Kuwait J. Sci. Eng. **27**(1) 2000

Effect of elevated temperatures on the residual fracture toughness of epoxy modified concrete

HISHAM ABDEL-FATTAH*, MOETAZ M. EL HAWARY* AND AHMAD FALAH**

**Department of Civil Engineering, Kuwait University, P.O. Box 5969, Safat 13060, Kuwait. e-mail: hisham@civil.kuniv.edu.kw*

***Public Authority for Housing Care, Kuwait*

ABSTRACT

An experimental investigation was carried out to study the residual fracture toughness of beams made of epoxy modified concrete. The beams were pre-notched with an edge crack at mid-span and tested under four point bending after being subjected to different temperatures. The temperatures were varied between 22°C and 200°C (22, 50, 100, 150, 200°C). Different percentages of epoxy in the mix were investigated (0, 10, 15 and 20% by weight of cement). The results show that the residual fracture toughness increases with the increase in epoxy content in the mix and decreases with an increase in temperature. A numerical model based on the finite element method in conjunction with the basic fundamentals of fracture mechanics was used to evaluate the fracture toughness of the beams. Experimental results such as the failure load, unit weight and the modulus of elasticity were used as input for the model and the results were shown to converge to the correct solution for a crack extension of 0.2 mm.

Keywords: Compliance; Concrete; Epoxy; Fracture; Temperature.

INTRODUCTION

Polymer Portland Cement Concrete (PPCC) mixtures are normal Portland Concrete mixtures to which a polymer has been added during the mixing process. In epoxy modified mixtures, the polymer is formed after the components of the epoxy (base + hardener) are added to the concrete mix where the polymerization process occurs concurrently with the hydration of the cement. Polymer-modified Portland Cement Concretes and mortars exhibit improved strength properties such as flexural strength, tensile strength and abrasion resistance over similar unmodified concretes and mortars (ACI Committee 548, 1995). PPCC applications include overlays of bridge decks, precast members, patching, industrial floors and floors of parking decks (ACI Committee 548, 1992).

The fracture behavior of concrete plays an important role in the overall assessment of the concrete performance in structures. One important fracture parameter is the fracture toughness K_{IC} which is defined as the ability of the material to absorb energy in the presence of cracks. Tests to determine K_{IC} were carried out at different temperatures on different sizes and shapes of notched concrete specimens (Cherepanov 1979, Bazant & Prat 1988, Brameshuber 1989, Maturana *et al.* 1990). The tests showed that unlike metals, the value of K_{IC} for concrete decreases at elevated temperatures. Fracture tests carried out on specimens made of different concrete strengths (John & Shah 1989) showed that K_{IC} increases with the increase of concrete strength (fc'). The effect of cyclic heating (Abdel-Fattah & Hamoush 1997) showed that the residual fracture toughness decreased considerably after every heating and cooling cycle. Studies on the fracture behavior of epoxy polymer concrete (Vipulanandan & Dharmarajan 1989) concluded that K_{IC} for epoxy polymer concrete increases with the increase in polymer content and decreases with increase in temperature.

All the above mentioned studies were carried out on Portland Cement Concrete where the binding material is the cement, or Polymer Concrete where the binding material is the polymer. Little research has been carried out to study the properties of PPCC where both the cement and the polymer act as the binder.

In the present study, the main objective is to evaluate the fracture toughness of PPCC made of the local materials available in the Gulf region. The polymer used was an epoxy recommended for grouting which is widely used in Kuwait. The study also aims to investigate the residual fracture toughness of PPCC beams after being subjected to temperatures as high as 200°C.

An experimental program was carried out in which a total of 40 beams were tested under four point bending. Four different ratios of epoxy were investigated (0, 10, 15 and 20%) at five temperatures (22, 50, 100, 150 and 200°C). A numerical model based on the compliance approach was used to predict the fracture toughness of the beams.

