MODELLING THE ELASTIC BEHAVIOUR OF REFRACTORY CONCRETE REINFORCED WITH GLASS FIBRES

MICHAL PŘIBYL, VÁCLAV ŠEVČÍK, JAROSLAV KUTZENDÖRFER

Department of Glass and Ceramics,
Institute of Chemical Technology, Technická 5, 166 28 Prague

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Composites based on hardened alumina cement pastes reinforced with 3 to 10 wt.% of glass fibres were prepared for the purpose of increasing the bending strength of the refractory concrete at 500 °C - 1000 °C. On the basis of measuring Young's modulus and Poisson'constant of the model reinforced material (water-to-cement ratio 0.30, 5 wt.% of fibres) at 20 °C, a simple isothermic mechanical model was proposed, on the basis of Hook's law for a linear elastic continuum. The model describes the development of stress in the loaded material in the course of uniform compression up to the elasticity limit.

INTRODUCTION

Concrete alone is a naturally strong material; however, it is liable to fail by brittle fracture under load and this property is disadvantageous for many applications. The character of fracture can be changed by incorporating glass fibres in the concrete, while at the same time increasing the bending strength.

Shah and Ouyang [1] found that an addition of glass fibres improves significantly the tensile strength of the cement matrix. There are additional positive effects of glass fibres on the mechanical properties of the cement-based matrix, e.g. as summarized succinctly by Hannat [2]:

a) increase in tensile and bending strength and toughness,
b) increase in impact strength,
c) change in the original character of fracture and fracture behaviour,
d) reduction of apparent weight,
e) change in the rheological properties and flow characteristics of the cement pastes.

Information from the available literature indicates that the relations between the content of incorporated fibres and the bending strength of composites based on alumina cement and glass fibres have not yet been dealt with. This is why the present authors' study was oriented at this subject.

EXPERIMENTAL

For all of the experimental measurements, the specimens were prepared from the Fondu Lafarge alumina cement (Table I), using water ratios of 0.25 and 0.30, and 0 % to 10 wt.% of glass fibres. The Cem-FILL glass fibres (Table II) were added to the cement paste in the form of cut slivers, where a sliver contained about 200 intertwisted fibres coated with the lubricant. In the course of mixing the fibres get gradually apart and form a homogeneous random-oriented mixture with the paste. The quality of the dispersing was assessed visually on fracture surfaces. under the optical microscope.

Following the setting, hardening and drying at 20 °C, the test specimens in the form of parallelepipeds were tested by compression and three-point bending at 20 °C after previous 6-hour drying at 300 °C, 500 °C, 800 °C and 1000 °C. The dimensions of the test specimens for the determination of strength, material properties and for modelling are listed in Table III.

The mechanical properties of the reinforced cement pastes were established according to the standards for the testing of cement [6], with the use of the Amsler 5 MN hydraulic tester, controlled by the PDP 11/34 processor and fitted with the Peekel Instruments' Autolog and Dynalog measuring logger. The longitudinal deformations were measured by a couple of induction sensors of 1mm range on the base 150 mm in length, while the transverse deformation was measured by one induction sensor at the plane of the blades of the longitudinal sensors. The induction sensors had a sensitivity of 1 m m^{-1}. Following their preparation (Table IV), the test specimens 100/100/400 mm in size were provided with a 1.5 mm coating of a molten mixture of sulphur, fly-ash and silica sand. For the sake of comparison, all of the measurements were also carried on non-reinforced paste prepared with the same water ratio.

The strength of reinforced cement paste specimens - evaluation and discussion of results

Series of reinforced specimens were prepared by adding 0 - 10 wt.% of fibres to alumina cement pastes with specific water ratios. The reinforced specimens exhibited higher bending and lower compressive strengths compared to the non-reinforced ones.

Table I. Chemical composition of the Fondu Lafarge alumina cement

	Main components [wt.%]			
	Al_2O_3	CaO	SiO_2	Fe_2O_3 + FeO
Typical mean values	38 - 40	37 - 39	3 - 5	15 - 18
Limit values	>37	<41	<6	<18.5

Table II. Chemical composition of the fibres

Composition	SiO_2	ZrO_2	Na_2O	Al_2O_3	TiO_2, Fe_2O_3, CaO, K_2O
(wt.%)	70.27	16.05	11.84	0.24	<0.07

Table III. Dimensions of the specimens

Type of measurement	Paralellepiped dimensions [mm]
Determination of strengths	20*20*100
Det. of material properties	100*100*400
Modelling	40*40*160

Table IV. Treatment of test specimens

Medium	Time	Temperature
Moulds	24 hours	20 °C
Water	6 days	20 °C
Oven	24 hours	110 °C

Figure 1 demonstrates the effect of strengthening by the fibres for pastes with a water ratio of 0.25. The experimental results have borne out the information on improving the bending strength by incorporation of fibres, and in addition to this, the fibre reinforcement was shown to be effective even above the temperature of decomposition of the hydraulic minerals. The highest strengthening was obtained with pastes containing 7 wt.% and 10 wt.% of fibres at temperatures of 800 °C and 1000 °C.

