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Meniscus Effects and Fracture in Portland Cement Paste

by J.J. Beaudoin

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ABSTRACT

On the basis of results of fracture mechanics experiments at different humidities, it is suggested that meniscus forces generated by drying of portland cement paste contribute to crack growth processes.

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RÉSUMÉ

Se basant sur les résultats d'expériences de mécanique de la rupture réalisées à différents degrés d'humidité, l'auteur avance que l'action des ménisques due au séchage de la pâte de ciment Portland contribue aux processus intervenant dans l'allongement des fissures.

Meniscus effects and fracture in Portland cement paste

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Recent studies have indicated that relative humidity, temperature, and stress corrosion in crack tip regions are among the factors that influence crack growth of Portland cement paste [1-3]. Several suggestions regarding crack growth mechanisms have been advanced, including one that meniscus forces have a significant effect. This letter presents the results of fracture mechanics experiments designed to clarify the role of meniscus effects in the fracture process.

Crack growth experiments were carried out on both cement paste and porous glass systems (Vycor glass was supplied by the Dow Corning Co, USA; porosity was 28% and surface area $175 \times 10^3 \text{ m}^2 \text{ kg}^{-1}$). Two test geometries — simply supported, centrally loaded notched beams, and double-torsion (DT) specimens — were used to obtain critical stress-intensity factor (K_c) data and crack velocity against stress-intensity factor ($V-K_I$) curves. Test beams were $12 \text{ mm} \times 1.27 \text{ mm} \times 75 \text{ mm}$ long for the paste and $6.4 \text{ mm} \times 6.4 \text{ mm} \times 75 \text{ mm}$ long for porous glass. The mid-span notch was 0.25 mm wide by half the specimen depth. DT specimens for paste were $38 \text{ mm} \times 76 \text{ mm} \times 1 \text{ mm}$ thick, with a $1.5 \times 0.5 \text{ mm}$ deep centrally located guide groove along the length. The glass specimens were 6 and 8 mm thick and the guide groove was half the specimen depth. The test procedures have been described previously [4-6]. All tests were performed at 22°C in an environment chamber mounted in an Instron machine. Care was taken to avoid carbonation of the cement samples.

Stress-intensity factor is plotted against relative humidity for cement paste in Fig. 1. As drying proceeds from the saturated condition, K_c and $\bar{K}_I$ (median value of K taken from each $V-K_I$ curve, not presented) increase in both curves to a maximum at 32% r.h. This is followed by a decrease in K as humidity decreases

Figure 1 Stress intensity factor—relative humidity curves for Portland cement paste [1, 5]. W/C = 0.35. (---) Double torsion specimen, (—) notched beam specimen.

further to 11% r.h. Finally, K increases from 11% r.h. to the dry state.

Qualitatively, both test geometries provided similar results for the porous glass system (Fig. 2); each plot point represents the average obtained from at least three specimens. The dry state for the double torsion specimens was difficult to achieve because the majority of the samples cracked. Two were obtained with no apparent crack, however, and the plot point represents the results from these samples. K -adsorption data were obtained by drying to 32% r.h. and rewetting to the desired humidity. On desorption, the curves exhibit maxima at about 75% r.h. K decreases as humidity is lowered to about 60 to 70% r.h. It then increases until the dry state is reached. No maxima can be observed on the adsorption cycle. Non-porous glass does not exhibit a maximum on desorption [7]. That between 60 and 85% r.h. in the compressive strength—relative humidity curve for porous glass has already been reported by Hiller [8].

Figure 2 Stress intensity factor—relative humidity curves for porous glass. Curve 1, notched beam specimens: (O) desorption, (●) adsorption. Curve 2, double torsion specimens: desorption (O) 8 mm specimen, (□) 6 mm specimen; adsorption (■) 6 mm specimen.

Figure 3 Weight change isotherms for (1) porous glass and (2) cement paste (reversible isotherm) [9, 10]. W/C = 0.50.

Weight change and length change isotherms for porous glass and cement paste are sketched in Figs 3 and 4 [9, 10]. The cement paste isotherm has been separated by Feldman into "reversible" and "irreversible" components [10]. The reversible isotherm sketched in Figs 3 and 4 does not include the effects of interlayer water. The primary hysteresis loops (weight change) close at about 60% r.h. for glass and at 32% r.h. for cement paste. These relative humidities are close to those for which maxima occur in the K -r.h. curves for glass and cement paste.

Length change on desorption exceeds that for adsorption (in the region of primary hysteresis); contraction changes to expansion at 70% and 40% r.h. for glass and paste, respectively. Length change reversal on drying of paste has also been observed [11]. On further drying, contraction resumes at 60% and 32% r.h.

Length change reversal on drying of porous glass has been associated with meniscus rupture [9]. The meniscus effects are associated primarily with the desorption branch of these hysteresis loops. On adsorption (60 to 80% r.h.) there is only a small increase in the length of the porous glass owing to a compensation of forces arising from both capillary

Figure 4 Length change isotherms for (—) porous glass and (---) cement paste [9, 10].

condensation and continued adsorption. On desorption, it is thought that the two processes can be separated and that between 60 and 70% r.h. pores empty by evaporation from concave menisci [9] so that expansion results.

On the basis of such arguments and noted similarities between porous glass and cement paste, it is suggested that meniscus forces generated by the drying of Portland cement paste contribute to crack growth processes in this system.

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