EXPERIMENTAL PROGRAM

The test set-up is shown in Fig. 1. A total of 40 beams were tested in this study. The beam dimensions were 150×150×750 mm. The clear span for the beams was 600 mm which gave a span-to-depth ratio of 4. All beams were pre-notched with a 25 mm edge crack located at midspan. The ratio of crack length a to beam depth b was $a/b = 1/6$. The notch thickness was 2 mm and was made by placing a piece of plexiglass with the desired crack dimensions into the mold prior to casting. After hardening of the concrete and removal of the mold, the plexiglass piece was removed, thus leaving the desired notch. For each beam, three control cylinders of 100 mm in diameter and 200 mm in height were tested to determine the concrete compressive strength (fc').

The different mixes used in this study are summarized in Table 1. All mixes had a water/cement ratio of 0.5. Sand of fineness modulus of 2.6 and quartizite coarse aggregate of maximum aggregate size $\frac{3}{4}$ inch (19 mm) were used. The sand and the coarse aggregates were washed and dried before mixing. Type I cement was used and the polymer content in the mix was added as a partial replacement of the cement. The polymer used was an epoxy recommended for grouting which is widely used in the Gulf region. Polyamine hardener was used with the epoxy.

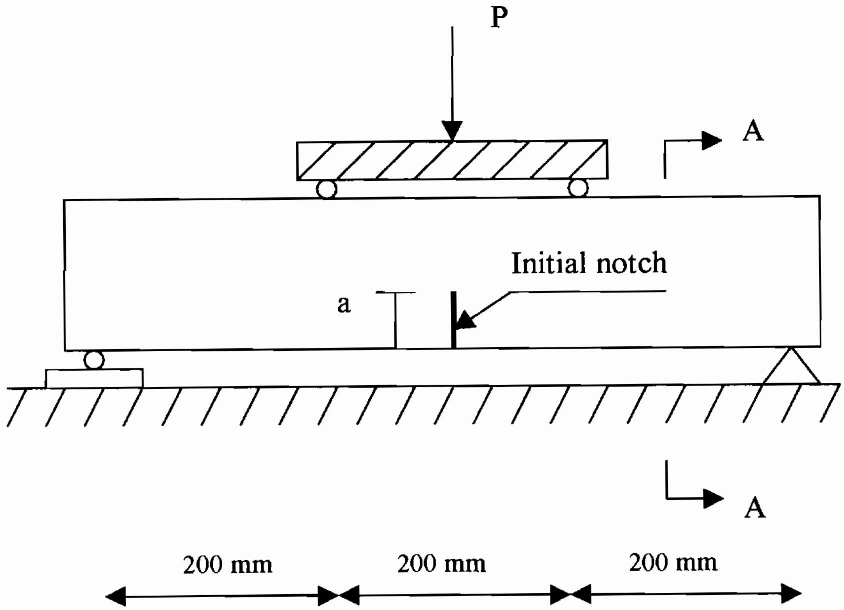

Fig. 1. Test set-up for beams.

Table 1. Concrete Mix Design.

Material	Quantity, Kg/m^3
Cement Type I	400
Fine aggregate (fineness modulus = 2.6)	594
Water	200*
Coarse aggregate:	1108
• $\frac{3}{4}''$ (19 mm)	465
• $\frac{1}{2}''$ (12 mm)	421
• 3/8″ (10 mm)	222
Epoxy content:	
• 0%	–
• 10%	40
• 15%	60
• 20%	80

*For 0% epoxy. When epoxy was added as a partial replacement of cement, the water was adjusted to keep the w/c ratio 0. 5.

All beams and cylinders were cast vertically in steel molds. During casting, the concrete was first hand-compacted with a rod and the molds were then put on a shaking table for 2–3 minutes. The molds were removed after twenty-four hours and all specimens were moist-cured in a curing room at 21°C and 95% relative humidity for 28 days. The beams were heated by placing them in an oven preheated to the desired temperature. Each beam was kept in the oven for twenty-four hours and then removed and left to cool at room temperature for another twenty-four hours before testing. The temperatures investigated were 22 (room temperature), 50, 100, 150 and 200°C. Two beams and three cylinders were prepared from each mix. For each test, the cylinders were subjected to the same heating conditions as the beams.

