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Autogenous shrinkage and induced restraining stresses in high-strength concretes

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Abstract

Development of internal stresses induced by restrained autogenous shrinkage in high-strength concretes at early ages was investigated. Effects of water/binder ratio and the presence of silica fume on the stress developed were evaluated and considered in conjunction with the creep behavior of the concretes. The restrained autogenous shrinkage resulted in a relatively high stress that sometimes caused premature cracking in the high-strength concrete. This occurred mainly when the ratio between the restraining stress and the tensile strength approached 50%. The stresses were not as high as expected from the autogenous shrinkage, since considerable relaxation took place due to creep. Thus, the viscoelastic nature of the concrete at early age has a considerable influence on the stresses generated.

Keywords: High-performance concrete; Silica fume; Shrinkage; Creep; Tensile properties

1. Introduction

In recent years, there has been a great interest in autogenous shrinkage of high-strength concrete. The mechanism of autogenous shrinkage of the concrete as well as the effects of mix proportion such as water/cement ratio, composition of cements and the addition of mineral admixtures on autogenous shrinkage have been experimentally investigated [1,2]. Autogenous shrinkage strain in high-strength concrete with a low water/cement ratio is so large that it may cause premature damage in the concrete. However, most of the studies focused on the estimation of the total strain due to free autogenous shrinkage in high-strength concrete and less information is available on internal damages, particularly on cracking tendency in conditions of restrained autogenous shrinkage [3,4]. Furthermore, there is a need for a better understanding of the restrained autogenous shrinkage behavior in terms of the creep characteristics of the concrete at early ages, where the development of the continuous restraining stress is expected to induce creep strain in concrete. A viscoelastic response at this time period may play a significant role in reducing the internal damage. Therefore, there is a need to investigate the development of restrained autogenous shrinkage stress in high-strength concrete and account for its magnitude by considering simultaneously the autogenous shrinkage, which induces tensile stresses and the creep relaxation.

In this study, the generation of internal stresses in high-strength concrete was investigated in restrained conditions. Effects of water/cement ratio and the incorporation of silica fume on the shrinkage behavior were discussed with emphasis on the development and relaxation of restraining stress at early ages.

2. Experimental

2.1. Materials and mix proportion of concretes

Low water/binder, w/b concretes were prepared with and without silica fume. The cement was ordinary Portland cement. The coarse aggregate was graded crushed dolomite with a maximum size of 7 mm. The fine aggregate was sea sand with F.M. of 1.52. A condensed silica fume with

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Table 1
Mix proportion of concretes

	Unit content (kg/m^3)						
w/b	Water	Cement	Silica fume	Sand	Gravel	SP (% wt. of binder)	Slump (mm)
0.25	144	576	–	572	1145	5	50
0.25	140	505	56	572	1145	5	110
0.33	167	506	–	572	1145	1.5	100
0.33	163	444	49	572	1145	1.5	110

SP: Superplasticizer.

specific surface area of 19 m^2/g was used. Superplasticizer was of the naphthalene formaldehyde sulfonate type. Replacement ratio of silica fume was 10% by weight. Mix proportions of the concretes are given in Table 1.

2.2. Restrained and free shrinkage tests

The restrained and free shrinkage tests of sealed specimens were conducted in controlled environment at 30°C. Concretes mixed with a pan mixer were directly cast into the molds of the restrained and free shrinkage testing apparatus (Fig. 1). To avoid the frictional resistance between the specimen and the mold, a thin vinyl sheet was placed between them. The testing apparatus shown in Fig. 1 consists of two identical specimens and the measuring devices. The specimen size is $40 \times 40 \times 1000$ mm. Those twin specimens were sealed immediately after casting. One of them provided free shrinkage conditions, while the other a full restraint.

