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Zero-eccentricity direct-tension testing of thermally damaged cement-based materials

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Abstract

This study presents some results on direct-tension strength of two cementitious mortars using a test set-up specifically designed to virtually eliminate any load eccentricity. The tests were conducted on cement mortars with and without condensed silica fume after being exposed to high temperature (200, 300, 400 and 500 °C). Direct-tension tests were also carried out at room temperature (20 °C) for reference. The specimens were exposed to high temperature and were then allowed to cool to room temperature before testing up to failure. The strength values measured in this study exhibit a trend that is similar to that exhibited by the compressive strength cited in the literature. The results show that mortar specimens exhibited a small increase in strength at temperatures up to 200 °C for regular mortar and up to 230 °C for silica fume mortar. At temperatures above 200/230 °C, the residual tensile strength of the mortar decreases significantly and rapidly. Adding silica fume to the cement mortar increases the resistance to high temperature.

Keywords: High temperature; Mortar; Silica fume; Stiffness; Tensile properties

1. Introduction

1.1. Tension testing

The tensile strength of cementitious materials is measured by means of flexural-tension tests, splitting-tension tests and direct-tension tests. Flexural-tension testing yields the modulus of rupture (f_r). Splitting-tension testing is typically conducted with a concrete cylinder of the same size as used in compression testing. It yields the design parameter known as tensile-splitting strength. This tensile strength refers to the cross section at right angles to the direction of the applied load. Flexural and splitting test methods involve a nonuniform stress distribution throughout the test specimens. The nonuniform stress distribution impedes crack propagation and thus delays the ultimate failure [1], resulting in values obtained during flexural and splitting tests that may be higher than those in direct tension. While statistically the larger sample size involved in the flexural and splitting tests should result in a higher chance of crack propagation to failure, the fact that both of these tests involve nonuniform stress distributions results in higher tensile-strength values. Any crack that begins does not immediately propagate to failure because the stress in the sample can distribute itself around the aggregate particles and voids [1].

Direct-tension testing is the true measure of concrete tensile strength; however, the gripping mechanism and the eccentricity of the applied load often result in a premature failure of the specimen. Thus, direct-tension tests often lead to values lower than the predicted tensile strength of concrete. The problems associated with direct testing explain why this procedure has been rarely used to measure tensile strength. The present study uses a testing machine that eliminates any eccentricity in the loading and does not cause failure near the gripping mechanism. However, the testing mechanism limits the sample size so that the probability of there being a crack large enough to propagate and cause a brittle failure is greatly reduced. As delineated by Neville and Brooks [1], the brittle-fracture theory predicts that failure is initiated by the largest crack at right angle to

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the applied load. Consequently, the problem is reduced to a simple issue of probability. A large sample has a much greater probability of the occurrence of a crack being at right angle to the applied load and large enough to begin the process of failure. This means that for the same mix design, sample preparation and curing the size and the shape of the sample definitely affect the strength. In this study, we have eliminated two serious flaws in direct-tension testing: gripping mechanism and load eccentricity.

1.2. Direct-tension testing

In a previous study to limit the effects of load eccentricity in direct-tension testing, Toutanji [2,5], Toutanji et al. [3], Toutanji and El-Korchi [4] and Rosati and Natali-Sora [6] conducted tension tests on cementitious-based materials, ceramics and cement-based materials wrapped with fiber-reinforced polymer (FRP) sheets. Fig. 1 shows the hydraulic pressure chamber with the specimen-piston assembly. The tensile-strength values of these composites were determined using a simple hydraulic system that produces a uniform stress distribution throughout the specimen. Rather than using a device that pulls on the ends of the specimen, this testing apparatus effectively applies a uniform pressure throughout the specimen until failure. Hydraulic pressure equalizes the lateral force around the specimen and creates a uniform pressure on the inner faces of the gripping mechanisms. Toutanji et al. modified several cementitious specimens by replacing 8% (by mass) of the cement with silica fume. The tensile strength of these cementitious specimens was close to 12% of the compressive strength compared with 10% in traditional tests. This was basically due to the minimization of load eccentricity and gripping effects, which unavoidably occur in traditional ordinary tests [5].

