Fracture Mechanics of Concrete Structures
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EFFECT OF LOW TEMPERATURE ON FRACTURE ENERGY OF CONCRETE JOINTS AND REPAIR MATERIALS

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Abstract

One of the important causes of cracks in concrete dams operating in sub-arctic regions is the seasonal temperature variation, where the difference in temperature may be as high as 70 °C with minimum temperature reaching -40 °C. Cracks usually occur due to the weak preparation of the horizontal interface between two successive lifts of concrete, or when the interval between lifts is longer than necessary. In order to measure the strength of joints and interfaces between concrete materials under severe thermal conditions, a large scale experimental program has been implemented at the University of Manitoba, Canada. This program is intended to identify the strength of the rather weak concrete interface with and without repairing material using fracture mechanics concepts. The fracture parameters are extracted for the specimens tested at low temperature as well as room temperature.
Keywords: Low Temperature; Concrete Joints, Repair Materials.

1 Introduction

It is well established that many operating concrete dams present zones of extensive cracking especially between adjacent lifts. Such situations are unusual for reinforced and pre-stressed concrete structures, where cracking is restricted at the design level. The appearance of detectable cracks in such structures is interpreted as a structural failure, and usually as a consequence, repair measures are immediately undertaken. In the case of large structures, such as dams, a certain amount of cracking is unavoidable, and the structural analyst should guarantee the global stability of the construction even when long cracks exist .

One of the important causes of cracks is the seasonal temperature variations, especially in the northern territory of Canada where the season difference in temperature may be as high as 70^{o} C with minimum temperature reaching - 40^{o} C. In such cases cracks usually occur due to inadequate preparation of the horizontal interface between two successive lifts of concrete, or when the interval between lifts is longer than necessary. Information on the basic fracture characteristics at low temperature is necessary to understand the interface crack behavior of concrete dams in sub-arctic regions. Bazant and Prat (1988) investigated the temperature and humidity effects on fracture energy of concrete using bending specimens and eccentrically loaded specimens at + 20^{o} C to $+200^{o}$ C in pre-dried and water saturated condition using various specimen sizes, they found that the size effect is applicable not only at room temperature but also at elevated temperature up to 200^{o} C. Elices (1987), evaluated the fracture behavior of saturated concrete at temperatures ranging from -170 °C to 20 °C. He found the toughness of concrete increases with low temperature and the fracture energy increases at a ratio of 3 to 1 over the room temperature.

Concrete joints and interfaces between dissimilar cementitious materials are usually weaker than the base-material, especially at low temperatures and in corrosive environments. In order to measure the mechanical properties of these joints, when subjected to severe thermal conditions, a large scale experimental program has been initiated at the University of Manitoba. This program is intended to identify the fracture properties of the often weak concrete interface at various temperature levels with and without repairing material. As structural repair materials, polymers and their composites are required to withstand high stresses under extreme service conditions. A knowledge of their fracture properties, under various temperature conditions is vitally important in selecting the appropriate type. In the past, different attempts have been made to study the temperature effects on fracture properties of concrete and repair materials. This paper investigates the fracture behavior of two different types of injected epoxy materials at various temperatures using the wedge splitting test, at two different temperatures, namely, room temperature and - 50° C. The effect of applying repair materials to a moist cracked surface was also investigated.

2 Materials and specimen preparation

In this program, concrete was tested using aggregates from two different sites(limestone and crushed granite). For each mix, six standard 15 cm x 30 cm cylinders were tested for the determination of the concrete material properties. The dimensions of the wedge splitting(ws) specimens tested in the experimental program are shown in Fig. 1.

A total of sixty specimens were cast according to two procedures. The specimens were cast according to two procedures. They were either cast from a single mix or cast in two stages. In the later case, one half of the specimens was poured and left to cure for a period of 7 hours, the concrete surface is then roughened by sandblasting (loose material and dust were removed by air jet) and subsequently, the second half was poured in the following day. Specimens were then repaired by gluing the two halves using two different types of epoxy, given the names K and W, with a viscosity ranging between 150-200 poise at room temperature. Epoxy-K: is a two component, low viscosity, high modulus. It has a convenient 2:1 (by volume) mixing ratio and employs special colorants for contrasting component color. Epoxy-W is a two component, low viscosity, high modulus with a hardener mix ratio of 5:1 by volume.