In the restrained shrinkage specimen, one gripped end was fixed and the other was connected to a motor through a universal joint. This system is a computer-controlled closed loop one. When shrinkage occurs and its level is approaching a strain of 5×10^{-6} (i.e. 5-μm shrinkage for the 1000-mm-long specimen), the motor automatically starts the motion to pull the specimen back to the initial position, to keep the length of the specimen constant at 1000 mm. The load cell records the load induced in this motion. Details of the testing equipment and the analysis of the data in terms of elastic and viscoelastic responses were described elsewhere [3,5].

The viscoelastic response is presented in terms of creep strains, which can be calculated using the analytical procedure described in Ref. [5]. In the case of the restrained test, the creep is the viscoelastic strain induced in a system where the stress is continuously changing at a very slow pace. In an ideal classical test, the creep is determined under a constant load. Such classical tests were also carried out with these concretes [6] and the results were similar to those obtained here, based on an analysis of the data of the restrained and companion free shrinking specimens.

Length changes of both specimens and the restraining force generated in the restrained shrinkage specimen were continuously recorded. The test was conducted for 7 days after casting. However, if the stress developed beyond 80% of the capacity of the load cell (5000 N), the restrained shrinkage test was terminated.

2.3. Strength tests

Cube specimens of $50 \times 50 \times 50$ mm were produced. They were also sealed immediately after placing, and

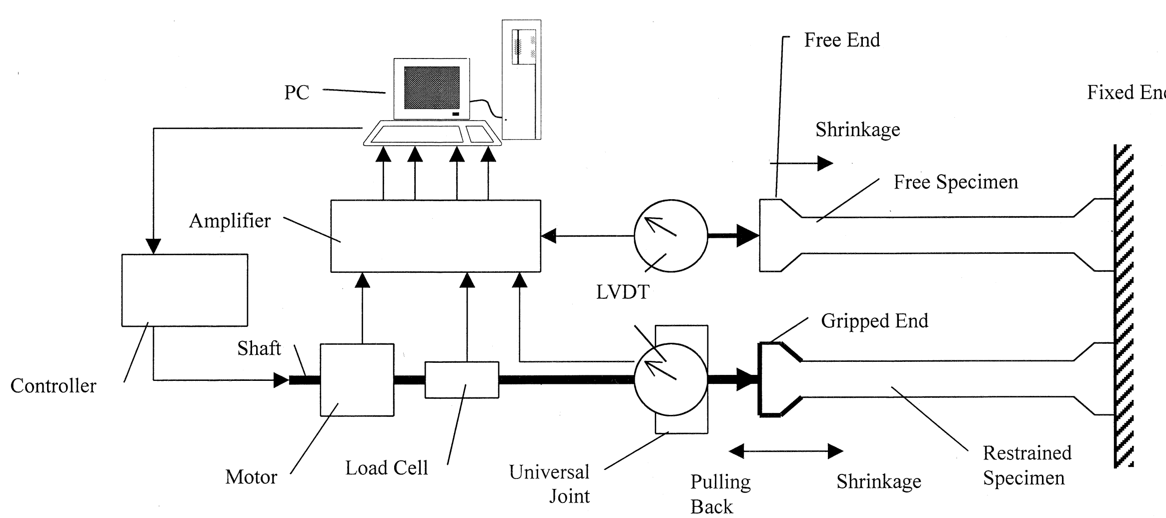

Fig. 1. Schematic description of the restrained shrinkage testing apparatus.