1.3. High-temperature testing

A large number of studies have been conducted on the effects that high temperature has on the compressive strength of concrete. Felicetti and Gambarova [7] focused on assessing the mechanical properties of high-strength concrete, such as compressive strength, concrete toughness and strength recovery in time. Terro and Hamoush [8] studied the effects of confinement on compressive strength in a high-temperature environment. Castillo and Durrani [9] conducted exhaustive studies into the effects that transient high temperatures have on compressive strength and other mechanical properties under unloaded and preloaded conditions. The main objective of their research was to compare the mechanical properties of high-strength concrete with those of normal-strength concrete. Noumowe et al. [10] carried out splitting-tension tests on cylindrical specimens (160×320 mm) and direct-tension tests on I-shape specimens of 100×100 mm cross section (useful length of 400 mm). The residual tensile strength was measured on concrete specimens heated up to 600 °C. The test results showed that the residual tensile strength decreased almost linearly with the temperature. The tensile-strength values for ordinary concrete and high-performance concrete measured in splitting tests were 15% and 19% higher than those obtained in direct tension, respectively. Splitting test values showed a higher dispersion than those in direct tension. Ghosh and Nasser [11] examined the effects of high

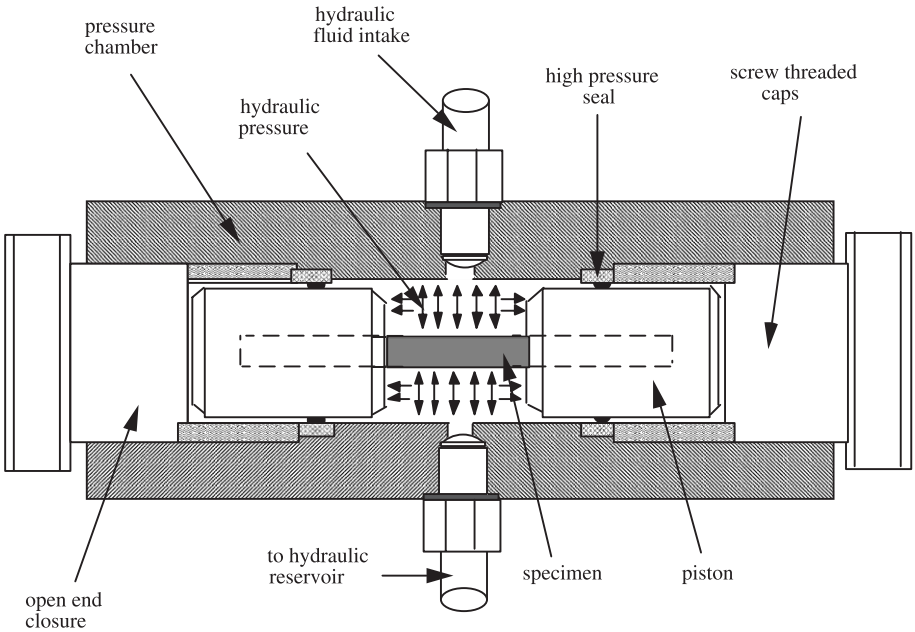

Fig. 1. Hydraulic pressure chamber with specimen-piston assembly.

temperature on the compressive strength of fly ash and silica fume concrete. Their study focused on the paste microstructure and on the chemophysical transformations in the paste because of high temperature. The review of these results was instrumental in comparing our findings on the tensile strength with the trends exhibited by the compressive strength.

A misconception regarding the hydration process is that a reversal of the hydration process may take place under dry conditions. The exposure to dry conditions does not remove the water that has already been consumed in the hydration process. The hydration process is not reversed nor does the concrete go back to its prehydration conditions. The excess water that is requested for workability does remain in the concrete, trapped in the pores and absorbed by the different materials in the concrete, and the full hydration process will continue for years after the full design strength has been obtained. This excess water, when exposed to high temperature, is removed by various processes (evaporation, phase changes and explosive spalling). The strength loss in the paste due to dehydration is discussed later in this paper. The RILEM-Committee 44-PHT [12] lists several of the processes going on in concrete at high temperature, such as dissociation of the calcium hydroxide, changes in the crystalline silicon dioxide and severe splitting within aggregate because of loss of zeolithically bound water.