The compressive strength tests were carried out on an MTS machine equipped with a moving head platen. The load was applied in increments of 25 KN. The same machine was used for testing the beams and in this case the load was applied in increments of 1 KN. The beam deflections were measured by two LVDTs placed on the two sides of the notch and each located 25 mm away from it.

EXPERIMENTAL RESULTS

The variation of the concrete average compressive strength (in Mpa) with temperature is shown in Fig. 2. The figure shows the average compressive strength of three specimens at each temperature and for each concrete mix. Each set of three cylinders was subjected to the same temperature as the companion beam. The graph shows that the compressive strength of concrete decreases with the increase in temperature and increases with the increase of epoxy percentage. The decrease in residual compressive strength for 0% epoxy at 200°C is about 26%.

Figure 3 shows the effects of temperature on the residual fracture toughness K_{IC} for the different epoxy percentages. The figure shows that increasing the temperature decreases the residual fracture toughness, and the higher the percentage of epoxy in the mix, the higher the reduction in K_{IC} for the same temperature. For all mixes, the residual fracture toughness decreased by an average value of 21% when heated to 200°C. Computations of the fracture toughness were carried out using the equations in the Appendix. The fracture toughness for each beam was obtained by substituting the value of the ultimate load at failure into the set of equations.

The effect of the percentage of epoxy in the mix on the fracture toughness of the specimens that were not subjected to any heat ($T = 22$°C) is shown in Table 2. The table shows that, in general, the fracture toughness increases with the increase in epoxy content. Table 3 shows that the range for K_{IC} at room temperature was 0.467 to 0.603 MN/m$^{3/2}$. The table also shows that for ordinary Portland Cement Concrete the range of K_{IC} was 0. 371 to 0. 467 MN/m$^{3/2}$, and for Polymer Cement Concrete 0.378 to 0.603 MN/m$^{3/2}$. The loss in residual K_{IC} for PPCC was higher than that of ordinary Portland Cement Concrete. This is due to the fact that the epoxy properties are affected by the high temperatures and as a result, part of the bond between the aggregates was lost.

FINITE ELEMENT MODELING

Several numerical models have been developed to predict the fracture toughness of similar beams (Hamoush & Abdel-Fattah 1996, 1998). In the present study, a finite element model based on the compliance approach is used to predict the fracture toughness values for the different beams. The model can be explained as follows.