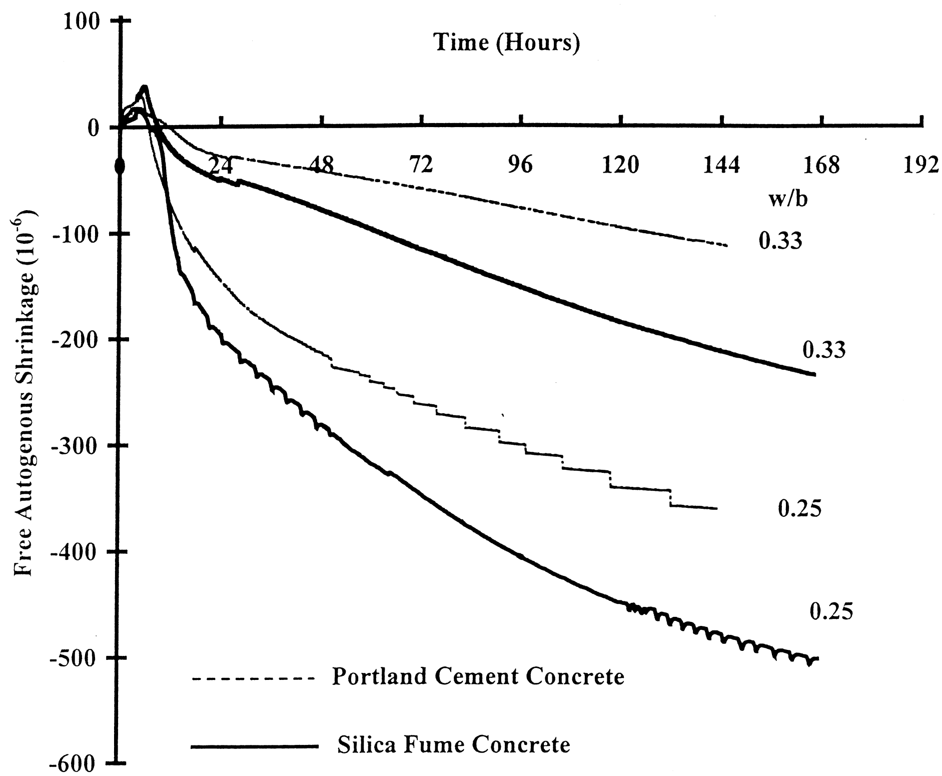

Fig. 2. Free autogenous shrinkage strain vs. time curves of high-strength concretes.

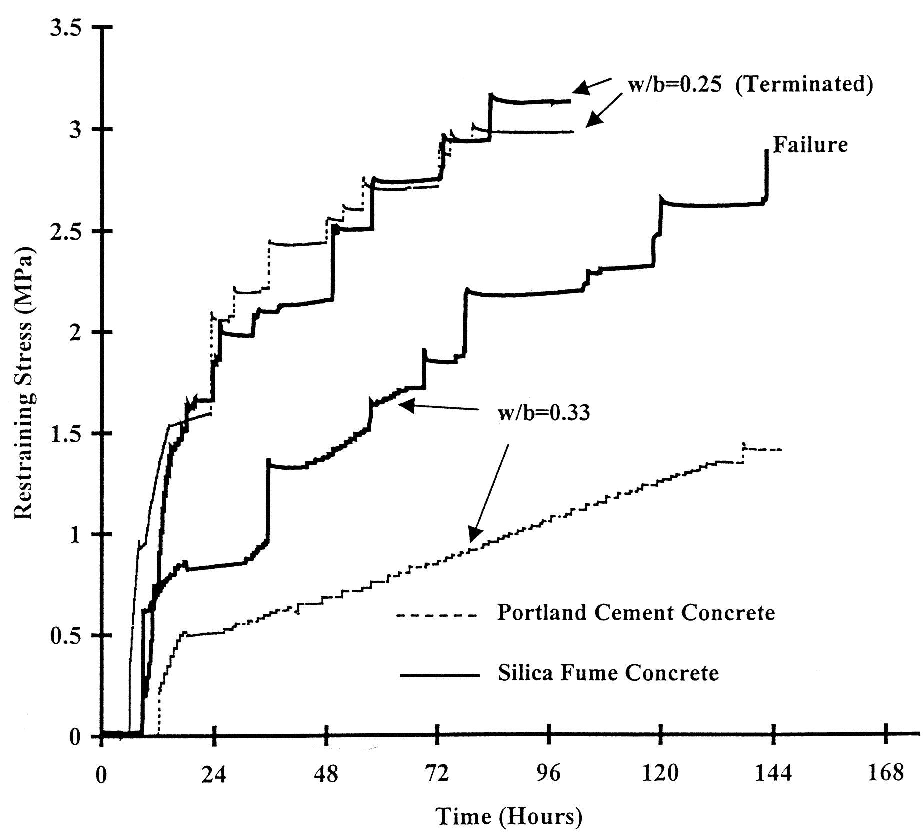

Fig. 3. Restraining stress vs. time curves.

stored in the same room at 30°C. Splitting tensile and compressive strength tests were carried out at the age of 1, 3 and 7 days.

