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MONITORING OF CRITICAL LENGTH OF CRACK-LIKE DEFECTS IN THE PLATE BONE CEMENT BECAUSE OF THEIR DIFFERENT GEOMETRY

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The article deals with structural elements of materials made of bone cement coupons of various impurities: diethylaminoethylacrylate, dimethylaminoethyl methacrylate and diethylaminoethyl methacrylate. Considering the stress intensity factor the characteristics of fracture factors with different soaking time intervals in simulated body fluid (0; 3; 6 months) and also with different impurities in fixed material (2…10 wt%) are presented. The data for the stress intensity factor used in the constructed models for different structural elements, allowing us to analyze the possible risk of such elements, provided that they contain crack-likes defect are given. Also the values of the critical length of each considered crack-like defect and calculated number of loading cycles in this object, that can be useful for engineering recommendations for the test material and concrete structural elements made from this material, are obtained.

Keywords: *bone cement, crack defect, different geometry, stress intensity factor, engineering advice, monitoring.*

Bone cements have been used clinically for a number of years in orthopedic surgery for the fixation of artificial joints with encouraging results [1]. Also in [2] the effect of the incorporation of comonomers containing amine groups on the mechanical and fracture properties of acrylic bone cements was studied. Cements were prepared with eitherdiethylaminoethylacrylate (DEAEA), dimethylaminoethyl methacrylate (DMAEM) or diethylaminoethyl methacrylate (DEAEM) as comonomers in the liquid phase. It was found that the strength and Young's modulus decreased with increasing comonomer content in the bending and compressive tests. It was also observed that fracture toughness is the critical value of the stress intensity factor (SIF) (K_{Ic}). These properties of cements were also evaluated after soaking the specimens in simulated body fluid (SBF) for 0, 3 and 6 months.

Application of fracture mechanics is impossible without having reliable criteria for evaluation of the crack-like defect length. This issue has received much attention. Different effects that affect the value of such criteria were studied. However, this work has not been completed, because in most countries there are no standards for determining the criteria of linear and nonlinear fracture mechanics of concrete. Existing theoretical solutions, which can estimate the stress distribution ahead of the crack-like defect, are very complex and cumbersome. In engineering practice their use is associated with considerable difficulties. Therefore one should look for relatively simple, even approximate solutions or models that would simulate criterion approaches to engineering estimates of the objects that contain defects [3].

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Object of investigation. A plate of sizes 3×10×75 mm made of bone cement, containing crack-like defects in its central part, are studied. The cases where the defect is located exactly in the center of the plate (case I), as well as the cases where the eccentricity defects are located slightly off-center plate (case II) are considered.

Using obtained in [2] values of the stress intensity factors (Table 1) and analytic models of structural elements in [4] the calculated values of the critical length of the crack-like defect, some models of structural elements containing a defect, are proposed. On the basis of these models the critical values a_{fc} for a crack-like defect are given. These critical values a_{fc} are given for three materials. The experimental bone cements were formed by adding the liquid component to the solid (powder) component at room temperature (25°C). The powder component consisted of Nictone beads, benzoyl peroxide and barium sulfate ($BaSO_4$) while the liquid component consisted of methyl methacrylate (MMA) (as the base monomer), dimethyl propiathetin and either DEAEA, DMAEM or DEAEM at 2; 4; 6 and 10 wt%; these quantities were incorporated by partial replacement of MMA in the liquid phase.

Table 1. Values of the K_{Ic} in SBF of acrylic bone cements with different soaking time [2]

Material	%	Soaking time in SBF, months		
		0	3	6
DEAEA	2	1.54	1.66	1.65
	4	1.54	1.62	1.76
	6	1.66	1.68	2.03
	10	1.83	1.56	1.51
DMAEM	2	1.38	1.62	1.9
	4	1.76	1.75	1.00
	6	1.75	1.15	1.41
	10		0.76	1.49
DEAEM	2	1.27	1.96	1.85
	4	1.36	1.54	1.96
	6	1.44	1.66	1.89
	10	1.75	1.95	1.83

The above methodology was applied in different cases of location of a plate containing a crack. Below there are the analytical expressions for calculating the SIF for each model according to which the critical crack length was identified.

Defect I: finite width plate containing two-dimensional centered cracks under bending [2, 3] (Fig. 1*a*):

$$K_{\mathrm{I}} = \frac{6M}{tW^2}\sqrt{\pi a}F_{\mathrm{I}}(\alpha), \tag{1}$$

where $\alpha = \frac{2a}{W}$; $F_{\mathrm{I}}(\alpha) = \alpha\frac{\sqrt{1-\alpha}}{1-\alpha^3}\left(1+\frac{1}{2}\alpha+\frac{3}{8}\alpha^2-\frac{11}{16}\alpha^3+0,464\alpha^4\right)$.

