DAMAGE OF THE PARTICULATE COMPOSITE DUE TO THERMAL INTERNAL STRESSES

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The present paper focuses on analytical and experimental investigation of particulate composite deterioration due to internal thermal stresses. The most common example of a particulate composite is plain concrete. In this type of material cracks appear at the interface of aggregate and cement paste because of the mismatch of the coefficients of thermal expansions. Taking into account the presence of cracks, Young's modulus as a function of temperature is obtained analytically and experimentally.

INTRODUCTION

It is widely accepted that there are three types of composite materials: Fibrous composites which consist of fibers in a matrix, Laminated composites which consist of layers of various materials, and Particulate composites which are composed of particles in a matrix. The subject of this paper are the particulate composites. The particles can be either metallic or nonmetalic as can the matrix. Our consideration will be focused on nonmetalic particle in a nonmetalic matrix. The most common example of this type of composite material is plain concrete. Concrete is made from particles of sand and rock that are bound together by a mixture of cement and water that has chemically reacted and hardened. Young's modulus of aggregate and cement paste are nearly the same, but coefficients of thermal expansions (CTE) are different. Usually α_a, CTE of aggregate is lower than α_c, CTE of concrete. This mismatch causes the tensile stresses at the boundary of aggregate and cement paste and cracking. In other words this cracking is the consequence of Thermal Incompatibility of Concrete Components (TICC).

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AGGREGATE AS A THERMAL INCLUSION

The problem of the aggregate as a thermal inclusion (Fig.1) should be first solved for the purpose to find the damage of the material containing components with different CTE. Due to temperature increase $\theta = T - T_0$ the stress in both aggregate and cement paste would occur, because of the mismatch of the CTE $\alpha_a < \alpha_c$. Compatibility condition for radial displacement at the boundary of aggregate and cement paste is satisfied if it is

$$\delta_{10}^{I} + \delta_{11}^{I} = \delta_{10}^{II} + \delta_{11}^{II}, \tag{1}$$

where δ_{10}^{I} and δ_{11}^{I} are the displacements in the region I due to temperature increment θ and the unknown radial stress $\sigma_{rr}(r = R) = X_1$ respectively. Coefficients δ_{10}^{II} and δ_{11}^{II} are displacements in the region II due to same influences as in the portion I. It is known from elasticity that the coefficients in the equation (1) can be found as,

$$\delta_{10}^{I} = \alpha_a R\theta;\ \delta_{11}^{I} = \frac{X_1}{E}(1-\nu)R;\ \delta_{10}^{II} = \alpha_c R\theta;\ \delta_{11}^{II} = -\frac{X_1}{E}(1+\nu)R \tag{2}$$

where R is the radius of the aggregate. Substituting (2) into (1) it is obtained,

$$X_1 = \frac{1}{2}E(\alpha_c - \alpha_a)\theta \tag{3}$$

which is tensile as is assumed. Once the expression (3) is known it is easy to obtain the stresses in the aggregate and cement paste.

BODY WITH THE SMALL CIRCULAR CRACKS

The stress obtained in the preceding section would cause the cracking on the interface between the aggregate and the cement paste. In this paper assumption of the small circular crack (small in comparison with the radius of the aggregate) would be considered (Fig.2). From the paper, Cotterell and Rice (1), the stress intensity factors for a slightly curved crack are:

$$K = K_I - iK_{II} = \frac{1}{\sqrt{\pi a}}\int_{-a}^{a}(q_I - iq_{II})\sqrt{\frac{a+t}{a-t}}dt, \tag{4}$$

where q_I and q_{II} in our case are given by:

$$q_I = \frac{E(\alpha_c - \alpha_a)}{2}\theta = \sigma_{rr};\quad q_{II} = \frac{1}{2}\alpha\frac{E(\alpha_c - \alpha_a)}{2}\theta = \frac{1}{2}\alpha\sigma_{rr}. \tag{5}$$

Substituting (5) into (4) finally it is obtained,

$$K_I = \sigma_{rr}\sqrt{\pi a};\qquad K_{II} = \frac{1}{2}\alpha\sigma_{rr}\sqrt{\pi a}. \tag{6}$$

Strain energy release rate from stress intensity factors can be calculated as,

$$G = \frac{K_I^2 + K_{II}^2}{E} = \pi a \frac{(\sigma_{rr})^2}{E}(1+\frac{\alpha^2}{4}) = \pi a \frac{(\sigma_{rr})^2}{E}(1+\frac{a^2}{4R^2}). \quad (7)$$