3. Results

Fig. 2 presents the free autogenous shrinkage vs. time curves. As expected, the concrete with a lower w/b ratio exhibited a greater autogenous shrinkage. It is also evident that the addition of silica fume increased the autogenous shrinkage, in agreement with other studies [1–3]. Differences in the free autogenous shrinkage between concretes with and without silica fume increased with time.

Fig. 3 presents the restraining stress vs. time curves for each of the concretes. A greater stress was generated in the specimens with w/b ratio of 0.25, in agreement with their greater shrinkage strains (Fig. 2). Effects of silica fume on the induced stress were different between concretes with w/b ratio of 0.25 and 0.33.

At the lower w/b ratio of 0.25, there is little difference between the curves of concretes with and without silica fume. The restrained shrinkage stresses for the concrete increased steeply for the first 12 h, and then the rate of rise gradually decreased. It should be noted that although the stresses were similar, the autogenous shrinkage of the silica fume concrete was greater (Fig. 2).

The trend is different for 0.33 w/b mixes. Here the stress generated in the silica fume concrete was considerably greater than the corresponding concrete without silica fume. At w/b ratio of 0.33, the stress in the silica fume concrete was about twice as much as in the silica fume-free concrete. As a result, a tensile failure occurred in the silica fume concrete at 6 days.

It can be seen from Figs. 2 and 3 that the stress induced in the concretes was not always consistent with the free autogenous shrinkage. This suggests that the evaluation of the internal stress based on free autogenous shrinkage only is not sufficiently accurate.

Fig. 4 shows the time-dependent variations of the creep strain developed in the restrained specimens. The creep deformation of a plain concrete with w/b ratio of 0.33 was relatively small during the test. However, the creep strain was increased when silica fume was added. The creep strain of the silica fume concrete with the same w/b ratio of 0.33 increased almost linearly with time.

For mixes with w/b ratio of 0.25, a large creep strain occurred in all the concretes, with and without silica fume. Particularly, the silica fume concrete with w/b ratio of 0.25 exhibited an immediate sharp increase in creep at early ages,