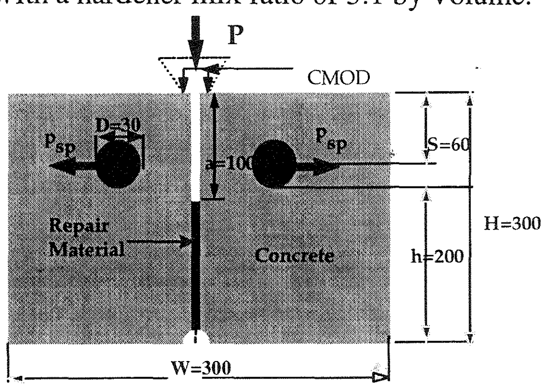


Fig. 1. Specimen geometry (mm)

3 Testing Method

Different methods are available to determine the fracture properties of concrete but there is no standard method adopted by any code of practice yet. The method used in this experimental program is the wedge splitting test. The wedge splitting test was used earlier by Linsbauer (1985). The method has also been used by Bruhwiler and Wittmann (1988) and Saouma *et al* (1989). The setup of the wedge splitting test is presented schematically in Fig. 2. First, a specimen was prepared by casting concrete and providing a notch and a groove. The specimen is then placed on a linear support, which is fixed on the lower plate of the testing machine. Two massive loading devices both equipped with rollers, are placed on the top of the specimen. A stiff steel profile with identical wedges is fixed to the upper plate of the testing machine. The actuator is then moved so that each wedge enters between the rollers on both sides. The dimensions of the groove and the notch are chosen so that the crack propagates in the vertical direction until the specimen is split into two halves. During the test, the applied load P_v (vertical component) and the crack opening displacement, *COD* were measured. The splitting force P_s is the horizontal component of the force acting on the rollers and was calculated in terms of the vertical force provided by the actuator and the wedge angle α via :

$$P_s = P_v/2 \tan \alpha \qquad (1)$$

The *COD* was measured by means of a clip gage fixed at the level where the splitting force acts on the specimen, i.e. at the axis of the rollers. The test stability i.e. (no sudden drop of load) was checked by means of a load-time plots. The tests were carried out by monotonically increasing the displacement of the actuator of the testing machine. During the test, both the splitting force P_s versus *COD* curve and the vertical force P_v versus vertical actuator displacement u curve were recorded. The fracture energy, G_F, was obtained from the area under splitting force P_s vs. *COD* curve by the projected fracture area.

4 Experimental Test Setup

A schematic representation of the test setup is illustrated in Fig. 2. It mainly consists of a cold chamber which can easily achieve and maintain a temperature of -50° C. The chamber is mounted on a mobile table to provide easy access in and out of an MTS 1.1 million pound servo controlled testing machine. The cold chamber has circular holes at its top and bottom ends in order to allow steel extension pipes with outside diameter of 168 mm and wall thickness of 14 mm to pass through.