The strengthening of pastes having a water ratio of 0.30 was similar to that shown in Figure 1.

For the sake of completeness it should be noted that in the case of compressive strength the additions of fibres tend to have the opposite effect, as the compressive strength is closely related to apparent density which decreases with the amount of fibres added. At 20 °C, the compressive strength of reinforced paste is lower by about 50 %, and at 1000 °C, by about 30 % compared to the non-reinforced paste.

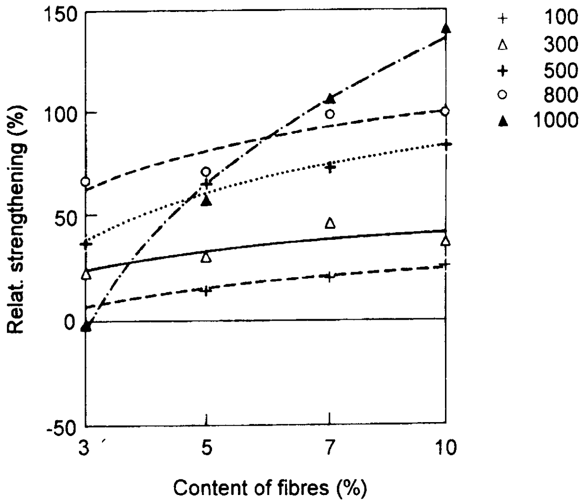

Figure 1. Increase in strength vs. the content of fibres

MECHANICAL PROPERTIES

On using a wider approach to the study of the stress development process in terms of deformation on hardened pastes reinforced with random-oriented fibres, it appears useful to consider the mixtures as homogeneous isotropic continua and to classify them, with respect to the character of their deformation, into the group of so-called composites II which contain high-modulus fibres with a weak bond to the matrix (Marshall [4]).

Having introduced the assumption of a linear elastic response of the composite to acting stress, we may utilize generalized Hook's law in the component tensor form to describe the stress-strain relationship (Brdička [5]):

$$t_{ij} = c_{ijkl} \cdot e_{kl} \tag{1}$$

On assuming the continuum to be isotropic, the relationship can be simplified to the form allowing Lamé's constants λ and μ to be included [5]:

$$t_{ij} = \lambda\delta_{ij}\, e_{kk} + 2\,\mu e_{ij} \tag{2}$$

The constant can be calculated by means of simple relationships, using the experimentally established values of Young's modulus E and Poisson's ratio σ [5]:

$$\lambda = E\sigma/(1+\sigma)(1-2\sigma)\ \mu = E/2(1+\sigma). \tag{3}$$

Modelling of mechanical properties - results and discussion

The process of deformation of the model reinforced paste (w/c=0.30, 5wt.% of fibres) can be described by Equation (2):

$$t_{ij} = 29.15\ \delta_{ij} e_{kk} + 18.88\ e_{ij}, \qquad (4)$$

where the Lamé's constants were calculated by means of Equations (3) and are given in GPa on the assumption of meeting the requirement of linear elasticity (Figure 2). Suitable workability and homogeneity of the model paste were the decisive criteria of its formulation. Table V lists the material constants of the reinforced and non-reinforced pastes.

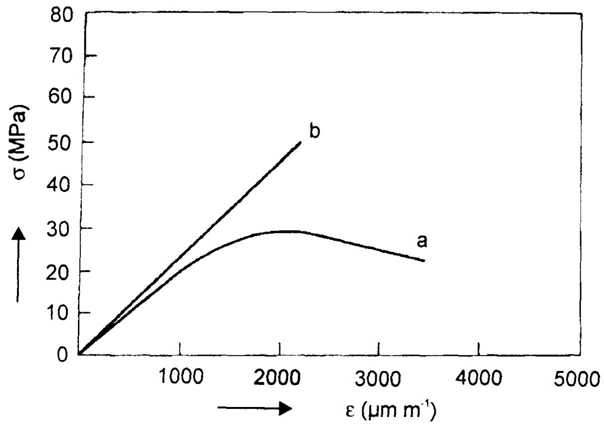

Figure 2. Relative longitudinal deformations measured across the length of base u
a) reinforced pastes, *b*) non-reinforced pastes

Table V. Material constants of pastes

Test mix	Compressive strength (MPa)	Young's modulus (GPa)	Poisson's ratio (-)
1	29.9	22.21	0.176
2	56.8	23.66	0.140

Test mix 1: w/c = 0.30, 5 wt.% of fibres
Test mix 2: w/c = 0.30

The deformation and failure processes of the two types of material are quite different: with the reinforced paste, the deformation proceeds in a plastic way (Figures 2*a* and 3*a*) and failure takes place over an oblique shear area, whereas with the non-reinforced paste the failure occurs by brittle fracture over a longitudinal fracture plane, accompanied by an explosive release of the accumulated energy (Figures 2*b* and 3*b*). Figure 4 shows the course of relative volume strain vs. stress (Figures 4*a* and 4*b*).