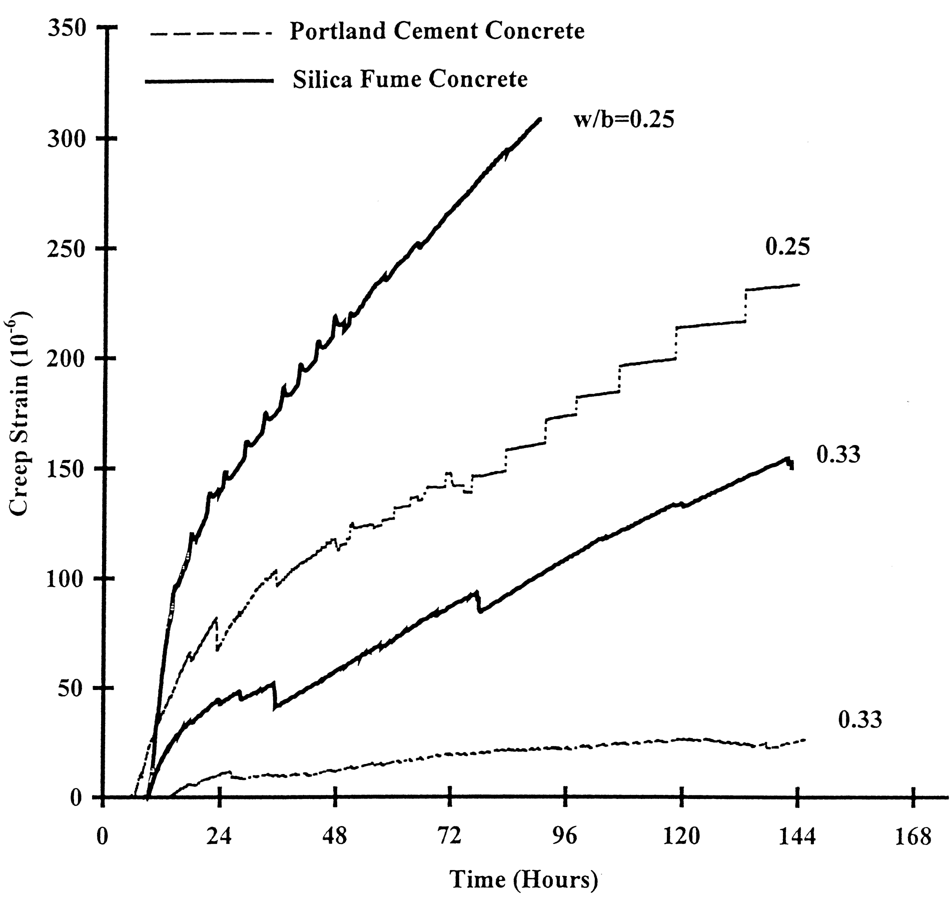

Fig. 4. Creep strain in restrained autogenous shrinkage specimens.

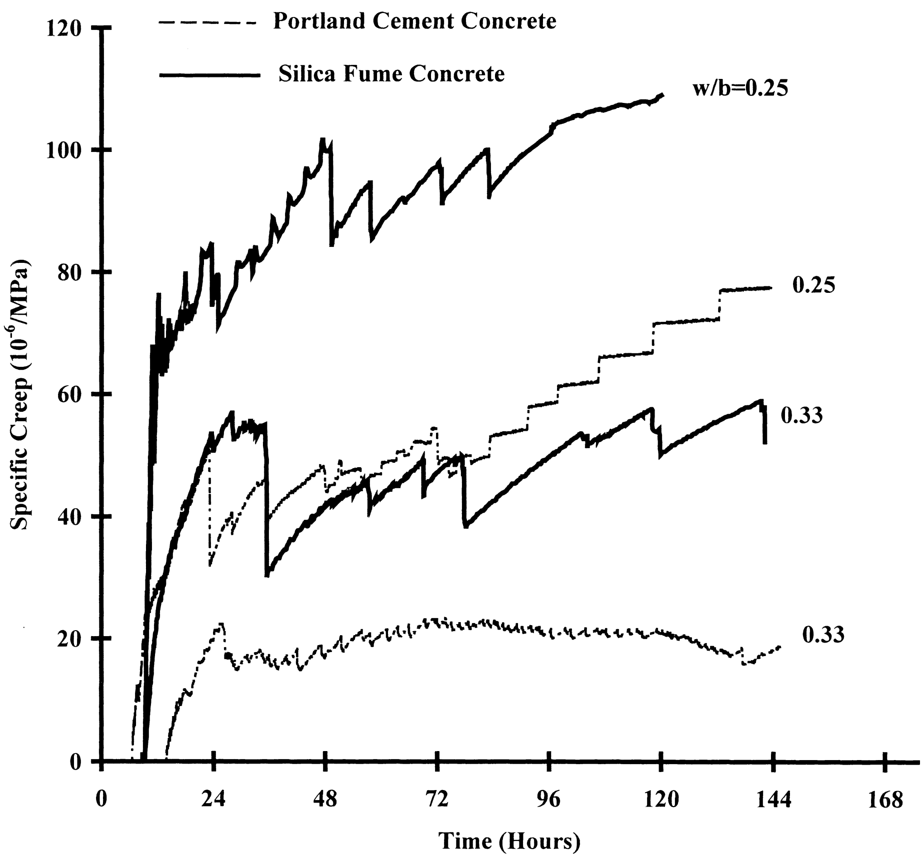

Fig. 5. Specific creep of high-strength concretes under restrained autogenous shrinkage conditions.