Defect II: finite width plate containing two-dimensional eccentric cracks under uniform tension [2, 4] (Fig. 1*b*):

$$\{K_{\mathrm{I}}\}_A = \sigma\sqrt{\pi a}\{F_{\mathrm{I}}(\alpha,\beta)\}_A, \tag{2}$$

where $\alpha = \dfrac{2a}{W-2e}$; $\beta = \dfrac{2e}{W}$; $\{F_{\mathrm{I}}(\alpha,\beta)\}_A = \sqrt{\sec\left(\dfrac{\pi\alpha}{2}\right)\cdot\dfrac{\sin(2\alpha\beta)}{2\alpha\beta}}$.

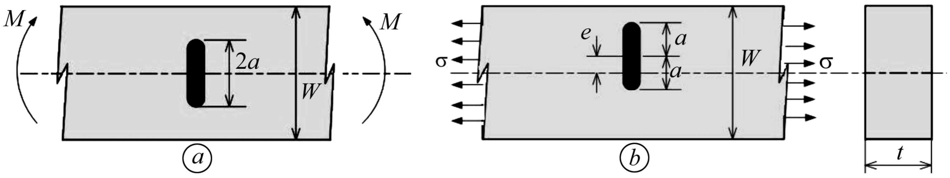

Fig. 1. Defect I: finite width plate containing two-dimensional centered cracks under bending (*a*) and defect II: finite width plate containing two-dimensional eccentric cracks under uniform tension (*b*): 2*a* – crack length; *t* – plate thickness; *W* – plate width; *M* – bending moment; *e* – crack eccentricity; σ – tension.

Result and discussion. For the better analysis of the results the diagrams of critical length of the crack-like defect, depending on the number of months, are obtained. The analysis of Fig. 2 shows the improved fracture toughness of the material, namely increasing length of the crack-like defects with increasing soaking time of the material. However, this trend is clearly observed only for products DEAEA and DEAEM. For the third material DMAEM the trend is different, which needs more research on this material.

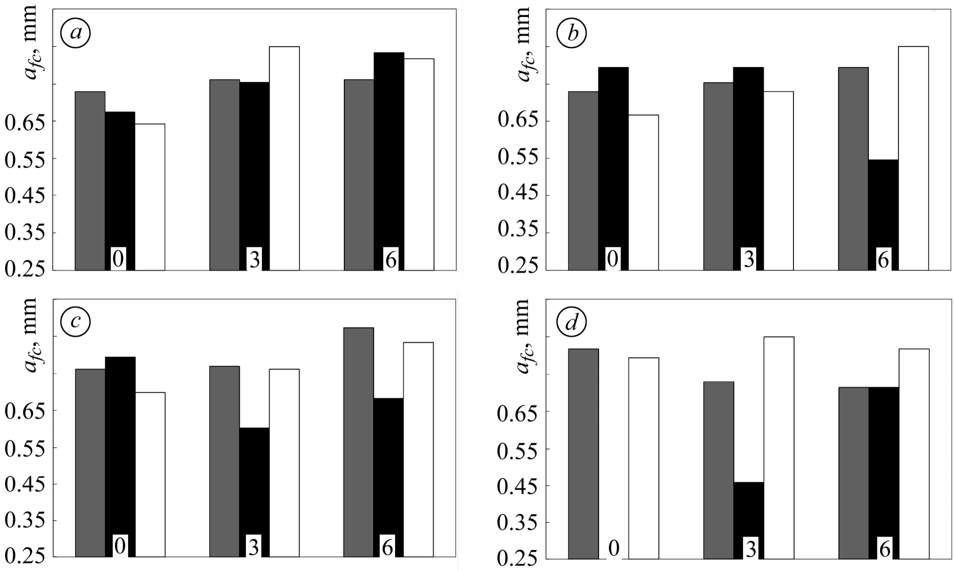

Fig. 2. Critical crack length (defect I) for materials DEAEA, DMAEM and DEAEM at 20 MPa for 2 wt% (*a*), 4 (*b*), 6 (*c*), and 10 wt% (*d*): *1* – DEAEA; *2* – DMAEM; *3* – DEAEM.

