used in all the concrete mixtures to obtain the desired workability.

2.3. Casting of concrete specimens

Cylindrical concrete specimens, 75 mm in diameter and 150 mm high, were prepared to determine compressive strength and split tensile strength, and static modulus of elasticity. The concrete constituents were mixed in a revolving drum type mixer for approximately three to five minutes to obtain uniform consistency.

Table 2
Properties of the selected coarse aggregates

Property	Calcareous limestone aggregate	Dolomitic limestone aggregate	Quartzitic limestone aggregate	Steel-slag aggregate
Physical properties				
Bulk specific gravity	2.39	2.54	2.70	3.51
Water absorption, %	4.95	2.20	1.60	0.85
Clay lumps and friable particles, %	0.78	0.65	0.41	0.12
Loss on abrasion, %	34.4	24.2	19.2	11.60
Chemical composition				
$CaCO_3$	99.0	95.0	75.0	10.0
SiO_2	1.0	5.0	25.0	–
Fe_2O_3	–	–	–	90.0

Additional mixing time of about two minutes was provided for the silica fume cement concrete mixtures to ensure homogeneity. After mixing, the cylindrical moulds were filled in two layers and fully consolidated on a vibrating table to remove any entrapped air. After casting, the specimens were covered with wet burlap and left in the casting room at a temperature of 20 ± 3 °C for a period of 24 h. The specimens were then demoulded and cured in saturated calcium hydroxide solution for 27 days.

2.4. Tests

2.4.1. Modulus of elasticity

The static modulus of elasticity was determined as per the procedure outlined in ASTM C 469. The specimens were tested in uniaxial compression at a constant rate of loading of 3.3 kN/s. The compressive load was applied utilizing a servo-controlled hydraulic testing machine of 3000 kN capacity. The stress–strain characteristics were determined after 3, 7, 14, 28, and 180 days of curing. The modulus of elasticity was measured as a tangent modulus in the elastic range. To measure the deformations a compressometer was fixed on the specimen parallel to the direction of the applied load. Two linear variable displacement transducers were fixed on the compressometer. The load and deformations were recorded using a data acquisition system.

2.4.2. Split tensile strength

The split tensile strength was determined as per the procedures outlined in ASTM C 496 to assess the split tensile strength of concrete specimens prepared with the selected aggregates.

3. Results and discussion

3.1. Compressive strength

The compressive strength of concrete specimens prepared with the selected aggregates was determined up to 180 days of curing. Fig. 1 shows the variation of compressive strength of the concrete specimens prepared with calcareous limestone aggregates. As expected, the compressive strength increased with age in all the concrete specimens. After 180 days of curing, highest compressive strength was noted in the 15% silica fume cement concrete specimens (54 MPa) followed by those prepared with 10% silica fume (52 MPa), and plain cement concrete (49 MPa).

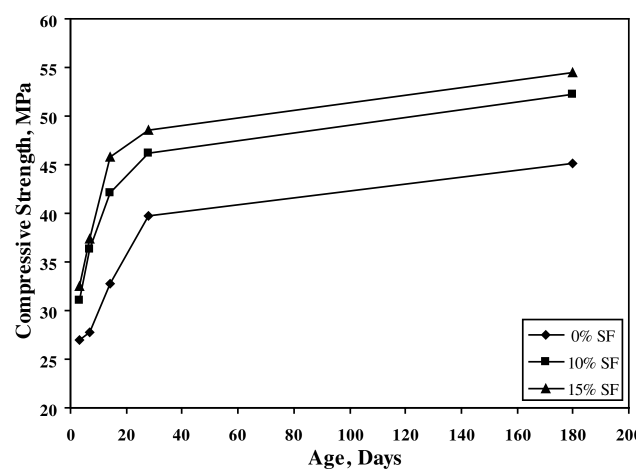

Fig. 1. Compressive strength of concrete prepared with calcareous limestone aggregate.