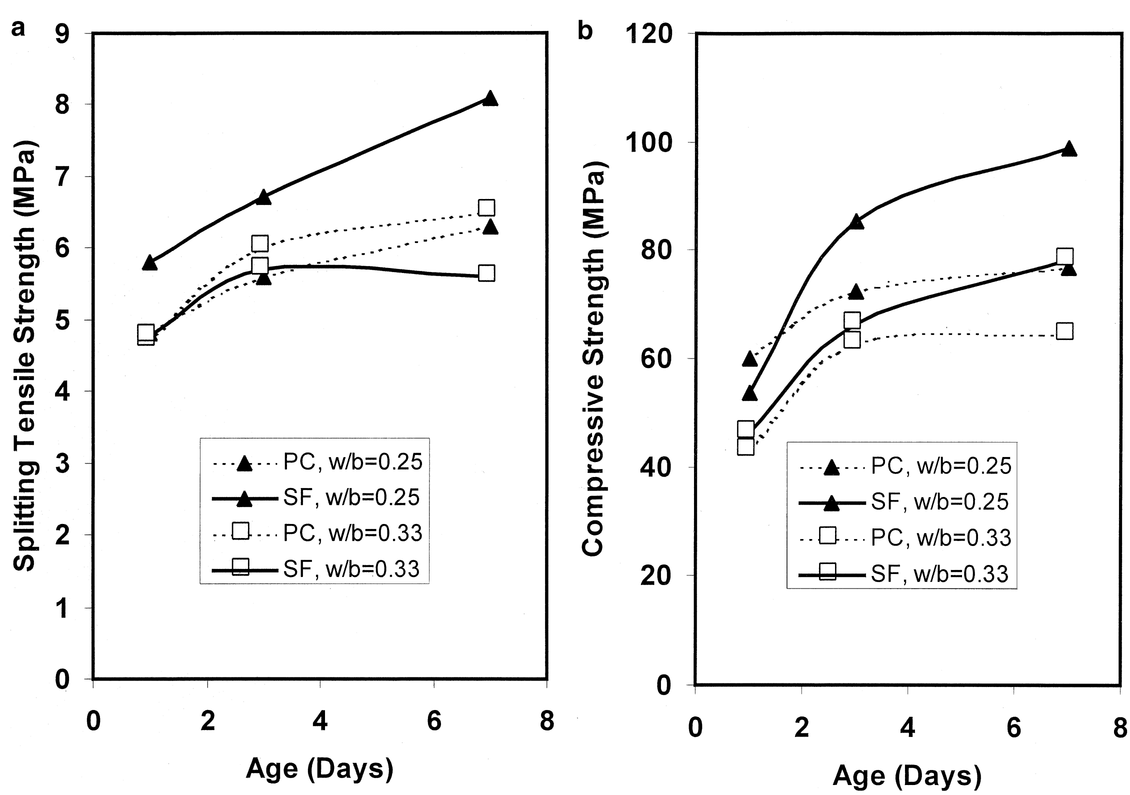

Fig. 6. Splitting tensile strength (a) and compressive strength (b) of high-strength concretes (PC: Portland cement concrete, SF: silica fume concrete).

and its creep strain was considerably larger than the plain concrete of the same w/b ratio of 0.25.

The absolute magnitudes of the creep strains are of the same order of magnitudes as the absolute free autogenous shrinkage strains: the absolute creep strain for the 0.25 w/b mix is about 75% of the absolute free shrinkage strain. Taking into the account such a large strain and the corresponding small elastic one, it is realized that the viscoelastic nature of the high-strength concretes at early ages plays a significant role in the restrained shrinkage behavior, as predicted in Ref. [7].