This research may be of some interest to the cement and concrete research community for three specific reasons. First, the authors maintain that direct-tension testing of cementitious materials can be conducted without the limiting factors of gripping problems and eccentric loading. Using a test set-up, which was developed to test the composite materials for space applications, enabled us to measure accurately the direct-tension strength of cement paste and mortar samples. Secondly, this research provides the engineering community with new information on the residual tensile strength of cement-based samples exposed to high temperature. As a matter of fact, while a great deal of data are available on the compressive strength of concrete exposed to high temperature, the data on the tensile strength are much more limited. Thirdly, since high-performance concrete is increasingly used in today's structures, there is a need to accurately quantify its tensile strength. For concrete members in bending, the tensile strength is generally ignored; however, in high-performance concrete, significant savings may be achieved, provided that designers have reliable data on concrete tensile strength.

2. Experimental program

The objective of this research is to study the effects that high temperatures have on the tensile strength of the cementitious materials. To this end, a testing apparatus used by NASA in their Composite Research Lab to eliminate load eccentricities and gripping failures was adopted. Testing was conducted with small hourglass-shaped mortar specimens (Fig. 2). Specimen size was as follows: length 121 mm, midsection width 6 mm, end width 14 mm and thickness 3.5 mm. The possible strength differences in cementitious materials with and without silica fume and exposed to high temperature were also investigated.

2.1. Specimen preparation

Twenty-four cementitious-based specimens were cast in Plexiglass moulds using two types of cementitious materials. The first type was made of cement, sand and water, and the second had a similar mix design but 20% of cement by mass was replaced with silica fume. The cement-to-sand ratio was 1 and the water-to-cement ratio was 0.33. ASTM Type I Portland cement and river sand were used. Each specimen was cast in two layers, each compacted 25 times with a 5 mm rod. In addition, a vibrating table was constantly used during casting to ensure full compaction. The specimens were kept in their moulds and sealed with plastic sheets for at least 24 h to prevent moisture evaporation. After demoulding, the specimens were moist cured at 50 °C for 30 days.

2.2. Testing procedure

The concrete specimens were exposed to five different temperatures (23, 200, 300, 400 and 500 °C). The furnace used in this project has a maximum sustainable temperature of 1400 °C and is heated by a bank of horizontally mounted molybdenum disilicide heating elements (Fig. 3). The fur-

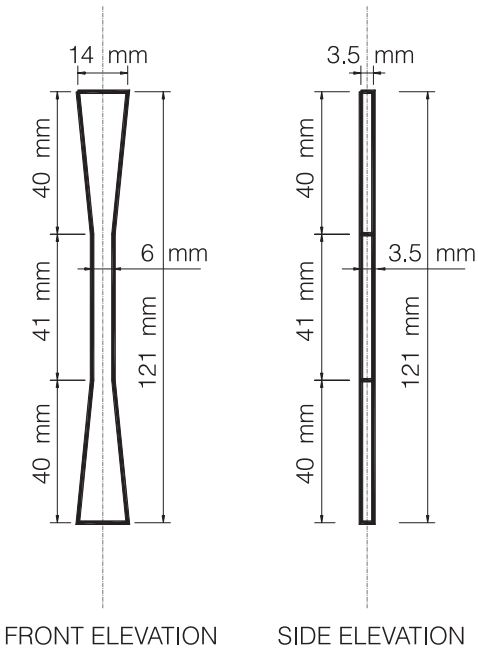

Fig. 2. Specimen geometry.

