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The role of silica fume in the direct tensile strength of cement-based materials

H. A. Toutanji[1], *L. Liu*[1] *and T. El-Korchi*[2]

(1) University of Alabama in Huntsville, Huntsville, AL 35899 (USA)

(2) Worcester Polytechnic Institute, Worcester, MA 01609 (USA)

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ABSTRACT

The direct tensile strength of silica fume cement paste and mortar were evaluated at various water-cementitious content ratios. Four different water-cementitious content ratios of 0.22, 0.25, 0.28, and 0.31 were used, and three contents of silica fume, 8%, 16%, and 25% by mass of cement. Superplasticizer content was adjusted for each mix to ensure that no segregation would occur.

Results show that partial replacement of cement by 8% of silica fume resulted in an increase in the tensile strength of mortar, but showed no effect on the tensile strength of cement paste. The replacement of cement by a higher dosage of silica fume (16 and 25%) resulted in a decrease in the tensile strength of both cement paste and mortar. However, this reduction was higher in cement paste than in mortar. It was also demonstrated that superplasticizer in combination with silica fume plays a more effective role in mortar than in paste mixes. This can be attributed to a more efficient utilization of superplasticizer in the mortar mixes due to better dispersion of the silica fume particles.

The direct tensile strength was evaluated using a new hydraulic tensile testing technique. The technique measures the intrinsic tensile strength of the cement-based composites by producing a uniform tensile stress along the length of the specimen, and thus minimizes misalignment and stress concentration at gripping. A brief description of this technique is presented in this paper.

RÉSUMÉ

La résistance à la traction directe de la pâte de ciment-fumée de silice et de mortier a été évaluée pour différents rapports eau/ciment. Quatre rapports eau/ciment ont été utilisés, 0,22, 0,25, 0,28, 0,31, avec un dosage de fumée de silice en pourcentage de ciment de 8%, 16%, et 25%. Pour chaque formulation, le dosage du superplastifiant a été ajusté afin d'éviter la ségrégation.

Les résultats ont montré qu'un remplacement partiel de ciment de 8% de fumée de silice engendre une augmentation de la résistance à la traction du mortier, mais aucun effet sur la résistance à la traction de la pâte de ciment. Le remplacement de ciment par un important dosage de fumée de silice (16% et 25%) résulte une diminution de la résistance à traction du mortier ainsi que la pâte du ciment. Cette diminution a été plus importante dans le cas de ciment que dans celui du mortier. Il est aussi démontré que l'utilisation du superplastifiant avec fumée de silice joue un rôle plus efficace dans le mortier que dans la pâte de ciment. Cela peut être attribué à une meilleure dispersion des particules de fumée de silice dans le mortier.

La résistance à la traction directe à été déterminée en utilisant un nouveau système hydraulique « hydraulique tensile testion technique ». Cette technique permet de mesurer la contrainte intrinsèque de traction du composite en exerçant une contrainte de traction uniforme le long de l'éprouvette, qui permet de minimiser la concentration des contraintes à l'ancrage de l'éprouvette. Cette nouvelle technique est décrite dans cet article.

1. INTRODUCTION

Silica fume (SF) is accepted as an important constituent in many concrete mixtures. It is a relatively new member in the family of pozzolans that are currently used in concrete. Silica fume was first used in 1969 in Norway, but only began to be systematically employed in North America and Europe in the early 1980s. Since then, the use of silica fume has been increasing rapidly, either as a partial replacement for cement or as an additive when special properties are desired. Silica fume is known to improve both the mechanical characteristics and durability of concrete [1-5].

One of the benefits of using silica fume in Portland cement-based composites is its performance as a filler in capillary pores and in the cement paste-aggregate interface. Some maintain that the influence of silica fume on concrete properties is not primarily pozzolanic [6], but rather that it fundamentally alters the nature of the transition zone between paste and aggregate [7]. The influence of silica fume on interfacial bond and fracture properties has been shown to be important. It strengthens the bond but it also tends to produce brittle interfacial regions [8-10]. Silica fume concretes are reported as being more brittle than ordinary concretes, although from the viewpoint of structural design, this is not a major problem provided steel proportioning and detailing are properly done [11-13].