The creep strains in Fig. 4 were normalized for the restraining stress, and the resulting curves of specific creep (creep strain divided by the applied restraining stress) are plotted in Fig. 5. It can be seen that reduction in w/b ratio and the incorporation of silica fume increased the specific creep. This implies that the concrete, which had the larger autogenous shrinkage, also had a greater creep potential. However, the variation of the creep potential with time seems to depend on the w/b ratio of the system. At the w/b ratio of 0.33, the specific creep remained almost constant after 24 h, whereas at the lower w/b ratio of 0.25 the specific creep increased monotonically even after the marked rise which occurred at the initial 24 h.

The splitting tensile strength and the compressive strength values are plotted in Fig. 6. As a whole, there are no significant differences in the strength values of the different concretes, although the silica fume concrete with w/b ratio of 0.25 had a somewhat greater splitting tensile strength than the others. The increase in the splitting tensile strength with time was modest, except for the silica fume concrete with w/b ratio of 0.25.

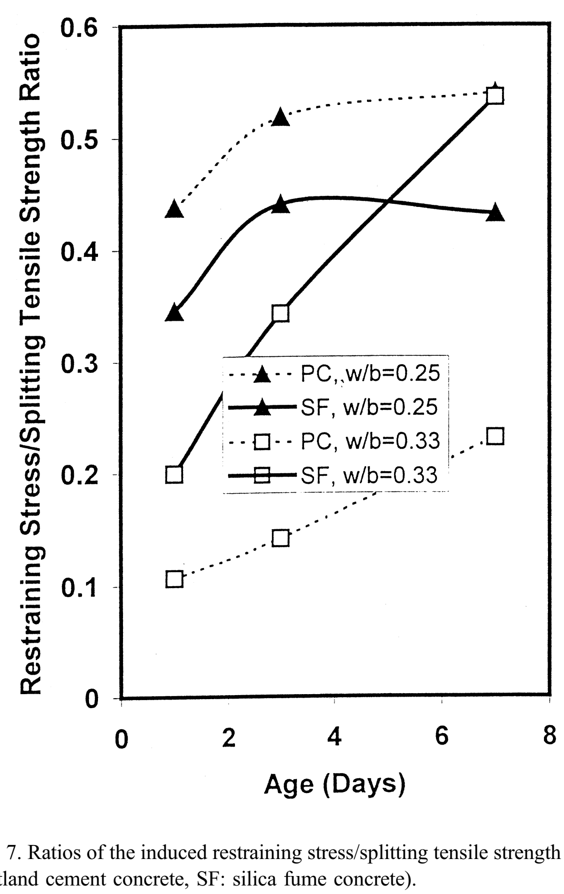

Fig. 7. Ratios of the induced restraining stress/splitting tensile strength (PC: Portland cement concrete, SF: silica fume concrete).

In Fig. 7, the relative values of the ratio between the induced restraining stress and splitting tensile strength are plotted. The tendency for the ratio to increase with time suggests that the rate of the development of stress induced by autogenous shrinkage was greater than the rate of strength gain. At w/b ratio of 0.25, a high ratio was already attained at the age of 1 day. On the other hand, the stress level for the w/b ratio of 0.33 was far lower than that for the ratio of 0.25 at 1 day, and then increased progressively. At w/b ratio of 0.25 the ratio was mildly higher for the plain concrete, whereas at 0.33 it was significantly higher for the silica fume concrete.

4. Discussion

4.1. Development of internal stresses in restrained autogenous shrinkage conditions

As shown in Fig. 3, the free autogenous shrinkage of concretes with low w/b ratios induced high tensile stresses. A tensile failure occurred in the silica fume concrete with w/b ratio of 0.33, but not in the plain concrete of the same w/b ratio. These results are consistent with the fact that in the low w/b ratio concretes and in the silica fume concrete with w/b ratio of 0.33, the stress/strength ratios exceeded 50%. This indicates that the gain of strength could not follow the increase in the stress induced by the autogenous shrinkage.