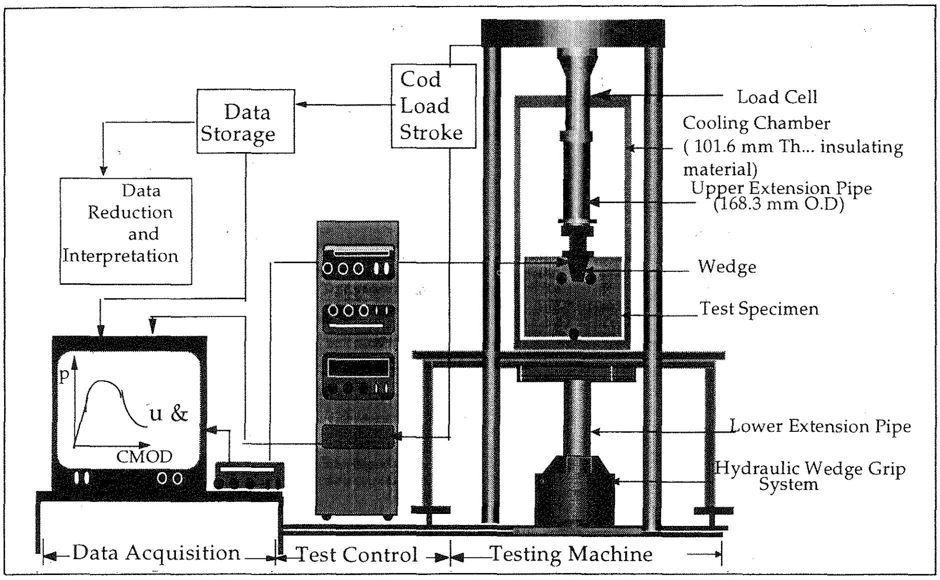


Fig. 2. Test setup

5 Testing Procedure

The specimens were tested under *COD* control, subjected to a constant *COD* rate of 0.5 μm/sec. The specimen was unloaded then reloaded to a *COD* value twice that of the first peak load and unloaded again. Subsequently, unloading and reloading of the specimen was performed with a corresponding increasing in *COD* value. The loading rate in the post-peak softening regime is increased to 3 times that of the pre-peak region. The test is terminated once the specimen is completely fractured, this normally occurs at a load level less than 1 kN. The load versus *COD*, load versus stroke and load versus time curves were displayed during tests on a computer monitor. The load versus time curve was used to maintain the stability of the test, e.g., if there is any sudden drop in load.

6 Test Results

Specimen dimensions were selected to enable a comparison with results obtained by other researchers. During the test, the vertical load, vertical displacement, time and the crack opening displacement, *COD* were measured. These results are shown in Figs. (3-9). All curves have the same general shape, i.e., the initial linear elastic response is followed by pre-peak non-linearity often referred to as slow crack growth. This is caused by the formation of micro-cracks ahead of the macro-crack. The softening regime corresponding to gradual crack growth with increased displacement and reduced load follows.

Table 1. Summary of experimental results (phase I)

Casting type	Temperature (°C)	Maximum load (kN)	Load (kN) max. split	Fracture energy (N/m)
full	room	7.9	14.7	230.7
full	-50	22.8	42.5	341
half	room	6.1	10.9	95
half	-50	14.1	26.3	155

The fracture energy G_F was obtained by dividing the area under the splitting force versus *COD* curve by the ligament area (ligament length x thickness). Main values of the experimental results for each case are summarized in Tables 1 and 2.

6.1 Influence of temperature on fracture energy

From the results plotted in Figs. 3 and 4, there is a large increase of fracture energy with decrease in temperature. The fracture energy increases by (35 - 50%) in the case of the specimens cast with joints and (25 - 50%) in case of specimens cast without a joint. It appears that structures are safer at low temperature, from a fracture point of view, than structures operating at room temperature when subjected to the same loading. Also the tensile strength of concrete increases considerably with reduction in temperature, the main influence upon this increase is exerted by the frozen moisture. Water saturated concrete may obtain a relative strength increases at - 50° C of 200 to 250% when compared with room temperature.

Table 2. Summary of experimental results (phase II)

Repair material	Condition	Temperature (°C)	Maximum load (kN)	Load (kN) max. split	Fracture energy (N/m)
epoxy K	Dry	room	13.5	25.2	125
epoxy K	Dry	- 5 0	2 0	39	--
epoxy K	Wet	room	8.4	15.72	174
epoxy K	Wet	- 5 0	17.6	36	209
epoxy W	Dry	room	11.9	22.2	135
epoxy W	Dry	- 5 0	14.5	27	--
epoxy W	Wet	room	5.8	10.9	77.5
epoxy W	Wet	- 5 0	2.15	4.1	47.5

6.2 Influence of temperature on the fracture energy of repair joints

In the case of the wet condition, epoxy-K showed a poor efficiency, with a decrease of 16 to 25% in the fracture energy in comparison with the joint before repair(interface joint), Figs. 6 and 7. At low temperature, epoxy K, showed good efficiencies with increase of approximately 15 to20% in the fracture energy and provided 30 to 40% increase in strength, although two of the specimens showed low performance. In general, this material seems to be more suited for the application. Epoxy-K in the wet condition showed very poor performance, especially at low temperature. In general, the performance of the two epoxies at low temperature was found to vary considerably.

6.3 Influence of aggregate on fracture energy

Fig. 5. shows schematically the influence of the tortuosity of the crack path on the stress transferring capacity in the descending branch. The tensile strength f_t and the fracture energy G_F are based partly on different material characteristic. The tensile strength depends on the undamaged material, while the fracture energy depends mainly on interlocking, which in turn depends on the strength and stiffness of the crack surfaces.