The use of silica fume as a partial replacement for cement in combination with superplasticizer improves the compressive strength of mortar and concrete, but has very little effect on the compressive strength of cement paste [14-18]. This is because the presence of silica fume in mortar or concrete produces a more densely compacted matrix at the interfacial zone, which significantly improves the transition zone and, thus, the compressive strength of the system. This accounts for the higher strength of silica fume mortar and concrete in comparison to paste.

Although silica fume is known to improve both the mechanical characteristics and durability of cementitious composites, there is some controversy as to its effect on tensile strength. Research on Portland cement silica fume composites has been conducted focusing on strength aspects of these composites, but very little work has been done on indirect tensile strength and very limited work on direct tensile strength. Hooton [19] has found that the addition of silica fume reduces the splitting tensile strength of concrete at an age of 91 days, and that the tensile strength of concrete with 15% and 20% silica fume exhibited a reduction in strength by 9.7% and 21%, respectively. On the other hand, other researchers have found that the addition of silica fume enhances flexural strength. Khedr and Abou-Zeid [20] found a gain in flexural tensile strength due to silica fume introduction. This gain was up to 20% and 33% with 15% and 20% of silica fume, respectively, at an age of 28 days. Mindess *et al.* [10] studied the influence of silica fume on the fracture properties of paste and mortar. They found that silica fume paste generally exhibited more brittle behavior than ordinary Portland cement paste. They concluded that SF cement paste exhibited lower strength than ordinary Portland cement paste, whereas the reverse was true for the respective mortar. Moreover, they concluded that SF cementitious materials were more early-age sensitive than ordinary Portland cement materials.

The lack of information on the direct tensile strength of SF-cementitious composites is not surprising. Accurate measurement of the direct tensile strength of cementitious composites, in general, is difficult to obtain due to the difficulty in producing a uniform tensile stress distribution in brittle materials such as cement-based materials; thus, the direct tensile strength test is rarely performed. The calculated direct tensile strength depends on the amount of eccentricity; a very small eccentricity in loading, for example 5-10%, could result in a load reduction of 25-50% [21]. In a different study, it was found that eccentricity may reduce the measured tensile strength by as much as 60% [22, 23].

To determine the tensile strength of cement-based materials, indirect tensile tests have been performed, such as the splitting cylinder and flexural tensile tests. Despite the simple procedure involved in carrying out these tests, the stresses obtained do not depict the uniaxial tensile state nor give an accurate value of the true tensile strength of the tested material. Furthermore, the stress and strain distribution of the direct and indirect tension tests are very different [22, 24]. The uniaxial tensile test represents the tensile strength of the materials and does not rely on the elasticity or plasticity in order to calculate the tensile stress. Therefore, to obtain an accurate measurement of the tensile strength, direct tensile tests should be carried out.

Interesting questions have risen from the interfacial work carried out by different researchers, such as: (a) what is the effect of silica fume on the direct tensile strength of both cement paste and microconcrete? (b) what are the effects of high dosage of silica fume on the tensile strength? (c) what would be the effects using different w/c ratios? The purpose of this research is to address these questions. To accomplish this, a new hydraulic tensile testing technique was used. The technique, which is referred to as the *Cementitious Composites Axial Tensile Technique* (CCATT), described in the next section, measures the true tensile strength of the cementitious composites.