A stress/strength ratio of about 0.4 to 0.5 at early ages, achieved in some of the systems, is relatively high. This level of stress falls in the range of initiation of microcracks in concrete subjected to either a tensile or compressive load [8,9]. Judging from the trend of continuous increase in the free autogenous shrinkage strain of the 0.25 w/b ratio concretes (Fig. 2), one would expect that the stress/strength ratio would increase beyond the levels attained at 3 days (Fig. 2) when the test was terminated. Therefore, the concrete with a w/b ratio of 0.25 might be considered to be in the range of cracking risk or damage after 3 days. Furthermore, such a high stress may result in the reduction in the load-bearing capacity under external tensile loading [10].

4.2. Effects of w/b ratio on the restrained autogenous shrinkage stress

Creep at early age is expected to decrease the stress generated in restrained autogenous shrinkage. Comparing the free autogenous shrinkage strains (Fig. 2) with the creep strains (Fig. 4) shows that the absolute creep strains were almost comparable to the absolute total free autogenous strain in the high-strength concretes. Creep capacity in concretes depends on many factors. The age of concrete at the time of loading and w/b ratio are important ones. In the restrained autogenous shrinkage test, the restraining force was induced within a few hours after casting. Therefore, a large creep deformation is expected to occur. Therefore, the stress expected to be induced by the restrained autogenous shrinkage will decrease to some extent due to the stress relaxation, which occurs in the early age concrete.

Generally, the creep in concrete with a low w/b ratio is smaller than in concrete with a high w/b ratio if a load is applied at the same age. This is ascribed to the lower water content and the formation of more rigid structure in concrete with a low w/b ratio. However, the data in Figs. 4 and 5 suggests that the creep in the 0.33 w/b ratio concrete was smaller than in the 0.25 w/b. This might be explained by the lower stress/strength ratio corresponding to smaller free autogenous shrinkage for the 0.33 systems (Fig. 2).

4.3. Effects of silica fume on the restrained autogenous shrinkage stress

From Figs. 4 and 5, it can be seen that the silica fume concrete exhibited a greater creep strain under the restraining stress. Generally, the creep in silica fume concrete is smaller than the concrete without silica fume if the creep load is applied when the concrete is well matured. This lower creep in matured silica fume concrete is attributed to the high strength of the silica fume concrete and the dense microstructure at the time of loading. The increased creep tendency in silica fume concrete loaded at early ages, and particularly at 1–2 days, cannot be accounted by the induced restraining stress/strength ratio. As shown in Fig. 7, the silica fume concrete at 1 and 2 days was not subjected to a considerable high level of stress compared to the plain concrete. This observation however is consistent with the report by Bissonnette and Pigeon [11] who showed that the silica fume concrete exhibited a greater creep deformation when loaded at early ages.

At this stage, we do not have a satisfactory explanation for the higher creep at early age in the silica fume concrete. This is a topic which needs additional studies. Perhaps it has to do with influences of early age autogenous shrinkage on the structure of silica fume concrete which may not be as rigid as one would expect on the basis of the low w/b ratio [12,13].

5. Conclusions

1. The restraint to autogenous shrinkage at early ages generated a relatively high internal stress in high-strength concrete. The induced stress/strength ratio could exceed 50%, and at this level it may cause a premature tensile failure.
2. The continuous restraint to autogenous shrinkage starting at very early ages induced a large creep strain in the high-strength concretes. This creep behavior significantly contributed to the reduction in the stress expected to develop in the high-strength concrete.
3. Lower w/b ratio of concrete resulted in a higher creep strain.
4. The silica fume concrete exhibited a greater creep tendency than that of a plain concrete in restrained shrinkage conditions. This behavior may be typical to loading at very early ages, and is different than the trend reported in literature for matured concretes.

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