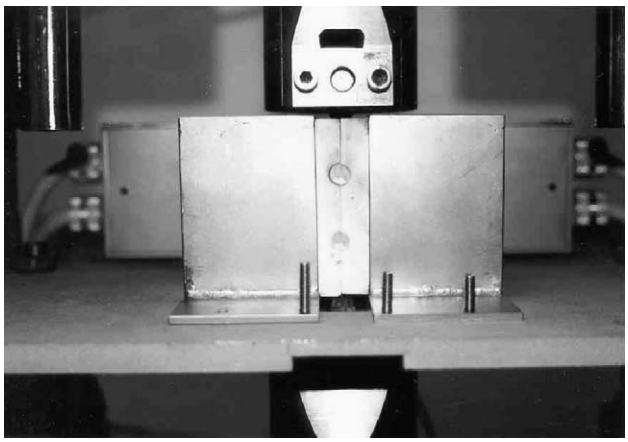

Fig. 3. 1400 °C furnace firing a sample.

nace is designed in such a way that the tests cannot be run at high temperature. The specimens rested at the prescribed temperature for at least 2 h were then allowed to cool to room temperature and to rest at least 30 min prior to testing. Fig. 4 shows the mortar specimen in the gripping mechanism, with the two halves of the furnace separated. All specimens were tested using the Composite Testing and Analysis Model HPCMC Deadweight Creep Frame. Fig. 5 shows the testing frame above and below the aluminum housings that support the sample. The knife-edge alignment mechanism used in this testing is specifically designed for ceramics and other brittle materials, where a load eccentricity as small as 5–10% could lead to strength reductions of 25–50% compared with direct tensile strength [3,5]. An extensometer was mechanically attached to the specimen. The displacement rate of the press was 0.08 mm/s. The load/displacement curve was continuously monitored and plotted using a WorkBench Data Acquisition System, and the data were continuously processed to obtain the stress–strain curve. The tapered specimens are all wedge shaped at the tops and bottoms. Fig. 6 shows specimens after failure

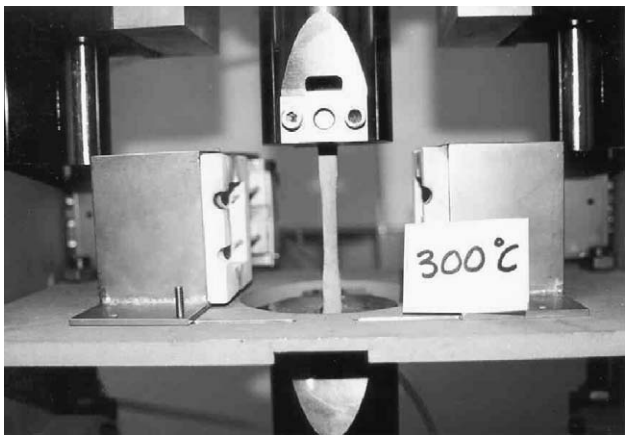

Fig. 4. Mortar specimen blocked between the beads of the gripping mechanism after 2 h at 300 °C.

Fig. 5. Overview of the composite tensile testing deadweight creep frame.

(posttesting). The specimens were inserted into a matching receiver machined from Hastelloy X, which provides edge loading to the wedge-shaped portion of the specimen. The specimen is then blocked into place with specially machined inserts on both sides that provide for accurate lateral spacing of the specimen. The assembly is then locked into place by means of a retaining plate on each side of the aluminum chamber to which the load is ultimately applied.

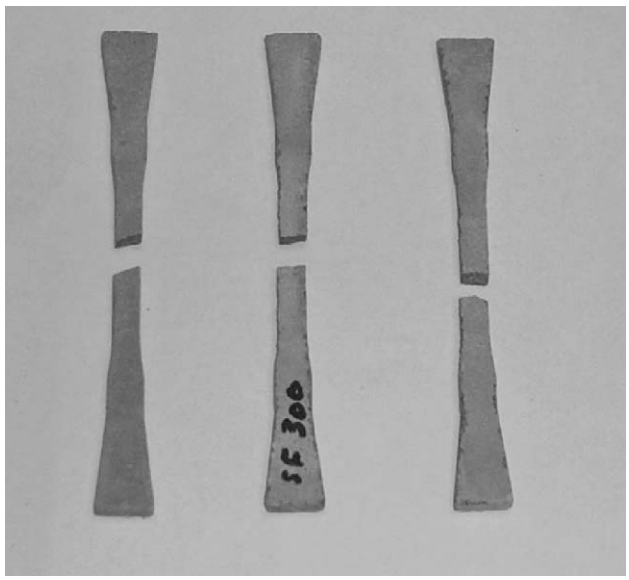

Fig. 6. Mortar specimens after testing.