2. EXPERIMENTAL PROCEDURE

2.1 Description of CCATT

Tensile tests were performed on high strength cement-based composites utilizing a self-aligning hydraulic technique initially developed by Baratta and Driscoll for high strength ceramics [25, 26]. The technique was altered to be used for cement-based composites and was referred to as CCATT, which stands for *Cementitious Composites Axial Tensile Technique* [22, 27]. The tensile test specimens are cylindrical bars measuring 16 mm (0.63 in.) in diameter and 120 mm (4.72 in.) in length. Forty mm (1.57 in.) on each end of the specimen rod is inserted into steel pistons and adhesively bonded in place with a high strength epoxy [28, 29]. The specimen-piston assembly is inserted into the pressure chamber of the hydraulic tester. The pressure is applied and increased until the specimen is broken apart by the hydraulic pressure acting against the pistons. The pressure chamber, with specimen inserted, is shown schematically in Fig. 1. The internal pressurization of the specimen suspended between the O-ring seals minimizes bending stresses. The tensile fracture stress may be calculated by using the hydraulic pressure at failure and geometric parameter of the specimen-piston assembly [26]. A small degree of triaxiality in the hydrostatic loading of the specimen exists, causing a small deviation from the uniaxial stress state, calculated to be less than 4% [22, 28]. These errors were accounted for and incorporated in the final results. In addition, to eliminate the effects of stress intensification at the rod to piston bond transition, data from specimens that fracture within one half the radius of the specimen from the piston glue line are not used. Fractures occurring in these locations are considered invalid tests [30]. The invalid test rate was about 6%.

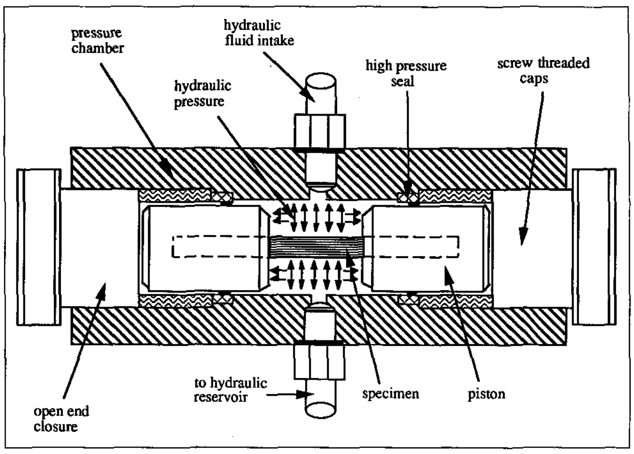

Fig. 1 – Hydraulic pressure chamber with specimen-piston assembly.

Although this tensile method is inherently self-aligning, a small degree of eccentricity or misalignment of the tensile specimens can still occur from two sources: the specimen can be slightly curved, or can be glued off-center in the pistons. As a result, small bending moments may develop along the gauge length. The procedures to correct for this error have been described [28, 29], and were applied to the data reported in this paper. The maximum correction for eccentricity in this study was equal to 4.54%, with an average correction of appriximately 2%.

The stress is related to the hydraulic pressure and test geometry by the following expression:

$$\sigma = \sigma_{nom} + \Delta\sigma = \left(\frac{A - A_s}{A_s}\right) P + \Delta\sigma \qquad (1)$$

where

σ_{nom} = nominal (uncorrected) fracture stress
A = cross sectional area of the piston
A_s = cross sectional area of the specimen
P = pressure at failure (machine read out)
$\Delta\sigma$ = correction for eccentricity which is equal to σ_{nom} x f(fracture origin location, specimen eccentricity, and diameter).

2.2 Materials

ASTM Type II Portland cement was used. Silica fume in powder form with an average of 95.75% of SiO_2, and an average particle size of 0.1 mm, was used. Its pertinent physical and chemical properties, as provided by the manufacturer, are listed in Table 1. The superplasticizer used was a naphthalene formaldehyde sulfonated superplasticizer, with 41% solids content and a relative density of 1.21. The superplasticizer was incorporated in all mixes and the content was adjusted for each mix to provide efficient dispersion of the cement particles. For mortar mixes, 1 part cement to 1.4 parts natural sand with a maximum size of 4.76 mm (0.1875 in.) was used. The specific gravity of the natural sand was 2.68; fineness modulus was 2.56; and the estimated saturated surface dry moisture content was 1.8%. The concrete sand was graded and particle size grading was within the limits of ASTM C33 [31]. Additional water was added to the mortar mixes to adjust for the moisture content of the aggregate, which should approach the saturated surface dry condition. Thus, the aggregate would not absorb water from or contribute water to the mortar mixture. Each of the paste and mortar mixes had four different water-cement ratios: 0.22, 0.25, 0.28, and 0.31, with silica fume contents of 0, 8, 16, and 25 percent by weight of cement.