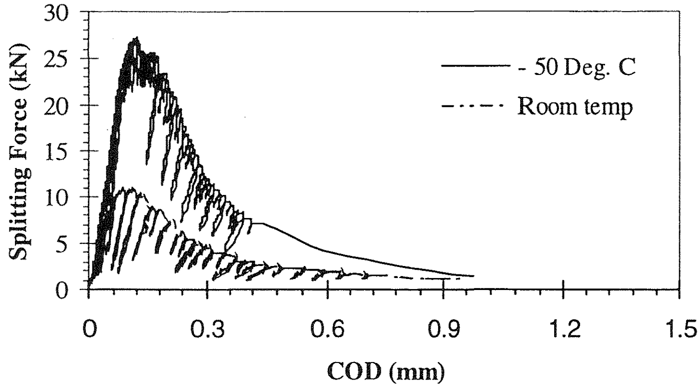


Fig. 3. Response of specimen cast in two blocks at low and room temperature

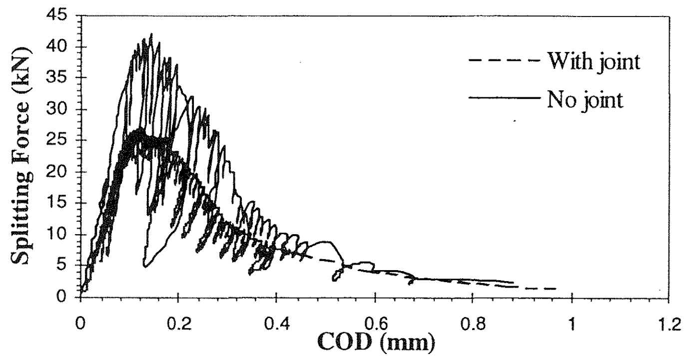
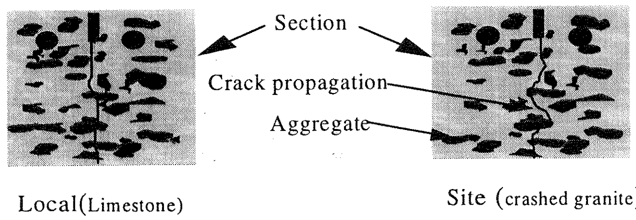


Fig. 4. Effect of simulated joint on the material response at low temperature

6.4 Effect of surface condition

From the results plotted in Figs. 6-9, the polymer repaired concrete has good performance in the dry conditions. Failure occurred within the concrete substrate away from the repaired joint. Both material polymers show low efficiencies when applied to wet fracture surfaces. A 52 % decrease in the strength and approximately 40 % decrease in the fracture energy (G_F) of epoxy-K, while epoxy-W shows a 56 % decrease in the strength and approximately 50 % in the fracture energy G_F .



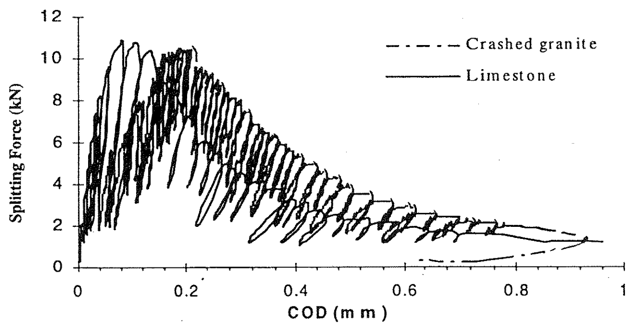


Fig. 5. Local aggregate versus site

7 Conclusions

From the experimental work, the fracture energy was obtained by means of the wedge splitting test. The influence of type of aggregate, compressive strength of concrete, type of repair material, surface condition as well as the effect of temperature on fracture energy were taken into consideration. The following comments can be made.

- The compressive strength of concrete increases with a reduction in temperature. This increase is due to the moisture in the concrete being frozen. The deformation modulus at low temperature can be twice the one obtained at room temperature. This is in agreement with published results for moduli measured in compression tests on saturated concrete.
- Fracture energy increases with decreasing temperature which suggests that at low temperature structures are safer (from a fracture point of view) than structures at room temperature .
- The peak load for specimens constructed with a joint, appear to be 40-50% lower than the one obtained from specimens without joints.
- The peak load for the specimens tested at low temperature, appear to be 50-100% higher than specimens tested at room temperature.

- The fracture energy of repaired concrete material is affected by temperature and moisture condition of the cracked surface.
- Temperature effect on the fracture properties of the materials are significant. In general, decrease in temperature causes increase in the fracture energy, G_F. This is not the case in the repaired specimens, where the effect depends on the type of the materials.