The higher compressive strength noted in the silica fume cement concrete, compared to plain cement concrete, may be attributed to the reaction of the silica fume with calcium hydroxide liberated during the hydration of cement. This process leads to the formation of secondary calcium silicate hydrate that fills up the pores formed as a result of the hydration of primary calcium silicate hydrate [14]. As sufficient calcium hydroxide is not available, at early ages (usually up to seven days) for pozzolanic reaction to take place, the compressive strength of silica fume cement concrete may be similar to that of the plain cement concrete at early ages. However, the compressive strength of silica fume cement concrete tends to be higher than that of the plain cement concrete

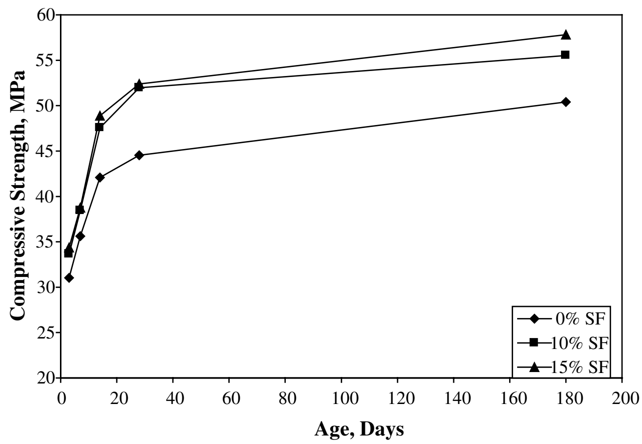

Fig. 2. Compressive strength of concrete prepared with dolomitic limestone aggregate.

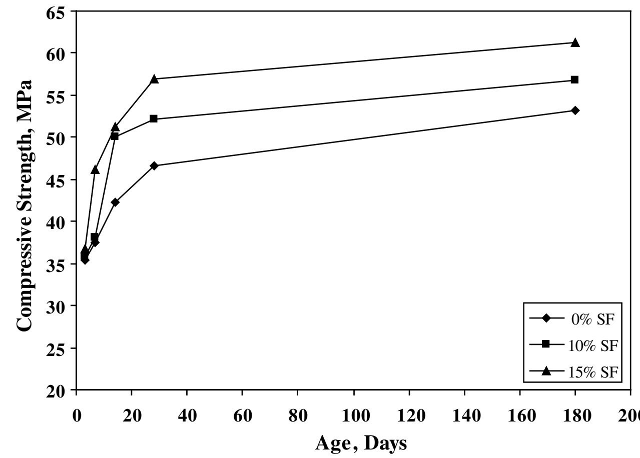

Fig. 4. Compressive strength of concrete prepared with steel-slag aggregate.

after at least seven days of curing, indicating the initiation of pozzolanic reaction. Further, the compressive strength of 15% silica fume cement concrete specimens was more than that of 10% silica fume cement concrete specimens. This is understandable since more than 20% calcium hydroxide, by weight of cement, is liberated as a result of cement hydration. Though 15% silica fume is beneficial from the compressive strength view point, such an addition is not recommended due to the possibility of increased shrinkage in the concrete specimens prepared with this quantity of silica fume, particularly in hot weather conditions. From this perspective, a dosage of 10% or less of silica fume is now commonly adopted.

The compressive strength development of the concrete specimens prepared with the other coarse aggregates is depicted in Figs. 2–4. In these specimens the compressive strength of silica fume cement concrete was also in excess of that of plain cement concrete specimens.

The influence of aggregate quality on the compressive strength of plain and 10% and 15% silica fume cement concretes is summarized in Figs. 5–7. These data indicate that the type of aggregate has a significant effect on the compressive strength of concrete. The highest compressive strength was measured in the concrete specimens prepared with steel-slag aggregates while the lowest compressive strength was noted in the concrete specimens prepared with calcareous limestone aggregates. These data also indicate that in a high-performance concrete, i.e., concrete prepared with low water to cement ratio and high cement content, the compressive strength is dependent on the quality of the coarse aggregates. In such a concrete, the bulk of the compressive load is borne by the aggregates rather than cement paste alone [12]. The failure in such concretes is often through the aggregates. As the calcareous limestone aggregate are known to be weaker than the

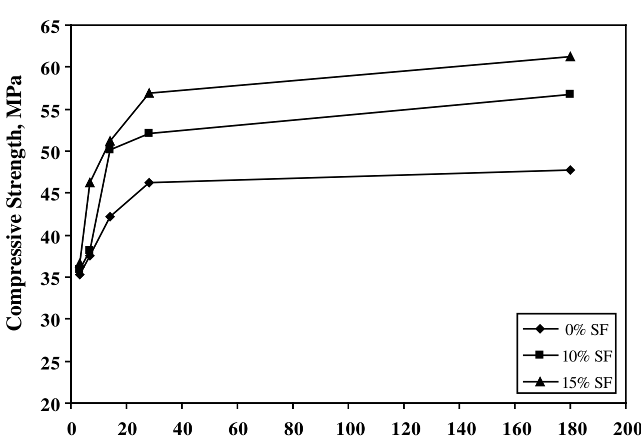

Fig. 3. Compressive strength of concrete prepared with quartzitic limestone aggregate.