The cement pastes and mortars were mixed in a Hobart mixer. The mixing procedure was as follows:
1) The cement and silica fume were placed in the mixer. When mixing mortar, the cementitious materials and the sand were placed in the mixer. The mixer was started at medium speed.
2) Half of the mixing water was added and mixing was continued for an additional 2 minutes.
3) The remaining water with the superplasticizer was added and mixing was continued at high speed for 2 more minutes in the case of mortar, and 3 more minutes in the case of paste.
4) The mixture was allowed to rest for 3 minutes, then mixed for an additional one minute in the case of mortar and an additional 2 minutes in the case of paste.

Superplasticizer was added as a percentage of the weight of the cementitious materials. The content of superplasticizer was added as follows: 2.5% for mixes of w/c ratios 0.22 and 0.25; 2.0% for mixes of w/c ratio 0.28; and 1.5% for mixes of w/c ratio 0.31. For the silica fume-cement paste mixes with a w/c ratio of 0.22, even with the addition of a relatively high dosage of superplasticizer, the mixtures were stiff and lacked workability; thus, extra vibration was necessary to mold the specimens. On the other hand, with the same w/c ratio and the same dosage of superplasticizer, the mortar mixes were relatively workable. In all other mixtures, the amount of superplasticizer used was sufficient, and thus, no bleeding or segregation was reported.

Specimens were cast in upright molds built of a composite material that made of acetal and crystalline thermo-

Table 1 - Chemical and physical properties of silica fume

Chemical composition	Chemical compound	Percent of total weight
	SiO_2	95.75
	Al_2O_3	0.35
	Fe_2O_3	0.21
	CaO	0.17
	MgO	0.09
	SO_3	0.42
	Na_2O	0.51
	Loss on ignition	1.44
Physical properties	Specific gravity	2.25
	Avg. particle size	0.1 microns
	Bulk density	2247 kg/m^3

plastic polymer, which offers many engineering advantages such as a high modulus of elasticity and strength. Each specimen was cast in two layers; each layer was compacted about 25 times with a small rod 4.76 mm (0.1875 in.) in diameter. In addition, the vibrating table was constantly used during the molding process to ensure full compaction. The specimens were kept in their molds sealed with plastic sheets for at least 24 hours to prevent moisture evaporation. Specimens with higher dosages of superplasticizer, those of w/c 0.22 and 0.25, exhibited a delay in setting; therefore, these specimens were kept in their molds at least 36 hours before they were placed in the curing room. Specimens were moist cured for 56 days at a temperature of 26°C (78°F) and at a relative humidity in excess of 95%; 384 cylindrical specimens were made, twelve for each mix.

2.3 Test specimens

Cylindrical bar specimens of 16 mm (0.63 in.) in diameter and 120 mm (4.73 in.) in length were prepared. All specimens were tested using the hydraulic tensile tester (ASCERA). The operating procedure of the ASCERA tester has been described [28], and this procedure was closely followed in testing the specimens.

3. TEST RESULTS AND DISCUSSION

The average direct tensile strength and standard deviation of the tensile specimens are summarized in Table 2. Each value represents the average of twelve specimens.

The addition of 8% silica fume resulted in an increase in the tensile strength of the mortar. The tensile strength increased between 4 and 13% depending on the w/c ratio. Specimens of w/c 0.28 exhibited the maximum increase in strength of 13%, whereas specimens of w/c 0.22 exhibited only a 4% increase, as shown in Fig. 2. In the case of cement paste, the addition of 8% silica fume did not appear to have an effect on tensile strength. Specimens of w/c ratios of 0.25, 0.28, and 0.31 showed similar strength with and without silica fume; however, at a w/c ratio of 0.22, the strength of the SF-cement paste decreased by 12%, as compared to the control cement paste (Fig. 3).