Let us to consider the effect of additives of DEAEA and DEAEM on bone cement critical length of a crack-like defect (Fig. 3). Bone cement with 4% DEAEA has the smallest crack development resistance and is the most stable at 6% content of DEAEM. The following trend should be noted: a critical crack length in the bone cement sample changes more dramatically after soaking in SBF for the period of 3…6 months than for 0…3 months of exposure. The bone cement sample with 4% DEAEM is more prone to fracture in the period of 0…3 months of soaking and its a_{fc} value dramatically increases in the case of 3…6 months exposure as well. This occurs both at loads of 20 and 25 MPa (Fig. 3).

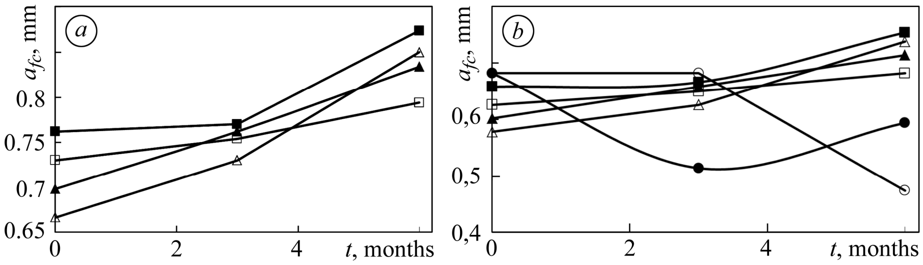

Fig. 3. Critical length of a crack-like defect (defect I) depending on soaking time for DEAEA, DMAEM and DEAEM at 20 MPa (*a*) and 25 MPa (*b*): □, ■ – 4 and 6% DEAEA; △, ▲ – 4 and 6% DEAEM; ○, ● – 4 and 6% DMAEM.

Similar trends are observed in principle for all models under consideration. Therefore, in this paper a detailed analysis of the critical length of the crack-like defect for materials DEAEA and DEAEM is presented.

Now let us analyze the behavior of defects of different geometry a_{fc} in the studied models. In the second simulated case the defect is not in the center of the design elements and is at a small distance *e* from center of plate. The cases of different values of *e* ranging from 0.05 mm to 2 mm are discussed. The distance of more than 2 mm was not considered. Analysis of the results showed that the most dangerous case is when the defect is more remote from the design elements. It should be also noted that in the case of 6 wt% DEAEA and 6 months of soaking the fracture toughness is significantly higher than in all other cases. Regarding this fact DEAEM showed in both studied cases the percentage of 4 and 6 wt% (Fig. 4).

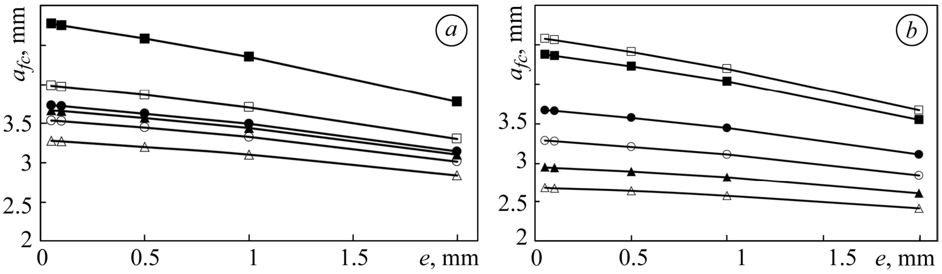

Fig. 4. Critical length of the defect (defect II) depending on eccentricity of the defect for materials DEAEA (*a*) and DEAEM (*b*) at 20 MPa: △, ▲ – 4 and 6%, 0 month; ○, ● – 4 and 6%, 3 month; □, ■ – 4 and 6%, 6 month.

Using fracture mechanics approach the value of the critical crack-like defect length is proposed for engineering evaluation.

The final value of the critical defect length is shown in Table 2 for each examined case. This table presents the length of the defect in the considered case, after reaching which its growth may occur spontaneously, which is likely to lead to the object fracture.

Also the number of loading cycles in these objects was calculated. This assist in engineering recommendations for the test material and concrete structural elements made of this material.

Here it is supposed that the crack growth rate diagrams [5] fully describe the propagation resistance of defects in the objects. They have been presented analytically using the well-known Paris equation:

$$da / dN = C(\Delta K_{\mathrm{I}})^n , \tag{3}$$

where *C* and *n* are the constants of the “material–environment” system. The parameters are calculated in [6]: $n = 7.07$ and $C = 0.0003$.