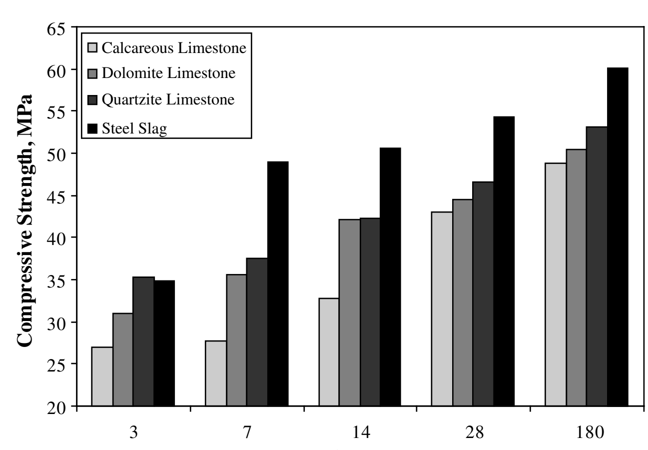

Fig. 5. Effect of aggregate type on the compressive strength of plain cement concrete.

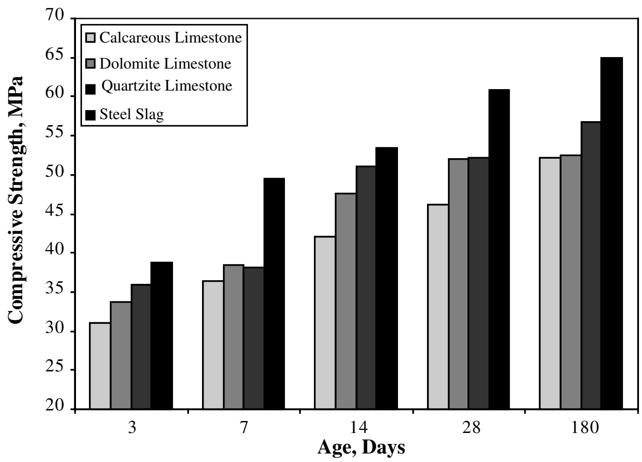

Fig. 6. Effect of aggregate type on the compressive strength of 10% silica fume cement concrete.

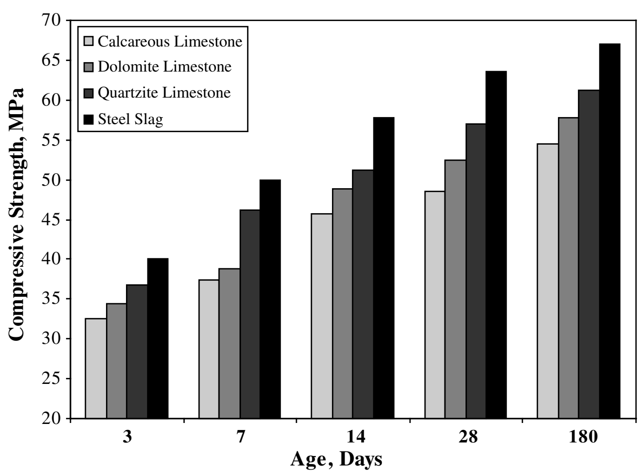

Fig. 7. Effect of aggregate type on the compressive strength of 15% silica fume cement concrete.

dolomitic and quartzitic limestone aggregates the low load-carrying capacity of concrete prepared with calcareous aggregate is understandable. Therefore, the marginally lower compressive strength of calcareous limestone aggregate concrete compared to dolomitic and quartzitic limestone aggregate concretes is understandable. The data on loss on abrasion of these aggregates (see Table 2) provide ample evidence of the weak nature of the calcareous and dolomitic limestone aggregates compared to the quartzitic limestone and steel-slag aggregates. The compressive strength of steel-slag aggregate concrete was 13–31% more than that of the quartzitic limestone aggregate concrete. This indicates that the steel-slag aggregate produce a stronger concrete than the limestone aggregate. The compressive strength of concrete prepared with quartzitic limestone aggregate was 8–35% more than that of concrete prepared with calcareous limestone aggregate.