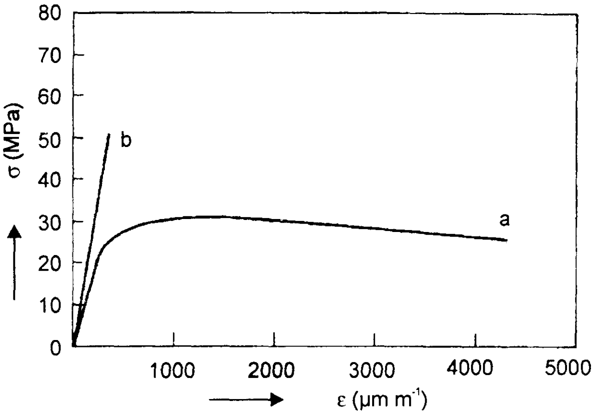

Figure 3. Relative transverse deformations of
a) reinforced pastes, *b*) non-reinforced pastes

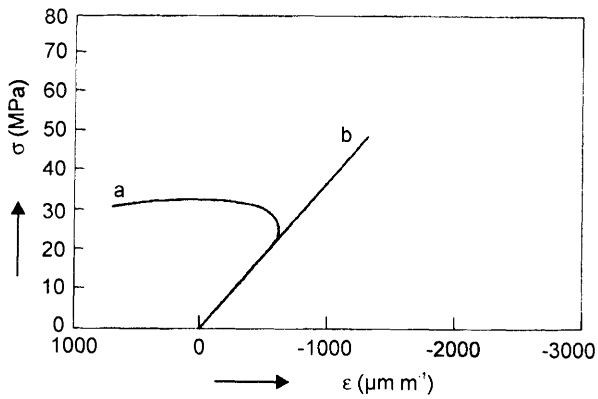

Figure 4. Relative volume deformations of
a) reinforced pastes, *b*) non-reinforced pastes

CONCLUSION

It may be concluded that the results obtained indicate a progressive increase in bending strength of the cement matrix in terms of the amount of glass fibres incorporated. From the standpoint of mechanics, the reinforced cement pastes exhibit a linearly elastic character of deformation; it is desirable to achieve the best possible dispersion of the fibres in the cement paste.

The isothermal model worked out for 20 °C represents just the first step of the envisaged stress-strain study of reinforced cement pastes. Calculations of the state of stress for a wider temperature interval require a thermoelastic model to be composed so as to be able to predict the development of mechanical properties of reinforced cement pastes in the course of their thermal exposure. The model example described above thus only represents an introduction to the application of mathematical modelling to refractory materials employed in cast-in-situ construction of kilns and furnaces. The subject matter will have to be further expanded to cover thermal and mechanical loading occurring under actual operating conditions.

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MODELOVÁNÍ ELASTICKÉHO CHOVÁNÍ CEMENTOVÝCH PAST VYZTUŽENÝCH CEMENTOVÝMI VLÁKNY

MICHAL PŘIBYL, VÁCLAV ŠEVČÍK, JAROSLAV KUTZENDÖRFER

Ústav skla a keramiky,
Vysoká škola chemicko technologická,
Technická 5, 166 28 Praha

Byly připraveny kompozitní cementové pasty na bázi hlinitanových cementů a alkalivzdorných skleněných vláken o vodních součinitelích *v/c*: 0,25, 0,30 a obsazích vláken 0 - 10 hmot.%. Vmícháním vláken do hlinitanového cementu byl připraven homogenní kompozitní vláknitý materiál s náhodným rozmístěním a orientací vláken.

Zkušební vzorky tvaru kvádru byly testovány v trojbodém ohybu a tlaku při 20 °C po šestihodinové expozici na 300, 500, 800 a 1000 °C. Zvýšení pevnosti v ohybu záviselo na obsahu vláken a teplotě expozice. Nejvyšší účinnosti vláknité výstuže bylo dosaženo ve směsích vyztužených 7 a 10 hmot.% vláken při teplotách 800 a 1000 °C. (obrázek 1).

K popisu mechanického chování uvedené modelové pasty bylo použito teoretického modelu vytvořeného postupem mechaniky kontinua. Experimentálně naměřené závislosti napětí na deformaci (obrázky 2 a 3) a obrázek 4 pro vybranou modelovou pastu (*v/c* = 0,30, 5% vláken) potvrdily předpoklad, že celá řada kompozitních žárobetonů se v elastické oblasti chová jako izotropní elastické kontinuum.

Pokud předpokládáme izotropii, t.j. nezávislost charakteru elastického přetváření na směru působícího zatížení, přetváření modelové soustavy (závislost napětí na deformaci) lze popsat Hookovým zákonem pro izotropní elastické kontinuum s konkrétními hodnotami konstant ve tvaru:

$$t_{ij} = 29{,}15\ \delta_{ij}\ e_{kk} + 18{,}88\ e_{ij}$$

Tento vztah popisující tvar závislosti napětí na deformaci při normální teplotě je nepřenosný na odlišné složení kompozitní cementové pasty a jinou teplotu.