To examine the propagation of the crack, the resistance or $\Re$ curve is needed. Without the real values for the $\Re$ curve, for the interface circular crack between the aggregate and the cement paste, it will be assumed,

$$\Re = R^2 C^2 \pi \frac{(a-a_0)^2 a}{R^2}(1+\frac{a^2}{4R^2}), \quad (8)$$

where C is constant to be determined from the experimental results. Equating expression (7) and (8) the size of the crack as a function of temperature is obtained,

$$a = a_0 + \frac{\sqrt{E}(\alpha_c - \alpha_a)}{2C}\theta. \quad (9)$$

If the size of the crack is known, then the increase of the compliance due to presence of one crack can be determined. From the reference (1), for small circular crack ($\alpha \to 0$), the stress intensity factors under plane stress state are,

$$K_I = \sqrt{\pi a}\left(\sigma_2' - \frac{3}{2}\frac{a}{R}\sigma_6'\right); \qquad K_{II} = \sqrt{\pi a}\left[\sigma_6' + \left(\sigma_2' - \frac{\sigma_1'}{2}\right)\frac{a}{R}\right]. \quad (10)$$

Potential energy increase is then,

$$\psi^{*(k)} = \int_{-a}^{a} \frac{K_I^2 + K_{II}^2}{E} da. \quad (11)$$

The increase of the compliance due to presence of one crack are obtained by differentiating the expression (11) with the governing stresses,

$$S_{ij}^{*(k)'} = \frac{\partial^2 \psi^{*(k)}}{\partial \sigma_i' \partial \sigma_j'}. \quad (12)$$

The expression (12) is given in the local coordinate system. Using transformation rule as is shown in the paper, Sumarac and Krajcinovic (4), the increase of the compliance due to presence of one crack in the global coordiante system is obtained. For ensemble of cracks the total compliance would be,

$$S_{ij}^* = N \int_{R_{min}}^{R_{max}} \int_{\phi_{min}}^{\phi_{max}} S_{ij}^{*(k)}(R,\theta) p(R) p(\theta) dR d\theta. \quad (13)$$

In the above expression N is the total number of cracks per unit area while p(R) and p(ϕ) are the uniform distribution functions of the radius size and orientation of the crack respectively. Total compliances allows the additive decomposition, Krajcinovic and Sumarac (3), i.e.

$$\overline{S}_{ij} = S_{ij} + S_{ij}^* \quad (14)$$

where S_{ij} is the compliance of the undamaged material, and S^{*}_{ij} stands for the increase of the compliance due to presence of all cracks and is given by (13).Transforming (12) and substituting obtained results into (13) for S^{*}_{11} it is obtained

$$S^{*}_{11} = \frac{\omega}{E}\left(1+\frac{a^2}{R_{max}R_{min}}\right), \qquad (15)$$

where $\omega = N\pi a^2$ is the measure of the damage se (Krajcinovic (2), and (4)). From (9), (14) and (15) taking for $S_{11}=1/E$ it follows,

$$\frac{\bar{E}}{E} = \left[0.911 + 0.086(1+0.008333\theta)^2 + 0.003(1+0.008333\theta)^4\right]^{-1}. \qquad (16)$$

Following values were taken in deriving expression (16): $C = 60\sqrt{E}(\alpha_c - \alpha_a)/a_0$ (MN/m3), N=7500 cracks/m^2, α_c=25.4x10^{-6}(^{0}C)$^{-1}$, α_a=11.9x10^{-6}(^{0}C)$^{-1}$ and R_{min}=0.4cm, R_{max}=3.1cm (obtained from the grading curves and aggregate mix). The initial, average length of crack is taken to be a_0=0.2cm. The expression (16) is valid only for θ = T-T_0 >0, where T_0=20^{0}C. For temperature T=20^{0}C (referent temperature) the material is undamaged.