When concrete is subjected to compressive loads, failure takes place at one or more of the following locations: (i) within the paste matrix, (ii) at the paste–aggregate interface, or (iii) within the aggregate. In a rich concrete mix, such as the one utilized in this study, the possibility of failure within the paste matrix alone is very rare, as this phase is very strong. Therefore, the failure plane has to pass through the paste–aggregate interface or through the aggregate itself. In both modes of failure, the quality of coarse aggregate significantly influences the mode of failure of concrete under compression.

Table 3 shows the improvement in compressive strength of plain cement concrete due to the addition of silica fume. The average improvement in the compressive strength due to the addition of silica fume was in the range of 12–17%. The improvement in compressive strength of concrete prepared with calcareous limestone, dolomitic limestone, quartzitic limestone and steel-slag aggregates, due to 10% silica fume replacement with cement, was 7.3%, 16.7%, 11.9%, and 12.0%, respectively. In addition, the highest improvement was noted in 15% silica fume cement concrete specimens prepared with quartzitic limestone aggregate followed by those prepared with dolomitic limestone and steel-slag aggregates, while the improvement in the compressive strength of calcareous limestone aggregate concrete specimens was the lowest. Moreover, the average rate of strength development, as shown in Figs. 1–4, was higher at early ages, where the ratio of 7–28 days strength, ranged from 0.74 to 0.80, compared to 0.73–0.82 reported by Berke et al. [15]. According to Carrasquillo et al. [16], the ratio of 7–28 days strength is between 0.60 and 0.65 in the case of normal strength concrete. Also, the ratio of 28–180 days strength was in the range of 0.88–0.93 compared to 0.85–0.95 reported by Berke et al. [15]. This observation is in good agreement with that reported by Carette and Malhotra [17], who investigated long-term strength development of plain and silica fume cement concrete prepared with w/c ratio ranging from 0.25 to 0.40.

3.2. Split tensile strength of concrete

Fig. 8 shows the split tensile strength of the concrete specimens prepared with calcareous limestone aggregate. The split tensile strength increased with age in all the concrete specimens. The highest split tensile strength was noted in the 15% silica fume cement concrete specimens followed by those prepared with 10% silica fume.

The split tensile strength of the concrete specimens prepared with dolomitic limestone aggregate is depicted in Fig. 9. In this group of specimens also, the split tensile strength of the silica fume cement concretes was more than that of plain cement concrete. After 90 days of

Table 3
Improvement in 28 days compressive strength of plain cement concrete due to the addition of silica fume

Quantity of silica fume	Calcareous limestone aggregate concrete		Dolomitic limestone aggregate concrete		Quartzitic limestone aggregate concrete		Steel-slag aggregate concrete	
	f'_c (MPa)	Change (%)	f'_c (MPa)	Change (%)	f'_c (MPa)	Change (%)	f'_c (MPa)	Change (%)
0%	43.09	0.00	44.53	0.00	46.62	0.00	54.33	0.00
10%	46.24	7.31	51.98	16.73	52.15	11.86	60.86	12.02
15%	48.50	12.56	52.39	17.65	56.93	22.12	63.55	16.97

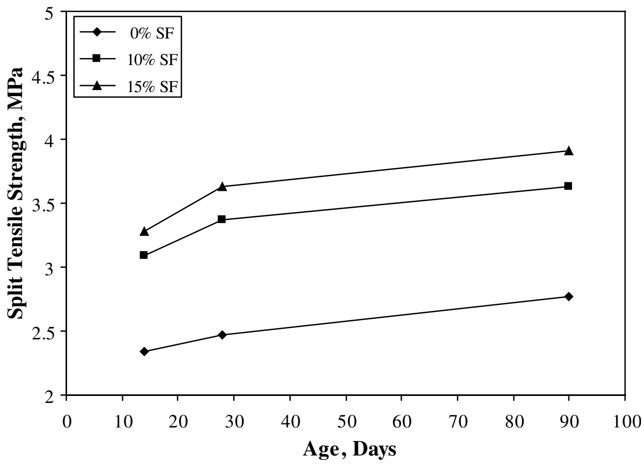

Fig. 8. Split tensile strength of concrete prepared with calcareous limestone aggregate.