3. Results and discussion

3.1. Direct-tension test

The tensile strength of mortar at room temperature was 3.5 MPa or 12.5% of its compressive strength. This value is slightly greater than that reported in the previous studies by Toutanji and El-Korchi [4] and Toutanji [5], one possible explanation being the improved gripping mechanism adopted in the present study, which provides a very uniform load distribution with less probability of stress concentrations than in a specimen glued to the press with high-strength epoxy. In the literature, the prediction for direct-tension strength range from 0.05 $\sqrt{f'c}$ to 0.07 $\sqrt{f'c}$ [13]. For a design compressive strength of 35 MPa, these values would be from 1.3 to 2.2 MPa. The tensile strength of specimens with silica fume at room temperature was 3.0 MPa or 11% of the compressive strength. This value is less than the previous study conducted by Toutanji and El-Korchi [4] and Toutanji [5]. While adding silica fume creates a denser microstructure, the brittleness is increased as well.

3.2. Effects of high temperature on strength

The results on the tensile strength as a function of the temperature are shown in Fig. 7. The tensile strength of the mortar, with and without silica fume, exhibits an increase up to 200 °C for mortar and 230 °C for mortar with silica fume. At temperatures above 200/230 °C, the tensile strength of the mortar specimens decreases. Adding silica fume to the mortar increases the resistance to temperature. The tensile strength of silica fume mortar started to decrease around 230 °C as compared with 200 °C for regular mortar. At 300 °C, the tensile strength of mortar was reduced by almost 35%, while at 400 and 500 °C the reduction was close to 55% and 60%, respectively. On the other hand, for mortar with 20% silica fume at 300 °C, the tensile strength still is 12% higher than at room temperature. At 400 °C, the tensile strength of the silica fume mortar plummets to 43% of that at room temperature. At 500 °C, the residual strength is only 37% of that at room temperature. Figs. 8 and 9 show the stress–strain curves for all types of samples (with and without 20% silica fume) at 23, 200, 300 and 400 °C. The data were collected by the WorkBench Data Acquisition system throughout the application of load.

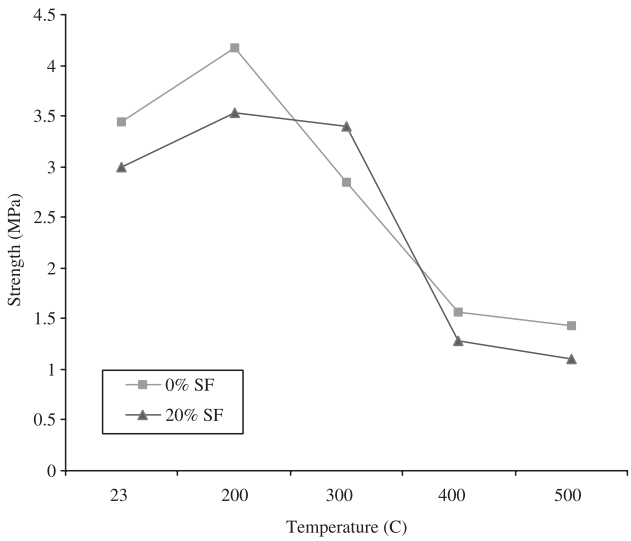

Fig. 7. Residual tensile strength as a function of the temperature.