The effect of silica fume on the tensile strength of cement paste and mortar with higher dosages of silica fume (16 and 25%) is shown in Figs. 4 and 5. In the cases of cement paste and mortar, the addition of silica fume caused a decrease in the tensile strength; however, the decrease of strength in paste was greater than the decrease in mortar. In the case of cement paste, the reduction in strength was highest at w/c 0.22; the tensile strength was reduced by as much as 27% and 39% with the incorporation of 16% and 25% of silica fume, respectively, as may be seen in Fig. 6. On the other hand, the strength of mortar at the same w/c ratio was reduced by only 12% and 18% with the incorporation of 16% and 25% of silica fume, respectively (Fig. 6).

Table 2 - Test Results of Specimens

Material	Nominal* w/c	Actual w/c	SF** (%)	SP† (%)	Tensile Strength MPa (psi)	Standard Deviation MPa (psi)
Cement paste	0.22	0.235	0	2.50	10.7 (1,551)	1.2 (172)
	0.25	0.265	0	2.50	10.8 (1,570)	1.8 (254)
	0.28	0.292	0	2.00	9.8 (1,421)	1.3 (183)
	0.31	0.319	0	1.50	8.8 (1,279)	0.7 (105)
	0.22	0.235	8	2.50	9.4 (1363)	1.0 (151)
	0.25	0.265	8	2.50	11.3 (1643)	2.9 (423)
	0.28	0.292	8	2.00	9.2 (1336)	2.2 (315)
	0.31	0.319	8	1.50	8.4 (1218)	0.8 (114)
	0.22	0.235	16	2.50	7.8 (1,133)	1.5 (222)
	0.25	0.265	16	2.50	8.4 (1,220)	2.4 (353)
	0.28	0.292	16	2.00	7.6 (1,105)	1.0 (140)
	0.31	0.319	16	1.50	6.9 (1,007)	1.4 (201)
	0.22	0.235	25	2.50	6.6 (950)	1.4 (199)
	0.25	0.265	25	2.50	7.9 (1,149)	0.8 (123)
	0.28	0.292	25	2.00	6.6 (961)	0.5 (76)
	0.31	0.319	25	1.50	6.0 (866)	0.7 (101)
Cement mortar	0.22	0.235	0	2.50	10.6 (1,537)	1.8 (265)
	0.25	0.265	0	2.50	10.2 (1,471)	1.3 (183)
	0.28	0.292	0	2.00	9.0 (1,310)	1.3 (193)
	0.31	0.319	0	1.50	8.2 (1,190)	0.8 (117)
	0.22	0.235	8	2.50	11.0 (1,596)	1.1 (159)
	0.25	0.265	8	2.50	10.7 (1,546)	1.2 (171)
	0.28	0.292	8	2.00	10.2 (1,483)	0.9 (129)
	0.31	0.319	8	1.50	9.1 (1,325)	0.7 (108)
	0.22	0.235	16	2.50	9.5 (1,372)	0.8 (122)
	0.25	0.265	16	2.50	9.0 (1,305)	0.7 (97)
	0.28	0.292	16	2.00	8.3 (1,209)	0.8 (119)
	0.31	0.319	16	1.50	7.8 (1,130)	1.2 (174)
	0.22	0.235	25	2.50	9.0 (1,306)	0.7 (97)
	0.25	0.265	25	2.50	8.7 (1,257)	1.2 (173)
	0.28	0.292	25	2.00	8.1 (1,180)	0.5 (73)
	0.31	0.319	25	1.50	7.1 (1,023)	0.7 (95)

w/c = water-cementitious content ratio by weight
* *the water in the superplasticizer is not included in the w/c*
** *SF = percentage of silica fume in the cementitious materials*
† *SP = percentage of superplasticizer in the cementitious materials*