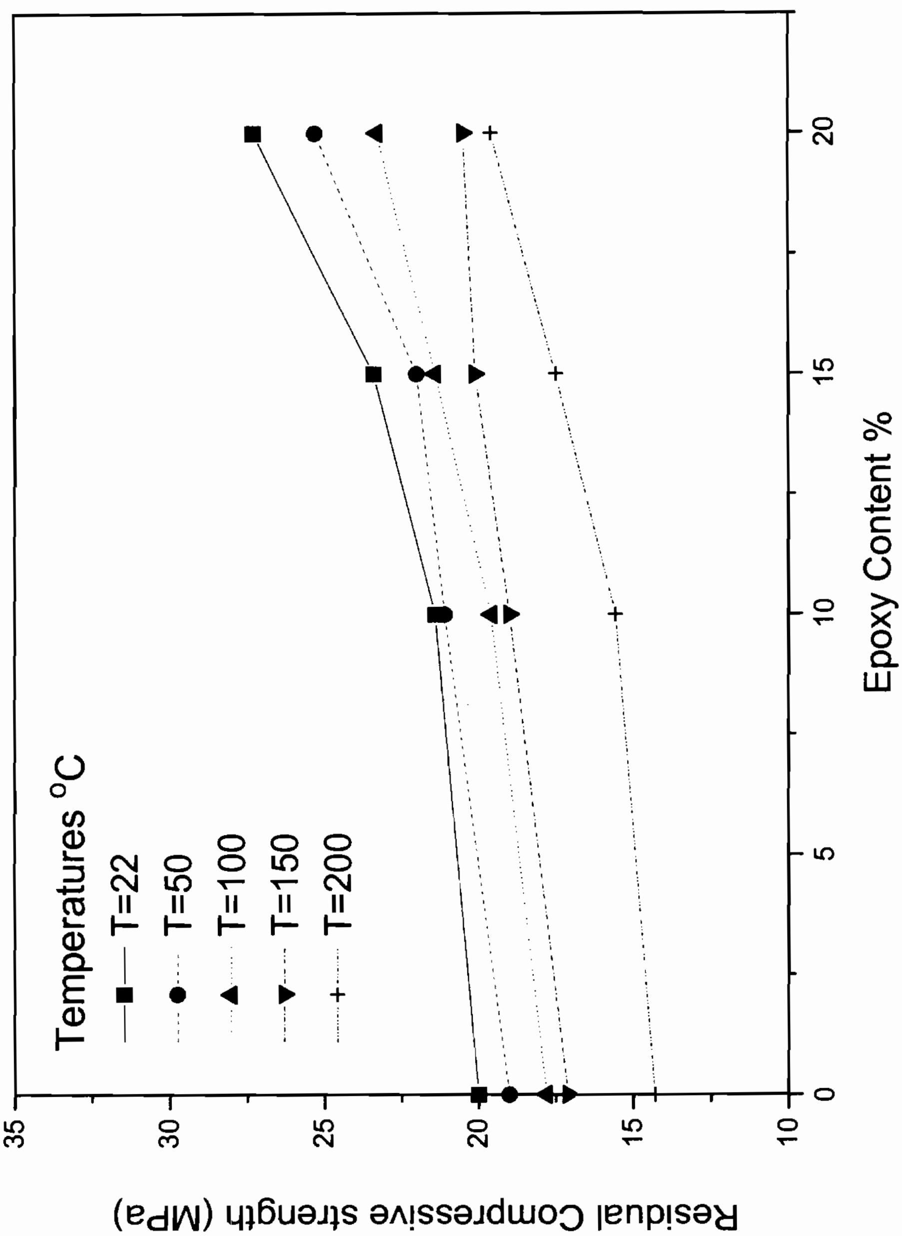

Fig. 2. Variation of concrete compressive strength with epoxy content for different temperatures.