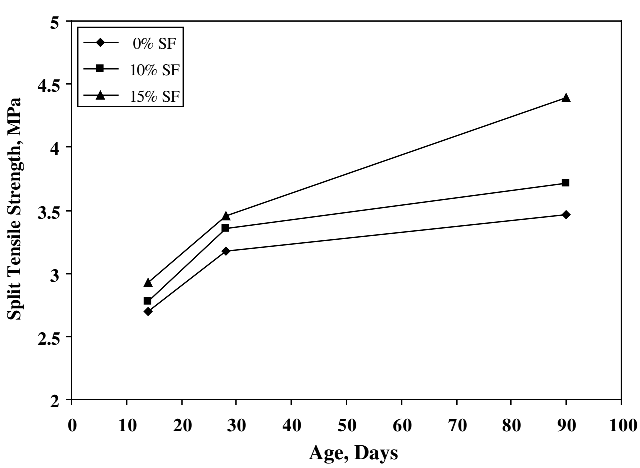

Fig. 9. Split tensile strength of concrete prepared with dolomitic limestone aggregate.

curing, the split tensile strength of 15% silica fume cement concrete was the maximum being 4.39 MPa.

The split tensile strength of the concrete specimens prepared with quartzitic limestone aggregates is shown in Fig. 10. The split tensile strength of the silica fume cement concrete specimens was more than that of plain cement concrete specimens. After 90 days, the split tensile strength of 10% and 15% silica fume cement concrete specimens was nearly the same, being 4.54 and 4.59 MPa, respectively.

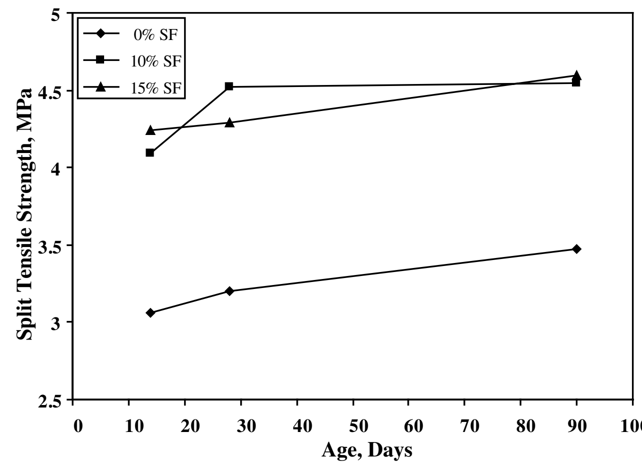

Fig. 10. Split tensile strength of concrete prepared with quartzitic limestone aggregate.

Fig. 11 shows the split tensile strength of steel-slag aggregate cement concretes. The split tensile strength of silica fume cement concretes was more than that of plain cement concrete.

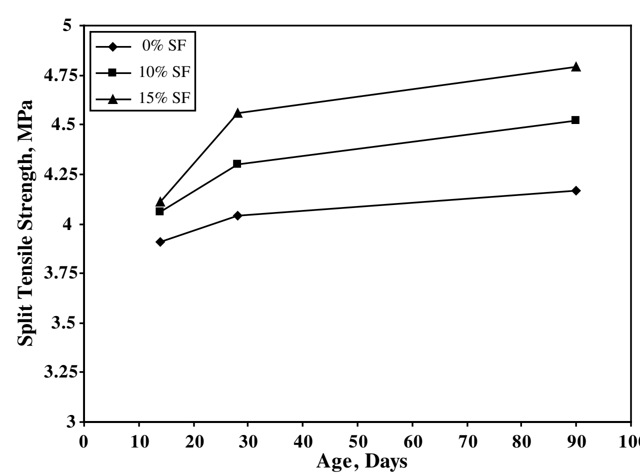

Fig. 11. Split tensile strength of concrete prepared with steel-slag aggregate.