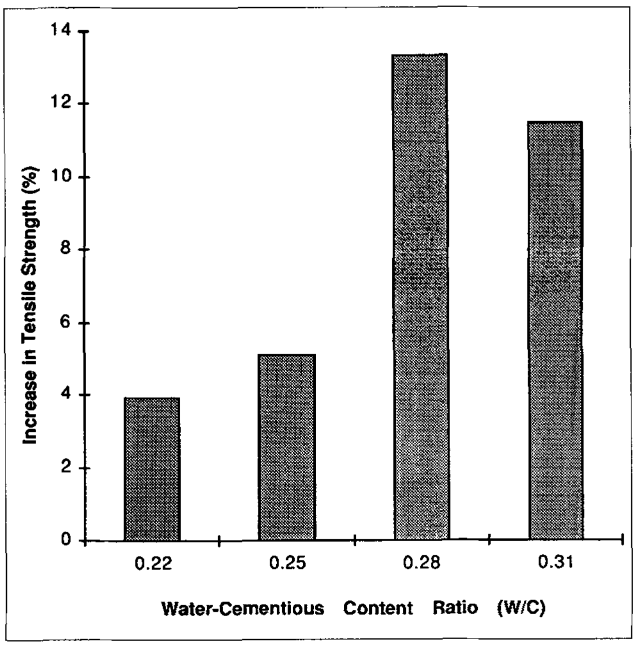

Fig. 2 – Increase in tensile strength of mortar due to the addition of 8% silica fume.

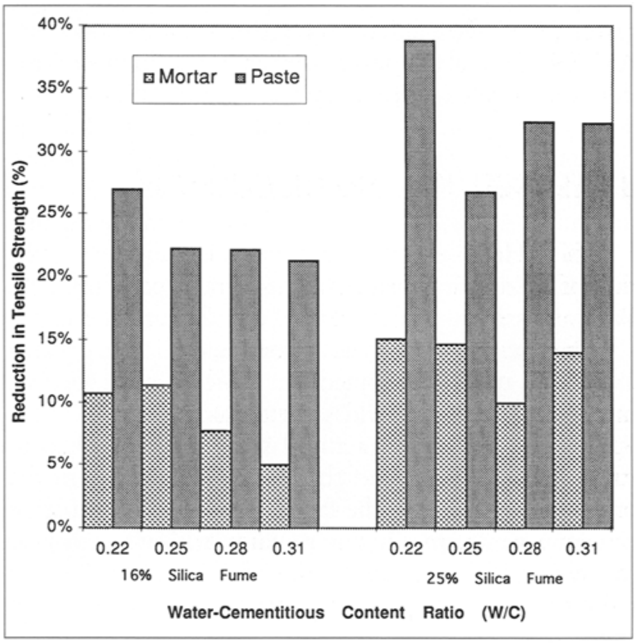

Fig. 3 – Tensile strength of cement paste and mortar with 8% silica fume.

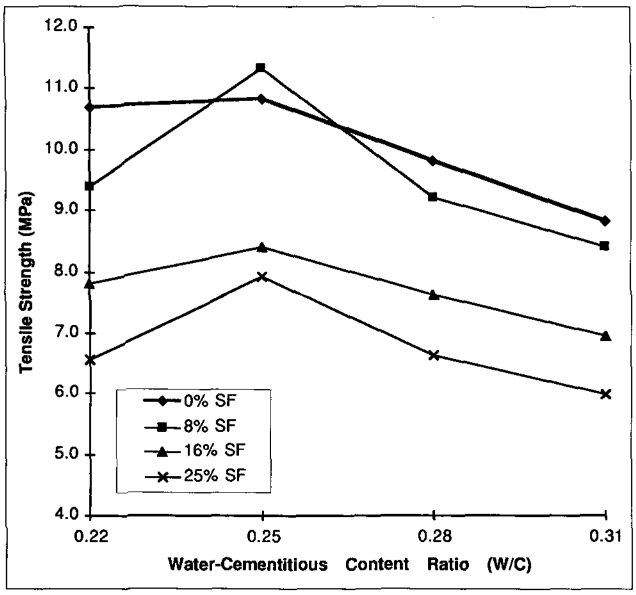

Fig. 4 – Tensile strength of cement paste as a function of w/c ratio.