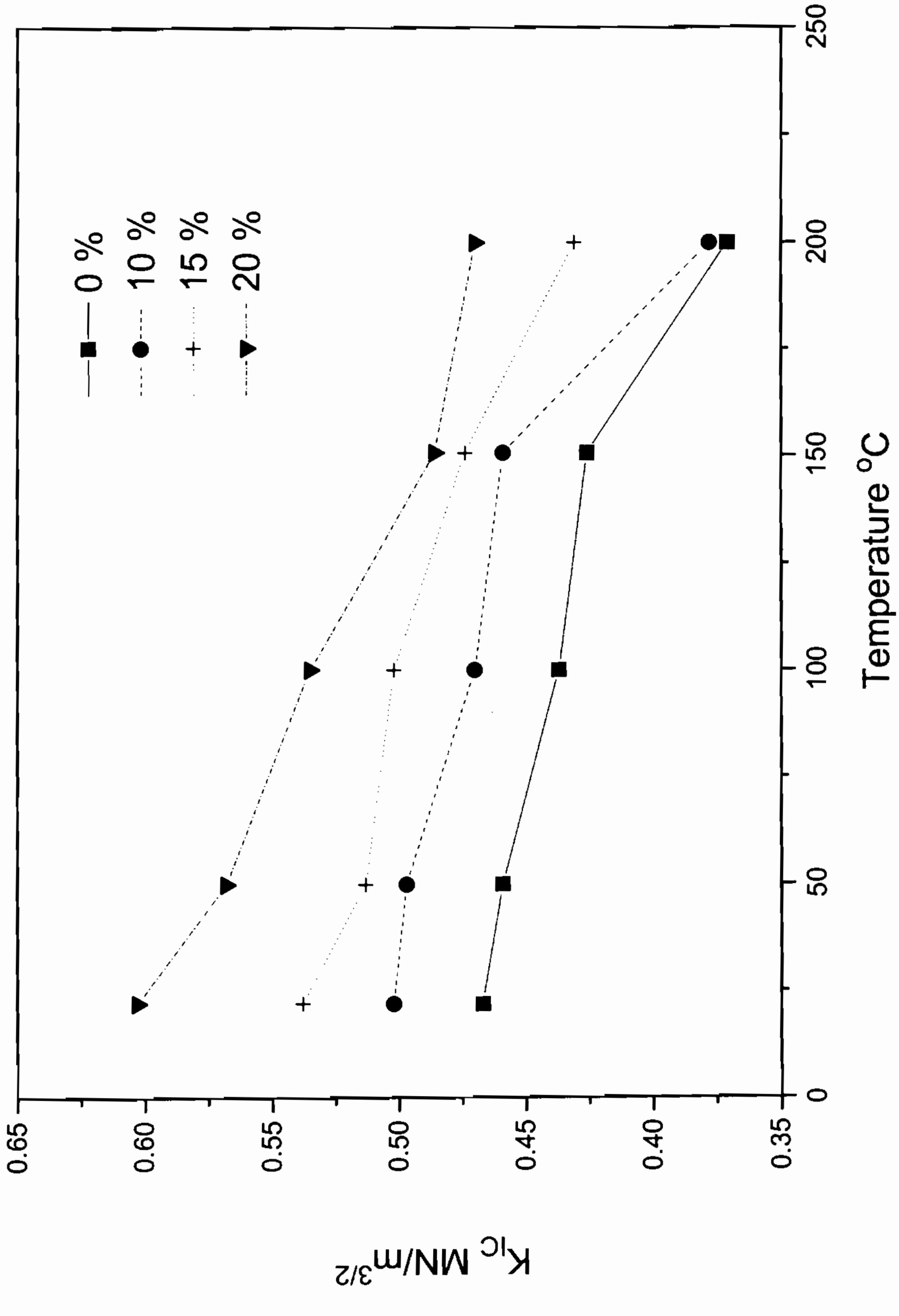

Fig. 3. Variation of concrete fracture toughness with temperature for the different epoxy ratios.

Table 2. Variation of K_{IC} with percentage of epoxy in the mix.

Percentage of epoxy in the mix	Percentage increase in K_{IC}
10%	7%
15%	15%
20%	29%

Table 3. Comparison between the experimental and numerical values for K_{IC} for $\Delta a = 0.2$ mm.

Percentage of Epoxy	Temperature °C	K_{IC} experimental MN/m$^{3/2}$	K_{IC} numerical MN/m$^{3/2}$
0%	22	0.467	0.462
	50	0.459	0.458
	100	0.437	0.438
	150	0.426	0.423
	200	0.371	0.376
10%	22	0.502	0.499
	50	0.497	0.487
	100	0.470	0.464
	150	0.459	0.458
	200	0.378	0.385
15%	22	0.538	0.536
	50	0.513	0.514
	100	0.502	0.499
	150	0.480	0.479
	200	0.431	0.425
20%	22	0.603	0.597
	50	0.568	0.561
	100	0.535	0.535
	150	0.486	0.481
	200	0.470	0.464

In general, when a crack in an isotropic homogeneous media of length a extends by a very small increment Δa to a new length $a + \Delta a$, the strain energy release rate G becomes:

$$G = \lim_{\Delta A \to 0} \frac{\Delta U}{\Delta A} \tag{1}$$

where ΔU is the change in the potential energy and ΔA is the newly formed crack area after the crack extension takes place. The strain energy release rate in plane stress conditions and under pure Mode I loading is expressed in terms of the Mode I stress intensity factor K_I, and the modulus of elasticity E as follows:

$$G = \frac{K_I^2}{E}. \tag{2}$$

Equation 1 can be expressed numerically as follows:

$$G = \frac{1}{4\Delta ab} \sum (P_i)(\Delta u_i) \tag{3}$$

where Δu_i are the change in nodal displacements in the direction of the loads P_i that caused the crack extension, and b is the thickness of the beam. By substituting the ultimate load at failure for P_i in Equation 1, we get the critical strain energy release rate G_{IC}, and substituting this value into Equation 2 gives the fracture toughness K_{IC}.