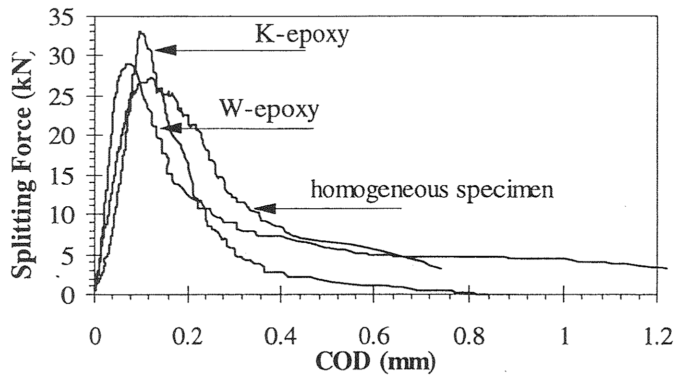


Fig. 6. Response of repair material at low temperature for dry condition

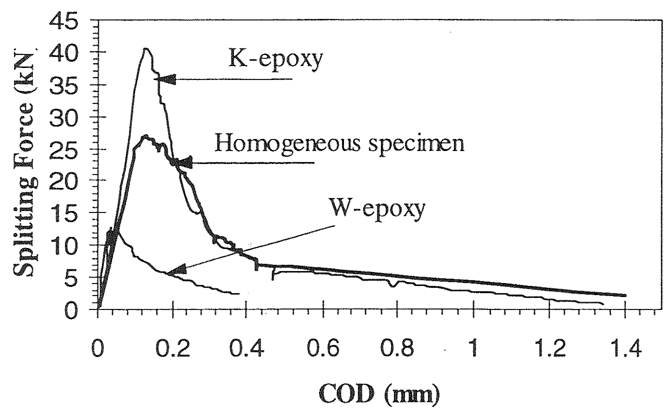


Fig. 7. Response of repair material at low temperature for wet condition

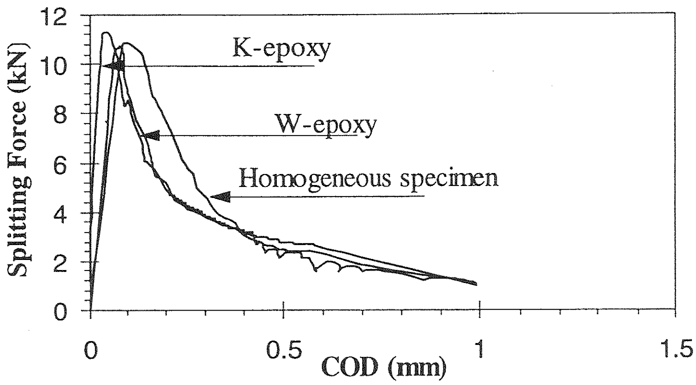


Fig. 8. Response of repair material at room temperature for dry condition

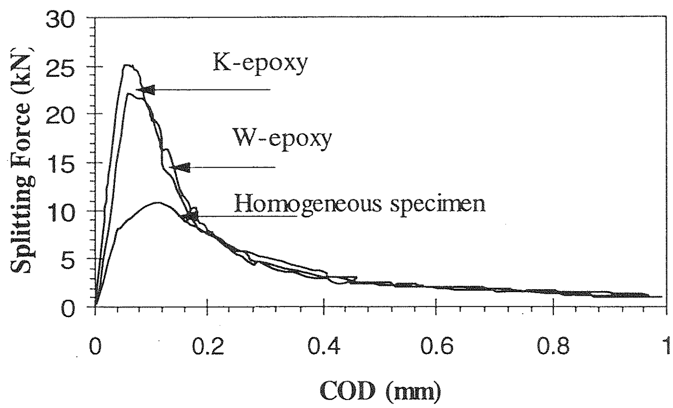


Fig. 9. Response of repair material at room temperature for dry condition

- Successive rehabilitation depends heavily on the type of repair material. Also, the response of repair materials depends on the condition of the cracked surface.
- This study gives the basic information on repair materials commonly used in concrete dams. It gives a practical method for repair of cracks in terms of surface preparation, surface moisture condition and application of repair material in the wet and dry conditions. This information is not available from manufactures; however, it is very essential for the repair process. Correct application of repair materials will results in significant reduction of cost and time used in the repair process.

8 Acknowledgments

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