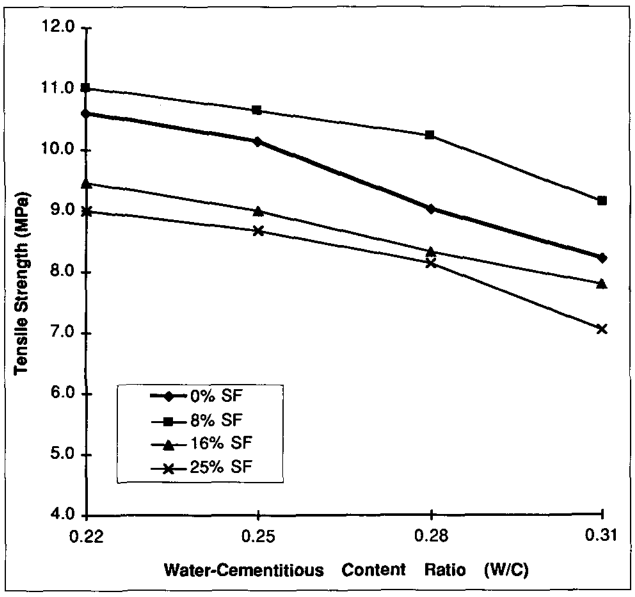

Fig. 5 – Tensile strength of mortar as a function of w/c ratio.

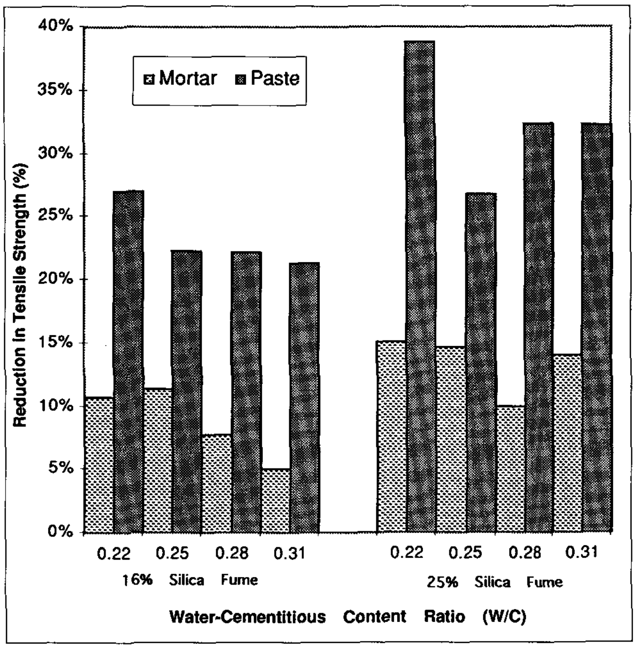

Fig. 6 – Reduction of tensile strength in cement paste and mortar due to the addition of silica fume.

The tensile strength of plain cement paste is greater than the tensile strength of plain mortar for all w/c ratios. This may be due to the weak interfacial zone between the cement paste and aggregate and the heterogeneous microstructure of mortar [16-18]. However, with the introduction of silica fume to the mixture, this is not true; the tensile strength of SF-mortars was always higher than SF-pastes, regardless of the w/c ratio. The largest difference appears to be at a w/c ratio 0.22 (Table 2). At this low w/c ratio, the SF-cement paste mixes were difficult to mix compared to SF-mortar. This was because of the presence of aggregate in the mortar, which provides a better mixing action, and, thus, better dispersion of the silica fume particles.

The reduction in tensile strength due to the incorporation of silica fume is higher in cement paste than in mortar, as may be seen in Figs 4 and 5. This reduction in both composites increases, with increasing silica fume content. An increase in the silica fume content may be associated with an increase in micro-cracking due to autogenous shrinkage [32-34] which mainly affects the tensile and flexural strengths [35].

