DETERMINATION OF THE STRESS INTENSITY FACTOR OF POLYMER COMPOSITES WITH RECYCLED MATERIALS

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Abstract. Recycled industrial residues are widely used in the production of new environmental, energy-saving, and low-cost building materials. Their use helps to reduce production costs, preserve natural resources, and protect the environment. The idea of the present work reflects the new requirements of the European Union (EU) originating from the worrying issues of ecology, recycling of construction residues, energy efficiency of buildings, etc. In addition, the production of recycled materials is encouraged to overcome the problems created by COVID 19 and revive the economies of the EU Member States affected by the pandemic. The application of such materials would help to save natural resources and reduce the resources invested in conventional materials. We study the mechanical behaviour of a single-edge-crack structural element prepared from different recycled and fresh sand textile reinforced polymer mortars, using the methods of linear elastic fracture mechanics. Stress intensity coefficients in Mode I are calculated for different initial crack lengths and different external loads, considering six types of partially or fully recycled composite materials. The values of the critical loads and the corresponding critical length of the initial crack are determined. The results are presented in tables and figures, and analyses and conclusions are made.

Keywords: edge crack, stress intensity factor, critical load, energy efficiency, recycled materials.

1. INTRODUCTION

The rapid development of the industry over the past century backed up by the discovery of composite materials and the development of Information Technology (IT), along with its positive aspects, raised to the public worrying issues of climate changes, environmental protection, and ecology. Regarding

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construction, the issues concern the management of construction residue, energy efficiency, and deep renovation of buildings [1–3], as well as intelligent management of the entire life cycle of buildings and facilities, sustainable construction, etc. [4–5].

To overcome COVID 19 issues and revive the economies of the EU member states, a review and adjustment of current or introduction of new laws started concerning circular economy, climate, energy, the energy consumption of buildings, innovations, etc. Moreover, the EU encourages the production of energy-saving recycled materials as well as sustainable (green) reusable products [6] via the Circular Economy Action Plan. The construction industry is one of the major consumers of natural resources as well as carbon emitter. As data on the whole life cycle of buildings in the EU show [5–7], it is in charge of half of the extracted materials; half of the consumed energy; one-third of the consumed water; one-third of the generated residues.

Until last year, a fundamental document for EU member states, including Bulgaria, was the "Europe 2020" program, which aimed at reduction of greenhouse gas emissions by more than 20% compared to 1990; extraction of 20% of energy from renewable energy sources; an increase of energy efficiency by 20%; use of at least 70% recycled materials. Although there is still no complete data on the implementation of the program, it is obvious that the sought utilization of recycled materials has not been achieved [6–7].

The issue of the use of recycled materials in Bulgaria has so far been partially resolved and the solution mainly concerns the recycling of road surface waste from road construction. In this regard, the launched green deal toughened the requirements, where construction tasks of cement preparation and steel manufacture are set to significantly reduce carbon emissions. The first steps show that the chosen path is correct, but construction material science needs more development and solutions. The outlined activities should prove efficient over the next few years since United Europe takes new and decisive steps to provide carbon security and climate neutrality via the Green Deal [5–7].

The task of different EU operational programs and the National Science Fund is the funding of basic research on various recycled building materials, whose application, in turn, would focus on energy-efficient buildings and structures. The studies must comply with the European requirements, regulations, and directives, as well as the Priorities and specific objectives of the National Strategy for Research Development in the Republic of Bulgaria 2017–2030. Note especially two of them: (i) improving the quality of life–food, health, biodiversity, environmental protection, urban environment, and transport, etc., and (ii) energy and energy efficiency, efficient use of natural resources [8].

Recently, the object of great interest is the study and analysis of the behaviour of different components fabricated from partially or fully recycled materials. Designed for use in construction, they are expected to be low-cost and cost-effective [9]. There are several studies on recycled polyester and polymer concretes [10] and polymer mortars with/without recycled aggregates [11–14], with high strength indicators. Apart from the fabrication of multifunctional structural elements, they are environmental and energy-saving composites conforming to the global requirements for environmental protection. Thus, natural resources can be preserved, achieving a reduction of energy and resources invested in conventional materials.

We study in the present work the behaviour of a single edge cracked constructive element from different recycled sand textile reinforced polymer and fresh sand textile reinforced polymer mortars, using the Linear Elastic Fracture Mechanics (LEFM). The Stress Intensity Coefficients (SIF) in Mode I are calculated for different initial crack lengths and different values of the external loads. The latter act on a specific structural component fabricated from six different partially or fully recycled materials. The critical values of the initial crack length and the respective critical loads are also found.

Parametric analysis and comparison are performed regarding the effect of the external load and the initial crack length on the fracture toughness of a laterally cracked structural element made of 6 different polymer mortars (with partially and completely recycled ingredients). The results are presented tabular and graphically, and analysis and conclusions are made.