Table 2. Values of the a_{fc} in the SBF of acrylic bone cements with different soaking time

Defect I	DEAEA			DEAEM		
	0 months	3 months	6 months	0 months	3 months	6 months
4%	0.73022	0.75416	0.79406	0.66638	0.73022	0.84992
6%	0.76214	0.77012	0.87386	0.6983	0.76214	0.83396
Defect II	DEAEA			DEAEM		
e = 0.05 mm	0 months	3 months	6 months	0 months	3 months	6 months
4%	3.28382	3.53918	3.98606	2.68532	3.28382	4.57658
6%	3.66686	3.7307	4.77608	2.94866	3.66686	4.37708
e = 0.1 mm	0 months	3 months	6 months	0 months	3 months	6 months
4%	3.27584	3.5312	3.9701	2.67734	3.27584	4.56062
6%	3.65888	3.72272	4.75214	2.94068	3.65888	4.36112
e = 0.5 mm	0 months	3 months	6 months	0 months	3 months	6 months
4%	3.20402	3.4514	3.86636	2.64542	3.20402	4.409
6%	3.5711	3.62696	4.58456	2.8928	3.5711	4.22546
e = 1 mm	0 months	3 months	6 months	0 months	3 months	6 months
4%	3.10826	3.3317	3.70676	2.58158	3.10826	4.19354
6%	3.44342	3.49928	4.35314	2.82098	3.44342	4.03394
e = 2 mm	0 months	3 months	6 months	0 months	3 months	6 months
4%	2.84492	3.02048	3.30776	2.42198	2.84492	3.66686
6%	3.10826	3.14816	3.77858	2.6135	3.10826	3.54716

The examples of calculations of the residual durability of structural elements with defects under cyclic loading in working environments are given. They were obtained on the basis of the well-known formula [3], which provides conditions for spontaneous fracture of the structural element.

$$N_{fc} = \int_{a_1}^{a_{fc}} \frac{da}{F(\Delta K_{\mathrm{I}})}, \tag{4}$$

where N_{fc} is the number of loading cycles to fracture of structural elements; a_{fc} and a_1 are sizes of initial cracks.

The calculated value of N_{fc} in the second case is rather close to each other and equal to $N \approx 6{\cdot}10^6$ cycles. In the first case the value of N_{fc} is significantly higher compared to the second case ($N \approx 5{\cdot}10^9$), which suggests that even despite of the higher value of the critical length of the defect, the second case is more unpredictable than the first one, because the defect develops much faster.

CONCLUSIONS

This paper gives models for various cases of structural elements containing a crack-like defect. On the basis of these models and experimental results, the SIFs were identified and critical lengths of defects were analyzed. This procedure was performed for structural element in the considered case for the defects of different geometry. The analysis of the data showed the specific safest defects in materials. These data for a_{fc} can be used in engineering recommendations for the test material and concrete structural elements made from this material. As the most important conclusion we can indicate that the best material is DEAEM. Also, it should be noted, that the second case is more unpredictable than the first one, because the defect develops much faster.

РЕЗЮМЕ. Досліджено конструктивні елементи, виготовлені з лікувального цементу, з урахуванням різних домішок, зокрема, дієтилового амінокислотного етилакрилату (DEAEA), диметиламіноетил метакрилату (DMAEM) і дієтиламіноетил метакрилату (DEAEM). З урахуванням значень коефіцієнта інтенсивності напружень (КІН) подано характеристики чинників руйнування для цих об'єктів за різного часу замочування в середовищі SBF (0; 3; 6 місяців), а також за різних вагових варіацій домішок в основному матеріалі (2…10%). Дані для КІН, які використані в моделях, побудованих для різних конструктивних елементів, дають можливість аналізувати ризик їх руйнування за умови, що вони містять тріщиноподібний дефект. Отримано значення критичної довжини тріщиноподібного дефекту в кожному розглядуваному випадку і розраховано кількість циклів навантаження в цьому об'єкті.

РЕЗЮМЕ. Исследованы конструктивные элементы, изготовленные из лечебного цемента, с учетом различных примесей, в частности, диэтилового аминокислотного этилакрилата (DEAEA), диметиламиноэтил метакрилата (DMAEM) и диэтиламиноэтил метакрилата (DEAEM). С учетом значений коэффициента интенсивности напряжений (КИН) приведены характеристики факторов разрушения для этих объектов при различном времени замачивания в среде SBF (0; 3; 6 месяцев), а также различных весовых вариациях примесей в основном материале (2...10%). Данные для КИН, которые использованы в моделях, построенных для различных конструктивных элементов, дают возможность анализировать риск их разрушения при условии, что они содержат трещиноподобный дефект. Получено значение критической длины трещиниподобного дефекта в каждом рассматриваемом случае и рассчитано количество циклов нагружения в этом объекте.

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