The data in Figs. 8–11 indicate that incorporation of silica fume in plain cement concrete improves its split tensile strength. The increased split tensile strength of the silica fume cement concrete may also be related to the reaction between $Ca(OH)_2$ and silica fume. The higher split tensile strength of silica fume cement concrete compared to plain cement concrete has also been reported by other researchers [16,18,19].

The influence of aggregate quality on the split tensile strength of plain and silica fume cement concretes is depicted in Figs. 12–14. These data indicate that the split tensile strength of steel-slag aggregate concrete was the highest, followed by that of concrete specimens prepared with the quartzitic and dolomitic limestone aggregates. Lowest split tensile strength was noted in the concrete specimens prepared with calcareous limestone aggregate. However, the split tensile strength of concrete specimens prepared with quartzitic and dolomitic limestone aggregates was similar after 28 days of curing. After this age, the split tensile strength of steel-slag aggregate concrete was 164% of that prepared with the calcareous limestone aggregate. Similarly, the split tensile strength of concrete prepared with dolomitic and quartzitic limestone aggregates was 129% and 130% of the concrete prepared with calcareous limestone aggregate.

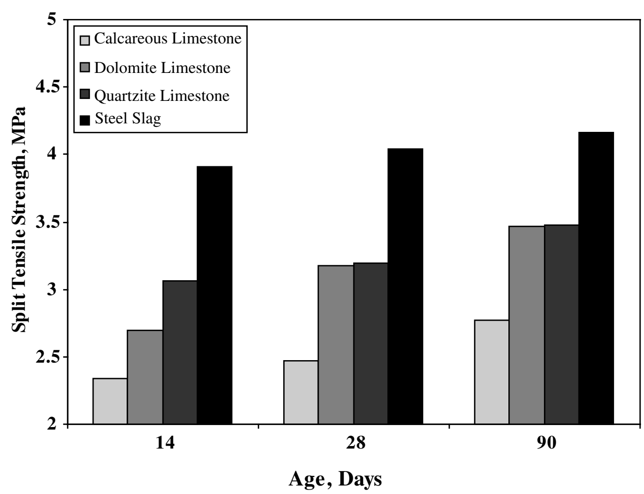

Fig. 12. Effect of aggregate type on split tensile strength of plain cement concrete.

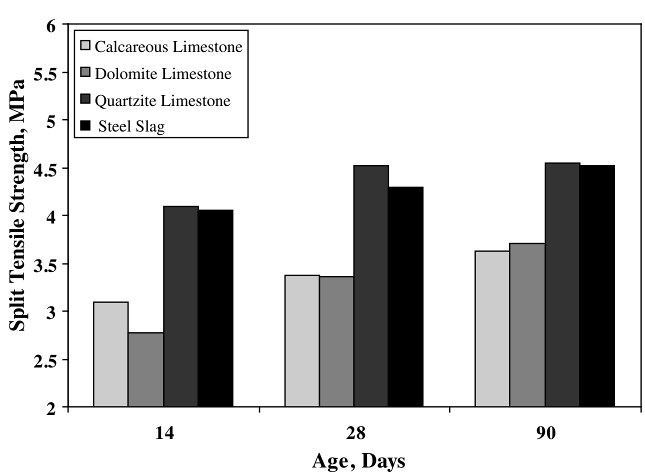

Fig. 13. Effect of aggregate type on split tensile strength of 10% silica fume cement concrete.

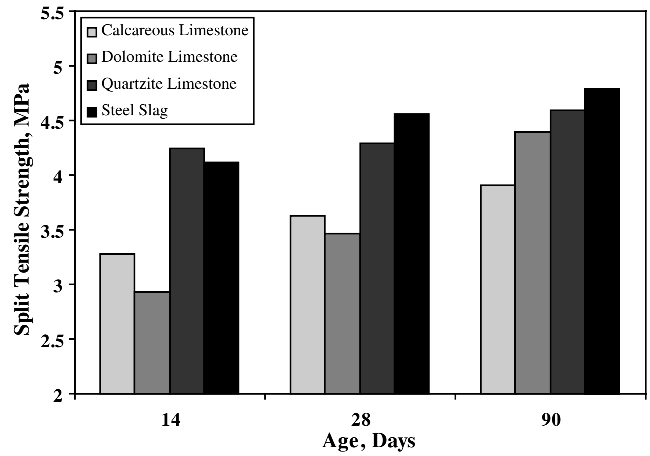

Fig. 14. Effect of aggregate type on split tensile strength of 15% silica fume cement concrete.