2. ANALYTICAL MODEL

2.1. Geometry and load

We consider a rectangular plate with thickness t, length l and width h, Fig. 1. It is assumed that there is a single edge crack with an initial length a_0. The plate is subjected to double-sided tensile external load σ.

2.2. Determination of stress intensity factor

The following between the two dimensions are assumed for the considered rectangular plate $l \times h$: $l/2h \geq 0.5$ and $a_0/h \leq 0.6$ [15–16].

A single crack of initial length a_0 is considered, and the stress intensity factor at the crack tip K_I under double-sided tensile external loading σ is

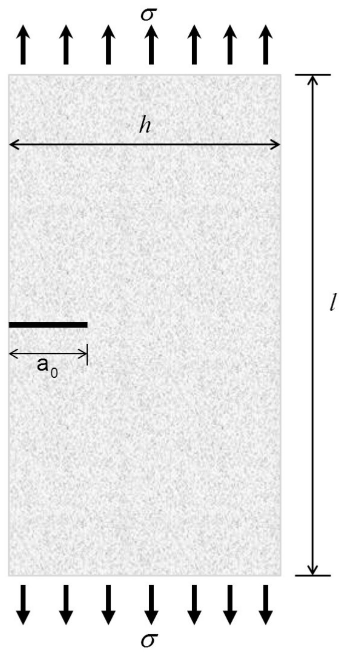

Fig. 1. Geometry and load
of the assumed structural element

used by means of the equation known from the pure Mode I literature:

$$K_I = \sigma\sqrt{\pi a_0}\left(1.122 - 0.231\left(\frac{a_0}{h}\right) + 10.55\left(\frac{a_0}{h}\right)^2 - 21.71\left(\frac{a_0}{h}\right)^3 + 30.382\left(\frac{a_0}{h}\right)^4\right). \quad (1)$$

3. RESULTS AND ANALYSIS

The geometry of the structure, the assumed constants and the varying values of the external load are presented in Table 1.

Six types of composite materials are used in the analysis: 3 types of polymer mortars reinforced with fresh sand (FS0, FS1 and FS2) and 3 types of Recycled sand textile reinforced polymer mortars (RS0, RS1 and RS2), as numbers 0, 1 and 2 correspond to the percentage of fibres in them. The material characteristics are taken from experimental data found in the literature [11] and given in Table 2.

Table 1. Assumed values of the external load and geometry of the structural element

External load, σ [MPa]	0.06–56.82
Plate length, l [m]	2
Plate width, h [m]	1
Plate thickness, t [m]	1
Initial crack length, a_0 [m]	0.0001–0.6

Table 2. Assumed experimental material properties for polymer mortars, [11]

Material	E [MPa]	K_{IC} [MPa.m$^{1/2}$]
FS0	16.03	1.13
FS1	12.39	0.86
FS2	10.71	0.53
RS0	10.96	0.85
RS1	4.31	0.49
RS2	4.12	0.31

3.1. Results for the critical stress in an uncracked structural element

Using equation (1) and the data in Tables 1 and 2, the values of the critical loads for the chosen constructive element constructed from different sand textile reinforced polymer mortars were calculated.

The results are presented in Table 3 for the six cases in which the length of a single crack is assumed to be $a_0 = 0.0001$ [m], i.e. the element has no crack.

The results show that the replacement of fresh (FSO) with recycled sand (FR0) in polymer mortars, as well as the addition of textile fibres (FS1, FS2, RS1, RS2) yields lower fracture toughness.

Figure 2 presents the critical stress values for an uncracked structural element prepared from 6 different polymer mortars (with partially and fully recycled components).

3.2. Results for the critical crack length and critical stress in a cracked structural element

We assume that the fracture criterion is met, i.e., SIF reaches a critical value K_{IC}. Using this failure criterion based on the expected material behaviour at the crack type (1), the values of the critical loads σ_{cr} corresponding to the

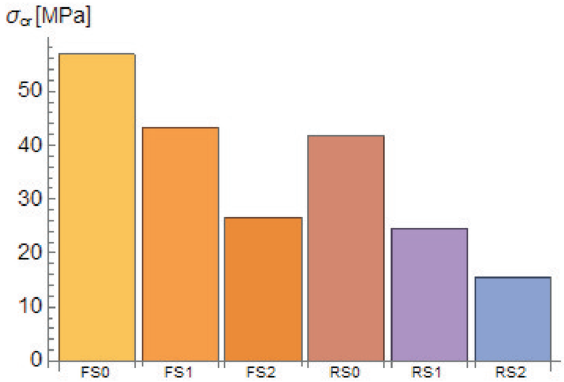

Fig. 2. Critical stress values for uncracked polymer mortar elements

Table 3. Calculated critical stress for polymer mortars

Material	K_{IC} [MPa.m$^{1/2}$]	σ_{cr} [MPa]
FS0	1.13	56.82
FS1	0.86	43.25
FS2	0.53	26.65
RS0	0.85	42.74
RS1	0.49	24.64
RS2	0.31	15.59

critical initial lengths of the edge crack a_{cr} in the structural element for the six types of polymer mortars are determined, Table 4.