At a low w/c ratio of 0.22, the cement paste specimens exhibited a significant reduction in strength, about 39% with the replacement of 25% of the cement by silica fume. This reduction in tensile strength at this low w/c ratio, may be attributed to the lower water-cementitious content ratio causing self-desiccation of the specimens. Although a rela-

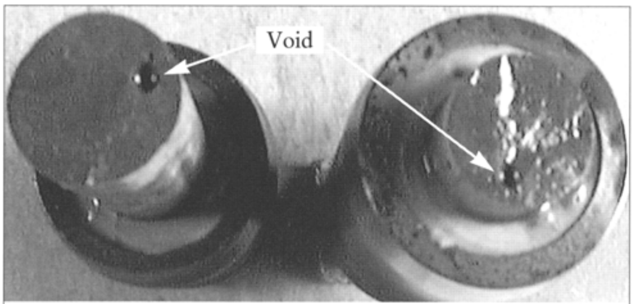

Fig. 7 (a): MIX 1, SF = 8%, W/C = 0.22

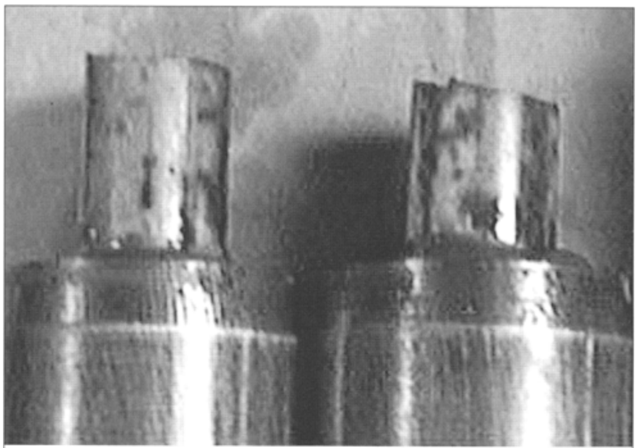

Fig. 7 (b): MIX 4, SF = 8%, W/C = 0.31

Fig. 7 – Typical fracture origin of tensile specimens: (a) Top view of the fracture surface, (b) Side view of the fracture specimen.

tively high dosage of superplasticizer was added to the mixtures – 2.5% by weight of cementitious materials (which is above the maximum recommended dosage) – the cement paste specimens were still stiff and lacked workability, especially at 25% silica fume content. This was due primarily to the high content of silica fume which increased the demand for water in these mixtures. Although the present work did not study the increase of water demand due to the use of silica fume, previous investigations have shown that the demand for water increases as much as 30% depending upon the amount of silica fume in the mixture [36, 37]. However, this behavior was less apparent in the mortar mixture compared to the cement paste mixture. With the same w/c ratio of 0.22 and the same dosage of superplasticizer, the mortar mixes were relatively workable. This may be attributed to the presence of aggregate in the mortar which provides a better mixing action.

Images of typical fractured surfaces were taken to examine the behavior of the failure mechanism of the fractured specimens. The failure origin or the initiation of failure was primarily due to voids or flows as may be seen in Fig. 7.

4. CONCLUSIONS

Specific conclusions can be drawn from the results of this study. These are summarized as follows:

1) The addition of 8% silica fume resulted in an increase in the tensile strength of the mortar whereas it showed no effect on the tensile strength of cement paste.

2) The replacement of cement with high dosages of silica fume (16 and 25% by mass), regardless of the w/c ratio, decreased the uniaxial direct tensile strength of cement paste and mortar. The decrease of strength in cement paste was greater than the decrease in mortar.

3) Comparison between cement paste and corresponding mortar values for a given w/c ratio showed that while the addition of sand generally lower the tensile strength for plain pastes, the opposite is true for SF-pastes; while SF reduces the paste strengths, it actually increases the corresponding mortar strengths.

4) The highest reduction in tensile strength occurred in the cement paste at w/c 0.22. This may be due to the lack of water in the mixture, resulting in self-desiccation of the specimens. However, this behavior was not manifested in the mortar mixtures. Scanning Electron Microscopy (SEM) evaluation of the fractured surfaces of the specimens may explain this behavior.

5) The presence of aggregate in the mix seemed to provide a better mixing action and thus a better dispersion of the silica fume particles.

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