The finite element mesh shown in Fig. 4 was used in the analysis. Only half the beam was analyzed because of symmetry. Four node elements were used and the mesh had a total of 220 elements. The unit weight and modulus of elasticity for each mix were measured, and together with the ultimate load at failure, were used in the computer input for each analyzed beam.

For each beam, one computer run was made for the original crack length ($a = 25$ mm) and other runs were made for a wide range of crack extensions Δa. For each new crack length $a + \Delta a$, the strain energy release rate was computed using Equation 3 and the fracture toughness computed from Equation 2. The analysis shows that for the geometry, loading and materials tested, the finite element model converges to the experimental values computed using the equations in the appendix when $\Delta a = 0.20$ mm. The results of the finite element model are shown in the last column of Table 3 which shows a comparison between the numerical and experimental values. From the table, it is clear that there is a very close match between both values which demonstrates the accuracy of the model.

CONCLUSIONS

The paper evaluates experimentally and numerically the residual fracture toughness of Polymer Portland Cement Concrete made of different ratios of polymer in the mix and subjected to elevated temperatures. A simple numerical method, based on the compliance approach, was used to evaluate the fracture toughness. The scope of the study was limited to beams since it is the common structural element for which standard toughness tests are available. Evaluating the experimental results and comparing them with the numerical model results in the following conclusions:

1. The addition of epoxy to a concrete mix as a partial replacement to the cement increases the compressive strength. The strength increases as the percentage of epoxy increases and decreases with an increase in temperature.
2. The fracture toughness of PPCC increases with increase of polymer content and decreases with an increase in temperature, but at a lower rate than that of the compressive strength.
3. Heating PPCC up to 50°C decreases its residual fracture toughness by a very small amount, but heating above 50°C decreases the fracture toughness considerably. For a temperature of 100°C, the fracture toughness for PPCC decreases by almost 21%.