EXPERIMENTAL RESULTS

To verify the theoretical results explained in the preceding section the authors planed the experimental tests for this research to comprise the thermal treatment of two series of specimens produced of concrete with two different aggregates. First group specimens, marked CL, was made of concrete with crashed limestone aggregate and with the second marked as RA river aggregate was used. Both series consisted of 10 samples: 8 prisms 12x12x36cm marked as CL1 to CL8 and RA1 to RA8 and 2 independent referent specimens (prism and a cube). Six specimens in each series were thermally treated by exposing them to the following elevated temperatures: 20, 55, 90, 125 and 160^{0}C. Thermal treatment commenced at 180 days concrete age and was performed in "Hereaus-Vatsch" VUK 500 climatic chamber. Procedure was completely the same for both groups-series of specimens. The measuring was performed by nondestructive methods, and it was focused on Resonant frequency (f). The dynamic modulus of elasticity is calculated as,

$$E=4\gamma f^2 l^2 \text{ (MPa)} \qquad (17)$$

where γ is density of concrete (kg/m^3), f-resonant frequency (Hz) and l length of specimen (m). Resonant frequency data were obtained by CNS-electronic "EURIDITE" equipment. Results obtained from the expression (17) and from the measured values for the dynamic modulus of elasticity are presented in Figure 3 (in dimensionless form) together with the theoretical results obtained from the expression (16). It is evident that the agreement is quite well in the whole range of investigated temperatures. The discrepancy between theoretical and experimental results is less than 3%. From Figure 3 it can be noticed that concrete made with the river aggregate showed a slightly slower degradation rate. At the end of thermal treatment (160^0C) E decreased for concrete with RA for 25,4% while for concrete with CL for 27,2%. It should be said that such droop of Young's modulus is a little bit unexpectable as temperatures up to 160^0C are not considered to be high for concrete. Finally it can be concluded that this study, theoretically and experimentally confirms that the moderate temperature change causes substantial degradation of concrete.

SYMBOLS USED

E = Young's modulus

S_{ij} = compliance tensor

ω = damage parameter

a = crack length

R = radius of the aggregate

θ = temperature increment

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REFERENCES

(1) Cotterell,B. and Rice, J.R., I.J.Fract., Vol. 16, 1980, pp.155-169.

(2) Krajcinovic,D., Mech. Mater., Vol. 8, 1989,pp.117-197.

(3) Krajcinovic, D. and Sumarac, D.,J. Appl. Mech.,Vol.56,1989, pp.51-56.

(4) Sumarac, D. and Krajcinovic, D.,J. Appl. Mech.,Vol.56, 1989,pp.57-62.

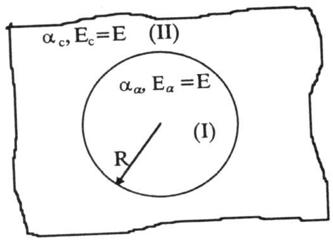

Figure 1 Aggregate as a thermal inclussion

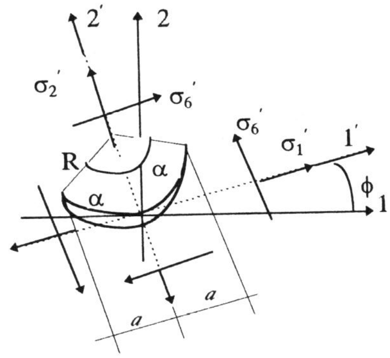

Figure 2 Circular crack in local and global coordinate system

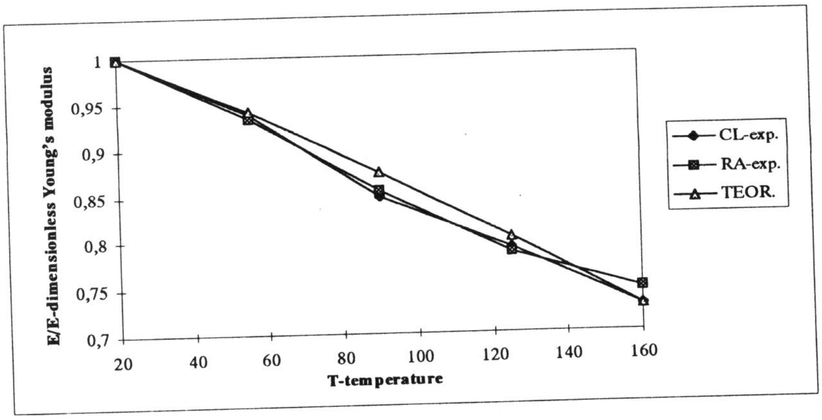

Figure 3 Young's modulus decrease-theoretical and experimental results