The critical stress for a critical crack size $(0.1 \leq a_{cr} > 0.6)$ is obtained and the critical stress diagram (a_{cr} versus σ_{cr}) for the given structural configuration is plotted in Fig. 3.

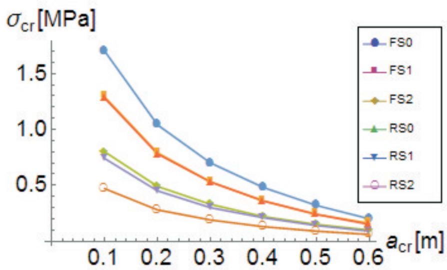

Fig. 3. Critical crack length and critical stress

Table 4. Critical crack length and critical stress

Material	a_{cr} [m]	σ_{cr} [MPa]	Material	a_{cr} [m]	σ_{cr} [MPa]
FS0	0.1	1.70	RS0	0.1	1.28
	0.2	1.04		0.2	0.78
	0.3	0.70		0.3	0.53
	0.4	0.48		0.4	0.36
	0.5	0.32		0.5	0.24
	0.6	0.20		0.6	0.15
FS1	0.1	1.29	RS1	0.1	0.74
	0.2	0.79		0.2	0.45
	0.3	0.53		0.3	0.30
	0.4	0.36		0.4	0.21
	0.5	0.24		0.5	0.14
	0.6	0.16		0.6	0.09
FS2	0.1	0.80	RS2	0.1	0.47
	0.2	0.49		0.2	0.28
	0.3	0.33		0.3	0.19
	0.4	0.22		0.4	0.13
	0.5	0.15		0.5	0.09
	0.6	0.10		0.6	0.06

It is obvious that for the length of the initial crack $a_0 > 0.1$, the critical values of the external load decrease sharply. Therefore, the SIF will quickly reach its critical value at lower values of the external load and higher values of the initial crack length. The structural element becomes increasingly unstable with the increasing length of the initial crack.

3.3. Results for the SIF at different values of the external load

Table 5 and Figure 4 show the results of the SIF found via a parametric analysis and at three different values of the external load $\sigma < \sigma_{cr}$, and six different lengths of the initial crack for selected RSO material. SIF has a critical value for this material $K_{IC} = 1.13$ [MPa.m$^{1/2}$].

The results in bold script show values of SIF, which are larger than the critical values, $K_{IC} = 1.13$ [MPa.m$^{1/2}$], and they are inadmissible for that specific material.

It is seen that the value of the stress intensity factor K_I increases with the increase of the crack length. It more quickly attains a critical value for larger external loads.

Table 5. SIF for three values of external load

		K_I [MPa.m$^{1/2}$]		
Material	a_0 [m]	$\sigma = 0.25$ [MPa]	$\sigma = 0.50$ [MPa]	$\sigma = 0.75$ [MPa]
RS0	0.1	0.16	0.33	0.50
	0.2	0.26	0.54	0.82
	0.3	0.39	0.81	**1.21**
	0.4	0.58	**1.18**	**1.77**
	0.5	**0.89**	**1.77**	**2.66**
	0.6	**1.38**	**2.77**	**4.15**

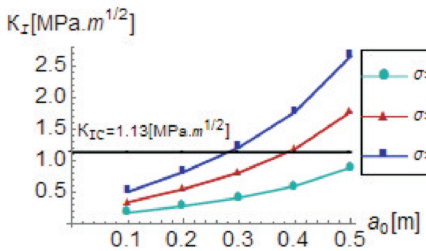

Fig. 4. Initial crack length values a_0 and K_I for different external loads

3.4. Generalized analysis

The following generalized analysis can be made based on the results found:

- The replacement of fresh with recycled sand in polymer mortars, as well as the addition of textile fibres contribute to weaker brittle behaviour of the polymer material and lower resistance to fracture toughness;
- For large values of the initial crack length, the critical values of the external load decrease sharply;
- SIF quickly reaches its critical value at smaller values of the external load and at larger values of the length of the initial crack.

4. CONCLUSIONS

Following the EU requirements to the recycling of construction waste and the production of new energy-saving recycled materials, the present work studies the behaviour of a laterally cracked structural element from different partially or completely recycled polymer mortars.

Using the appropriate failure criterion based on the expected material behaviour at the crack type, the stress intensity coefficients for different initial crack lengths and different external load values, as well as the values of the critical loads and their corresponding critical crack lengths, are calculated.

A parametric analysis was made regarding the influence of the values of the external load and the length of the initial crack on the resistance to failure of a selected structural element.

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