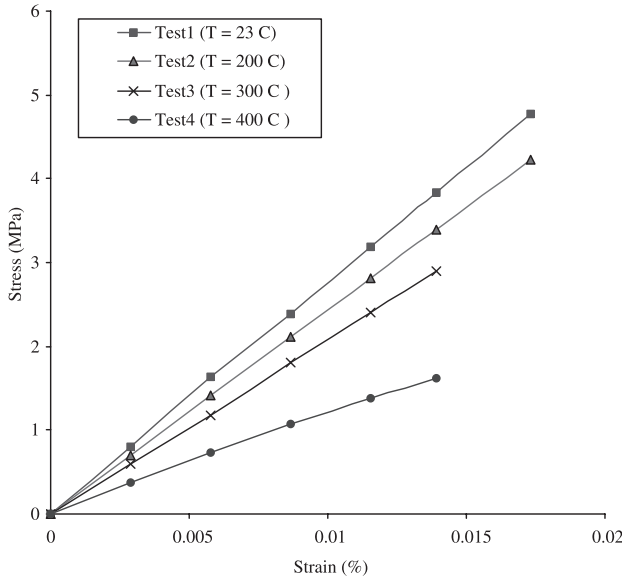

Fig. 8. Strain–stress curves for a mortar with no silica fume.

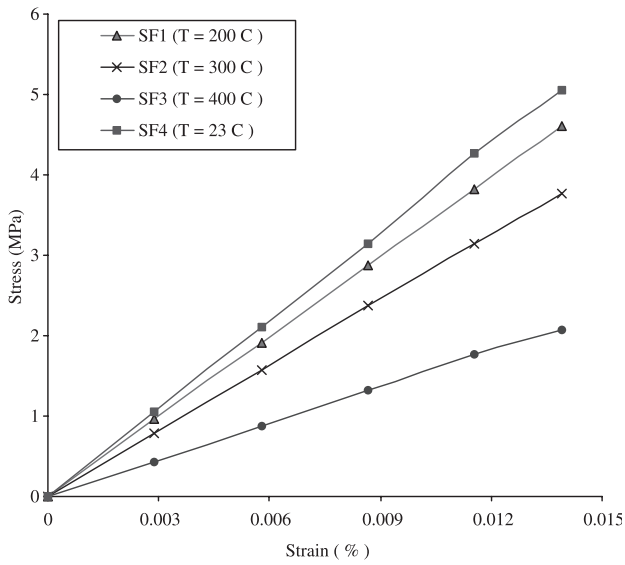

Fig. 9. Stress–strain curves for a mortar with 20% silica fume (by mass of cement).

3.3. Effects of high temperature on stiffness

The values of the tensile modulus of elasticity of mortar specimens ranged from 27.5 GPa at room temperature to 12.0 GPa at 400 °C. This decrease of 57% is almost identical to the loss of strength at 400 °C. However, with the addition of silica fume, the specimens had an average modulus of elasticity of 36.4 GPa at room temperature. This value is significantly higher than that of the mortar without silica fume. This is probably due to the fact that the silica fume creates a much denser microstructure as a result of its reaction with the lime during the hydration process. The stiffness of the silica fume specimens steadily decreases with exposure to high temperature. The stiffness decreases by 25% at 300 °C while the strength increases by 12% as mentioned in Section 3.2. At 400 °C, the modulus of elasticity of the silica fume specimens has been reduced by 60% compared with the room temperature value roughly equal to its percent strength loss. In Fig. 10, the modulus of elasticity of both types of materials (with and without silica fume) is plotted as a function of the temperature.

The greatest benefit of the addition of silica fume to concrete is that it creates a much denser microstructure [14]. A much lower porosity results when a percentage of the Portland cement is replaced with much finer particles such as silica fume. This fact leads to a higher compressive strength but does not necessarily bring in notable differences in terms of tensile strength. Two facts explain this behavior. Firstly, silica fume reacts with the lime released during the hydration process of the Portland cement. This chemical reaction creates a paste that is more fully bonded. Secondly, a denser cement paste should result in higher tensile strength when examined from a fracture mechanics viewpoint. There are simply less voids from which a failure crack might develop. In our tests, the results exhibit an initial decrease of the tensile strength but a marked increase of the stiffness in the specimens with and without silica fume, as should have been expected because of the denser and more brittle mixture in silica fume cementitious composites.