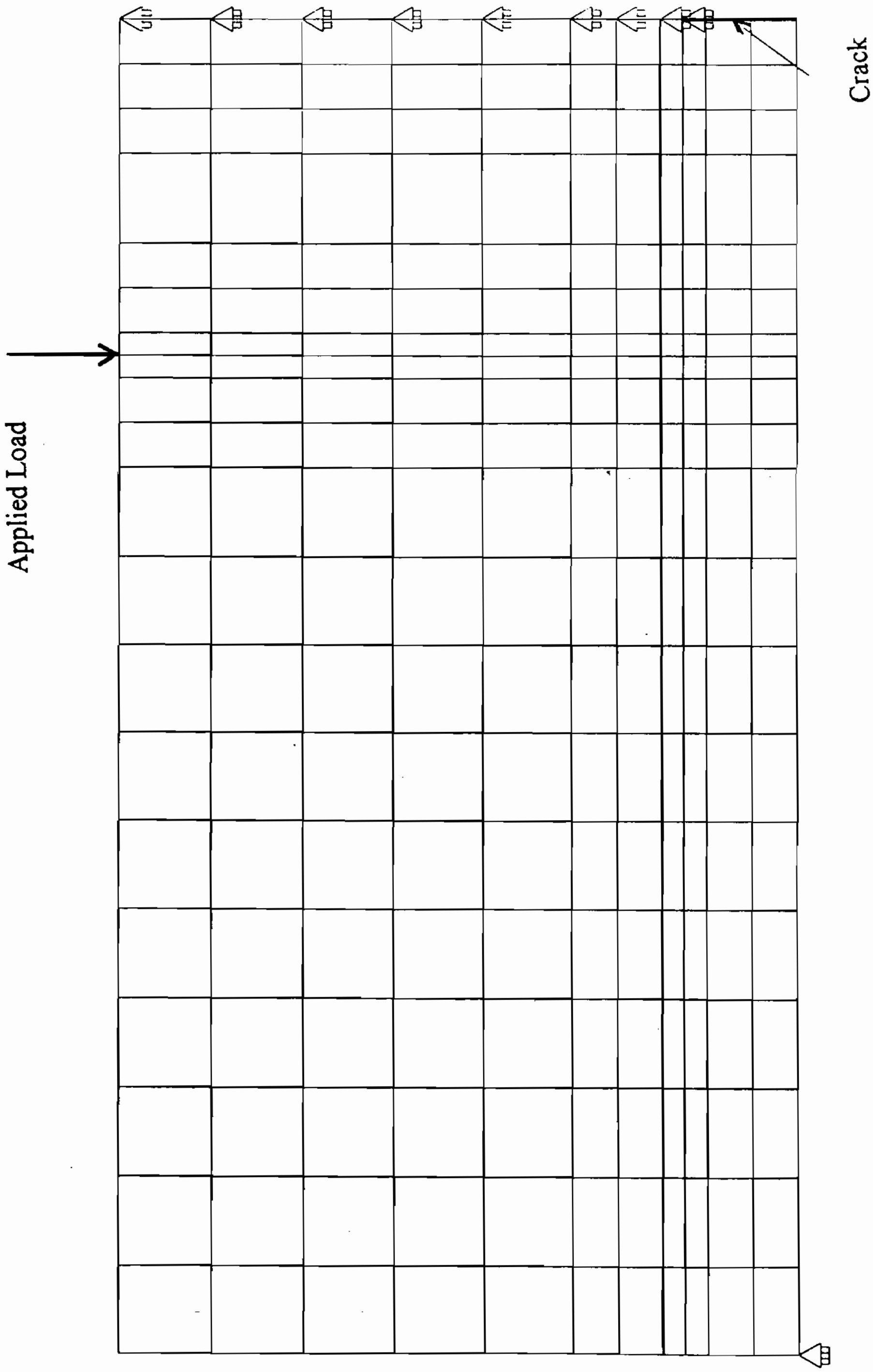

Fig. 4. Finite element mesh.

4. The effect of elevated temperatures on Polymer Portland Cement Concrete is greater than that on Ordinary Portland Cement Concrete. This suggests that more care should be taken when PPCC is used as a building material in places where high temperatures are expected (such as the Gulf region).
5. The compliance approach is suitable for evaluating the residual fracture toughness for prenotched beams under four point bending. For the geometry, loading and materials used in this study, the finite element solution converges to the correct values at a crack extension of 0.20 mm.
6. The results of this study provide ample design information that will help in limiting the occurrence of cracks and in designing more durable PPCC members.

ACKNOWLEDGEMENTS

The work presented in this paper was supported by Kuwait University grant No. EV085. The support by Kuwait University is greatly acknowledged.

APPENDIX

The Mode 1 stress intensity factor (K_I) for a beam with a central crack is computed as follows (Tada *et al.* 1985):

$$K_I = \sigma\sqrt{\pi a}F\left(\frac{a}{b}\right). \tag{A1}$$

The stress σ is calculated by:

$$\sigma = \frac{6M}{b^3} \tag{A2}$$

where

$$M = \frac{(P)(S)}{6}. \tag{A3}$$

The function $F(a/b)$ is evaluated as follows:

$$F\left(\frac{a}{b}\right) = 1.09 - 1.735\left(\frac{a}{b}\right) + 8.2\left(\frac{a}{b}\right)^2 - 14.18\left(\frac{a}{b}\right)^3 + 14.56\left(\frac{a}{b}\right)^4 \tag{A4}$$

where a is the crack length (25 mm), b is the beam depth (150 mm), S is the clear span (600 mm) and P is the applied load. The fracture toughness K_{IC} is computed from Equation (A1) after substituting the value of the critical load at failure into Equation (A3).