The data in Figs. 12–14 also indicate that the use of silica fume, as a partial replacement of cement, has improved the tensile properties of concrete prepared with marginal aggregates, such as crushed calcareous and dolomitic limestone aggregates. Similarly, there is a great improvement in the split tensile strength of concrete prepared with the quartzitic limestone aggregate due to the addition of silica fume. This is evidenced by the fact that the split tensile strength of concrete prepared with quartzitic limestone aggregate was similar to that of steel-slag aggregate concrete from the early age of 14 days. The split tensile strength of concrete prepared with calcareous limestone aggregate and 10% silica fume was similar to that of concrete prepared with dolomitic limestone aggregate.

The increase in the split tensile strength of limestone aggregate concrete has the advantage that the corrosion-resistance of such concretes will be improved. The split tensile strength of concrete is one of the parameters that control the rate of reinforcement corrosion. Therefore, increased split tensile strength of concrete indicates the potential for an increase in the useful-service life of the concrete structures.

3.3. Static modulus of elasticity of concrete

Table 4 shows the modulus of elasticity of concrete specimens prepared with the selected coarse aggregates.

Table 4
Modulus of elasticity of concrete after 28 days of curing

Aggregate	Modulus of elasticity, GPa		
	0% silica fume	10% silica fume	15% silica fume
Calcareous limestone	21.60	26.00	29.30
Dolomitic limestone	24.50	25.90	32.80
Quartzitic limestone	28.80	36.20	38.00
Steel slag	29.60	32.90	40.40

The type of coarse aggregate has a significant effect on the modulus of elasticity of concrete. After 28 days of curing, the modulus of elasticity of plain cement concrete prepared with calcareous, dolomitic, and quartzitic limestone and steel-slag aggregates was 22.0, 25.0, 29.0 and 30.0 GPa, respectively. The modulus of elasticity of steel-slag aggregate concrete was the highest while the modulus of elasticity of calcareous limestone aggregate concrete was the lowest. The lower values of the modulus of elasticity of concrete specimens prepared with calcareous limestone aggregate may be attributed to the soft nature of these aggregates. A more ductile failure results in the concrete specimens prepared with these aggregates. The effect of the type of the coarse aggregate on the modulus of elasticity has also been reported by other researchers [18,20–23].

The data presented in Table 4 further show that the modulus of elasticity of silica fume cement concrete was more than that of plain cement concrete. On average, the increase in the modulus of elasticity was 16% and 32% due to the incorporation of 10% and 15% silica fume, respectively. Moreover, the modulus of elasticity of concrete specimens prepared with steel-slag aggregate was more than that of concrete specimens prepared with limestone aggregate. It can, therefore, be postulated that the type of aggregate influences the modulus of elasticity of concrete.

The measured values of the modulus of elasticity were correlated with the compressive strength. The following equations show the relationship between the measured static modulus of elasticity and the square root of the compressive strength of concretes investigated in this study.

Calcareous limestone aggregate concrete :

$$E_c = 3540(f'_c)^{0.5} \tag{1}$$

Dolomitic limestone aggregate concrete :

$$E_c = 3730(f'_c)^{0.5} \tag{2}$$

Quartzitic limestone aggregate concrete :

$$E_c = 3880(f'_c)^{0.5} \tag{3}$$

Steel-slag aggregate concrete : $E_c = 4120(f'_c)^{0.5}$ (4)

where E_c = modulus of elasticity of concrete, MPa; f'_c = compressive strength of concrete, MPa.

The current ACI 318 M-89 expression for the modulus of elasticity of high-performance concrete, of normal density is:

$$E_c = 4700(f'_c)^{0.5} \tag{5}$$

However, ACI 363-84 recommends the following expression for E_c, which was suggested by Carrasquillo et al. [16].

$$E_c = 3300(f'_c)^{0.5} + 6900 \tag{6}$$

where 21 MPa $\leqslant f'_c \leqslant$ 83 MPa.