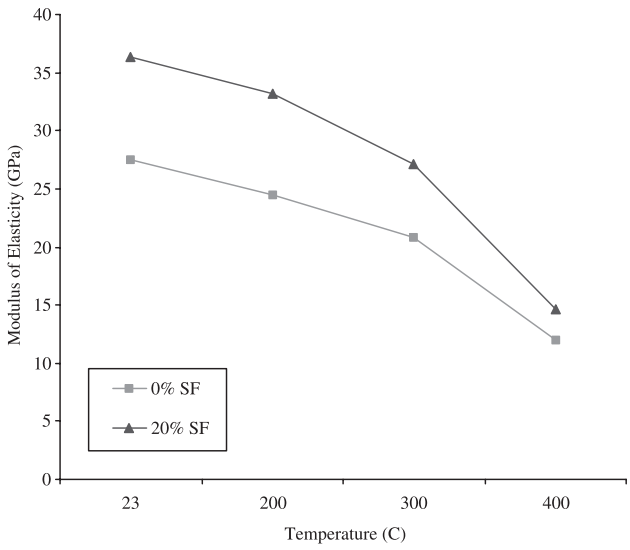

Fig. 10. Plots of the modulus of elasticity as a function of the temperature.

The specimens containing 20% of silica fume showed a higher tensile strength between room temperature and 300 °C. The studies by Carette and Malhotra [15], and Mehta and Gjorv [16] revealed that in concrete containing fly ash (normally characterized by a slow strength development) adding small percentages of condensed silica fume compensates for this slow development. In this study, our samples do not contain fly ash; however, we found that there are similarities between how silica fume compensates for a slow strength development of fly ash and how silica fume seems to strengthen the paste when exposed to high temperatures (less than 300 °C). Ghosh and Nasser [11] examined the change in matrix morphology of cement paste by using a scanning electron microscope (SEM). They found that the chemophysical properties of the paste microstructure changes from smooth, with dense lumps of calcium silicate hydrates (C-S-H) gel at 71 °C, to a matrix of C-S-H gel with lumps that are deformed and bonded together at 149 °C. Finally, at 232 °C, the paste structure had clearly changed to a loose white material that is very porous and weak looking. Ghosh and Nasser [11] verified also that this loose, porous white material was indeed the cause of the loss of strength by the use of energy dispersion spectrums. At 149 °C, the ratio of the gross counts of calcium and silicon is 0.7754; however, at 232 °C, the ratio decreases to 0.5035. Ghosh and Nasser [11] determined that the loss of strength in the concrete was indeed the result of a chemical transformation, from a highly adhesive gel to a loose, weak substance. Unfortunately, in the present study, the tests were carried out at very different temperature levels, and we could not ascertain at what temperature the strength of the specimens containing 20% silica fume peaked and began to decline. The peak strength temperature is likely to be between 200 and 300 °C. This peak temperature is higher than that found by Ghosh and Nasser [11], but our samples did not contain fly ash. Specimens containing silica fume showed greater resistance to the effects of high temperature compared with regular mortar, since the silica fume tends to delay the transition to the loose, white porous material described by Ghosh and Nasser [11]. Summing up, the determination of the exact temperature when the strength begins to decrease and the effects that silica fume has on this temperature need further studies.

4. Conclusions

Based on the test results obtained in this research project, the following conclusions can be drawn.

1. Edge-loaded specimens lead to higher tensile-strength values than the traditional gripped or hydraulically

loaded tests. This is due to the fact that the edge-loaded tests minimize eccentricity and gripping effects.

2. Cement paste specimens exhibit a small increase in the tensile residual strength up to 200 °C (regular mortars) and 230 °C (silica fume mortars); the trend is similar to that exhibited by the compressive strength, as shown by the references quoted in this study.
3. At temperatures above 200/230 °C, the residual tensile strength of the mortar decreases significantly and rapidly.
4. Adding silica fume leads to a somewhat lower residual tensile strength, since the microstructure is more brittle due to its greater density.
5. Adding silica fume to the mortar mix leads to a greater resistance to high-temperature detrimental effects.

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