REFERENCES

Abdel-Fattah, H. and Hamoush S.A. 1997. Variation of the fracture toughness of concrete with temperature. Construction and Building Materials **11(2):** 105–108.

ACI Committee 548 1992. Guide for the Use of Polymers in Concrete. ACI 548. 1R/92, American Concrete Institute, Detroit, MI, U.S.A.

ACI Committee 446 on Fracture Mechanics 1992. Fracture Mechanics of Concrete: Concepts, Models and Determination of Material Properties, Proceedings of the First International Conference on Fracture Mechanics of Concrete Structures **105:** Breckenridge, CO, U.S.A.

ACI Committee 548 1995. State-of-the-Art Report on Polymer-Modified Concrete. ACI 548.3R-95. American Concrete Institute, Detroit, MI, U.S.A.

Bazant, Z.P. & Prat, P.C. 1988. Effect of temperature and humidity on fracture energy of concrete. ACI Materials Journal **84:** 262–271.

Brameshuber, W. 1989. Discussion of effect of temperature and humidity on fracture energy of concrete. ACI Materials Journal **86:** 330–331.

Cherepanov, G.P. 1979. Mechanics of Brittle Fracture. McGraw-Hill, New York, NY, U.S.A.

Hamoush, S.A. & Abdel-Fattah, H. 1996. The fracture toughness of concrete. Engineering Fracture Mechanics **53(3):** 425–432.

Hamoush, S.A., Abdel-Fattah, H. & McGinley M. 1998. Residual fracture toughness of concrete exposed to elevated temperature. ACI Structural Journal **95(6):** 689–694.

John, P. & Shah, S.P. 1989. Fracture mechanics analysis of high strength concrete. International Journal of Materials in Civil Engineering **1(4):** 185–198.

Maturana, P., Planas, J. & Elices, M. 1990. Evaluation of fracture behavior of saturated concrete in the low temperature range. Journal of Engineering Fracture Mechanics **35:** 827–834.

Tada, H., Paris, P.C. & Irwin, G. R. 1985. The stress analysis of cracks handbook, 2nd Edition. Paris Productions, St. Louis, MO, U.S.A.

Vipulanandan, C. & Dharmarajan, N. 1996. Analysis of fracture parameters of epoxy polymer concrete. ACI Materials Journal **86(4):** 383–393.

(Accepted 19 June 1999)

تأثير الحرارة على متانة التشقق للخرسانة المضاف إليها الأيبوكسي

هشام عبدالفتاح* ، معتز ماهر الهواري* و أحمد فلاح**
*قسم الهندسة المدنية – جامعة الكويت
ص.ب. 5969 الصفاة 13060
**المؤسسة العامة للرعايا السكنية – الكويت

خلاصة

في هذا البحث تم عمل اختبارات معملية لدراسة تأثير التعرض للحرارة على متانة التشقق لكمرات مصنوعة من الخرسانة المضاف إليها الايبوكسي ، وقد تم عمل شرخ طرفي عند منتصف البحر لكل كمرة ثم حملت بطريقة التحميل ذو الأربع نقاط وذلك بعد تعريضها لدرجات حرارة 50م ، 100م ، 150م ، 200م ، وكانت نسب الايبوكسي في الخلطات المستخدمة 10 ، 15 و 20% ن وأظهرت النتائج أن متانة الخرسانة للتشقق لهذا النوع تزداد بزيادة نسبة الايبوكسي وتقل مع زيادة درجة الحرارة ، وقد تم عمل نموذج عددي باستخدام طريقة العناصر المحددة لمعرفة متانة التشقق للكمرات باستخدام الحاسب الآلي ، وقد أظهرت نتائج النموذج العددي أنه يطابق النتائج المعملية عند زيادة مقدارها 0.20 مم في طول الشرخ.