Table 5
Modulus of elasticity of concrete according to ACI equations and the data developed in this study

Aggregate	Modulus of elasticity, GPa			
	ACI 318 M-89	ACI 363-84	Developed equations	Actual value
Calcareous limestone	29.98	28.02	22.58	21.60
	30.48	28.35	23.01	24.70
	30.65	28.42	23.08	22.00
Dolomitic limestone	30.85	28.55	24.47	24.50
	31.93	29.34	25.36	25.20
	30.69	27.69	23.50	24.00
Quartzitic limestone	31.48	29.01	26.00	28.80
	33.86	30.66	27.94	27.00
	33.71	30.56	27.82	25.00
Steel slag	35.28	31.67	30.92	29.60
	34.7	31.25	30.41	31.70
	34.55	31.16	30.28	30.80

The values of static modulus of elasticity of concretes tested in this study are compared with ACI 318 M-89 and ACI 363 R-84 expressions (see Table 5). It is clear that both Eqs. (5) and (6) significantly over-estimate the static modulus of elasticity of concretes. The average over-estimation between the actual values and those calculated by ACI 318 M-89 and ACI 363 R-84 equations was 24% and 15%, respectively.

It is clear from Eqs. (1)–(4) that the static modulus of elasticity of the steel-slag aggregate concrete was more than that of limestone aggregate concretes. The modulus of elasticity of high-strength concrete is also high because of the mortar stiffness and improved mortar–aggregate bond. Hooton [24], Luther et al. [25], and Khatri and Sirivivatnanon [14] also reported that the elastic modulus is primarily a function of the compressive strength.

Based on the previous discussion, it can be concluded that the effect of the type of coarse aggregate is more significant on the modulus of elasticity of concrete as compared to its compressive strength. According to Aitcin and Mehta [26] and Baalbaki et al. [27], the nature of coarse aggregate significantly affects the modulus of elasticity of HSC. This influence was attributed to the highly dense paste structure and paste–aggregate bond that cause the concrete to behave like a composite material. Therefore, aggregate characteristics are factors that influence the elastic properties of concrete, particularly those incorporating low water/cement ratio and high cement content. According to Rashid et al. [28], the effect of the type of the coarse aggregate can be singled out as the most significant parameter that affects the modulus of elasticity of concrete.

4. Conclusions

The type of coarse aggregate has a significant effect on the compressive strength of concrete. The compressive strength of steel-slag aggregate concrete was more than that of concrete specimens prepared with the crushed limestone aggregate. The compressive strength of concrete specimens prepared with calcareous limestone aggregate was the lowest. The data developed in this study indicate that in concrete prepared using a low water-cement ratio and a high cement content, the compressive strength is dependent on the quality of aggregate. In such a concrete, the bulk of the compressive load is borne by the aggregates rather than the cement paste and the transition zone. The failure in such concretes is often through the aggregate. Since the calcareous limestone aggregate is known to be weaker than the dolomitic and quartzitic limestone aggregates; the low load-carrying characteristics of concrete prepared with these aggregates is understandable.

The type of coarse aggregate also influenced the split tensile strength of concrete. The split tensile strength of steel-slag aggregate concrete was more than that of limestone aggregate concretes. Lowest split tensile strength was noted in the calcareous limestone aggregate concretes. The addition of silica fume considerably improved the split tensile strength of concrete, especially that prepared with the marginal limestone aggregates. The type of coarse aggregate also influenced the modulus of elasticity of concrete.

Weaker aggregate tend to produce a more ductile concrete than strong aggregate. Further, it was noted that the effect of the type of coarse aggregate is more significant on the modulus of elasticity compared to the compressive strength.

A comparison of data developed in this study on the modulus of elasticity, with that proposed by ACI 318 M-89 and ACI 363 R-84, indicates that the ACI equations significantly over-estimate the static modulus of elasticity.

The incorporation of silica fume improved both the compressive and split tensile strengths of concrete. The beneficial effects of silica fume were more apparent in the concretes prepared with marginal aggregates, such as the limestone aggregates. Thus, supplementary cementing materials, such as silica fume, may be advantageously used in situations where good quality aggregates are not available. The improvement in split tensile strength results in an increase in the useful service life of a structure by decreasing cracking due to reinforcement corrosion.

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