Research Article

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Experimental study on hydraulic fracture behavior of concrete with wedge-splitting testing

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Abstract: The aim of this paper is to investigate the water pressure effects on hydraulic fracture behavior of concrete with wedge-splitting testing under dynamic loading. Five waterproof strain gauges are stuck along the crack path to observe the fracture process during the experiments. Four silicon water pressure sensors successfully measured the water pressure value on concrete face. The results show that the water pressure on crack faces accelerates the crack propagation of the concrete. The critical values of the splitting force decrease 26.7 and 25.6%, respectively, with the external applied water pressure of 0.2 and 0.4 MPa. Moreover, the hydraulic crack propagation speed increases at the beginning and tends to reach a peak value finally. The peak value of cracking speed is 11.08 m/s, which is high. Under dynamic loading, the water fails to fill the crack and only the trapped water interacts with the crack face. The water pressure is mainly a parabolic curve distribution along the crack path and the peak value decreases with the increase in the crack length.

Keywords: concrete, hydraulic loading, water pressure distribution, wedge splitting

1 Introduction

Concrete is a typical multiphase composite material composed of cement, water, sand, fine aggregate, coarse aggregate, and other admixtures. Due to the high strength and reliable performance, concrete has been widely used in civil and hydraulic engineering structures [1–3]. However, damage or microcracks are considered unavoidable in these concrete structures due to temperature effects, concrete shrinkage, or irregular settlement of foundation during the long-term operation [4,5]. The physical interaction between hydraulic and mechanical processes is easily induced in concrete because pores and fractures are common which can be fluid filled and deformable. A series of events including dam failures, landslides, and injection-induced earthquakes were believed to result from the water fracture interaction [6]. The pressurized water runs into the crack which affects the fracture properties of concrete and the stability of structures during the aggregation and propagation of microcracks [7,8]. Hence, it is of great importance to consider the water effect, particularly under dynamic conditions, in the design and simulation of these concrete structures and the hydraulic fracturing is a key problem that is worthy of further study.

Concrete is a typical quasi-brittle composite material and the crack propagation is steady. When the water contained in a crack experiences the sudden closing of crack, the water cannot flow out promptly and may induce additional fractures of the concrete. In order to investigate the influence of water on concrete fractures, a large number of experiments of concrete hydraulic fracturing have been carried out based on different geometries for three-point bending [9,10], compact tension [11], and wedge-splitting [12] tests. Bruhwiler and Saouma [13,14] first discussed the fracture behavior of concrete under various water pressures with a mechanical wedge-splitting device to simulate the true water environment. The relations between water pressure within crack, water front, and crack propagation have been investigated under different loading velocities and suddenly closed crack condition [15]. The trapped water within the suddenly closed crack unfortunately caused tensile stresses along the crack surface resulting in additional fractures in the concrete specimen. Based on the Double-K fracture model, the crack development in concrete has been studied under water pressure together with mechanical loading by series

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of wedge-splitting tests [16]. The results indicated that the cyclic hydraulic loading accelerated the crack propagation and decreased the maximum bearing capacity of concrete. Wang and Jia [17] carried out an experiment with a cylinder specimen to demonstrate the stress status at the ultrahigh gravity dam heel (over 200 m) indicating the importance of hydraulic effect. Many numerical models were proposed for the hydraulic fracture of concrete based on the experimental data [18–20]. The simulation results indicated that considering the water pressure in cracks leads to deeper and larger fracture propagation in concrete gravity dams [21]. However, the water pressure distribution along the propagating crack of concrete is complex and has usually been fitted into the form of linear, bilinear, polynomial, or exponential functions [13]. The calculated fracture parameters based on the softening curves are well consistent with the experimental results, while the prediction of the hydraulic pressure in the crack is limited [22]. The provision of experimental data on hydraulic fracture is necessary for numerical simulations but unfortunately insufficient and weak. There are still many things to be done in the experimental and analytical studies on the water pressure along the crack face and its influence on the fracture properties of concrete.

In this study, the hydraulic fracture test of concrete specimen under dynamic loading has been established with a wedge-splitting device in the laboratory. A sealing device with a silicone cover is employed to prevent the water pilling. Several instruments are installed on the specimen to measure the variations in the crack mouth opening displacement (CMOD), strains, and water pressure along the predicted crack path. With the experimental results, the influences of water on the fracture behavior have been discussed and the water pressure distribution is obtained using the polynomial functions.

2 Experimental methodology

2.1 Test specimens

With an advantage of a smaller material divergence between the structure and the specimen, the wedge-splitting test was usually employed to perform stable fracture mechanics tests on concrete and concrete-like materials [23,24]. Herein the specimen is cast into block shape for wedge splitting, where the size is 200 mm × 200 mm × 200 mm. Prior to casting, a steel plate was installed for fabricating a notch along the central plane and several spokes with nuts were arranged on the mold for casting holes, as shown in Figure 1(a). The angle between the notch and the top surface of the specimen is well controlled to be 90° ± 0.5°. The size of the notch is 2 mm × 80 mm × 200 mm and a precast hole with a size of ∅10 mm × 100 mm is designed for providing the hydraulic pressure. Other holes with the size of ∅1.5 mm × 140 mm are employed to record the water pressure along the crack. The configuration of the test specimen is detailed in Figure 1. Sand, fine aggregate, coarse aggregate, and ordinary Portland cement with a strength grade of 32.5 MPa are mixed and stirred thoroughly with water. The mixture proportion by weight is listed in Table 1, where the water-to-cement ratio is 52%.

During the pouring process of a concrete specimen, all operations, such as weighing, brushing, mixing, and vibrating, are performed strictly according to the hydraulic concrete standard [25]. The concrete specimen is cured in the steel mold for 24 h and then released and stored in a constant environment with a temperature of 20°C and a relative humidity of 98% for 4 weeks. Meanwhile, specimens with dimensions of 100 mm × 100 mm × 100 mm and 150 mm × 150 mm × 300 mm are prepared with the same

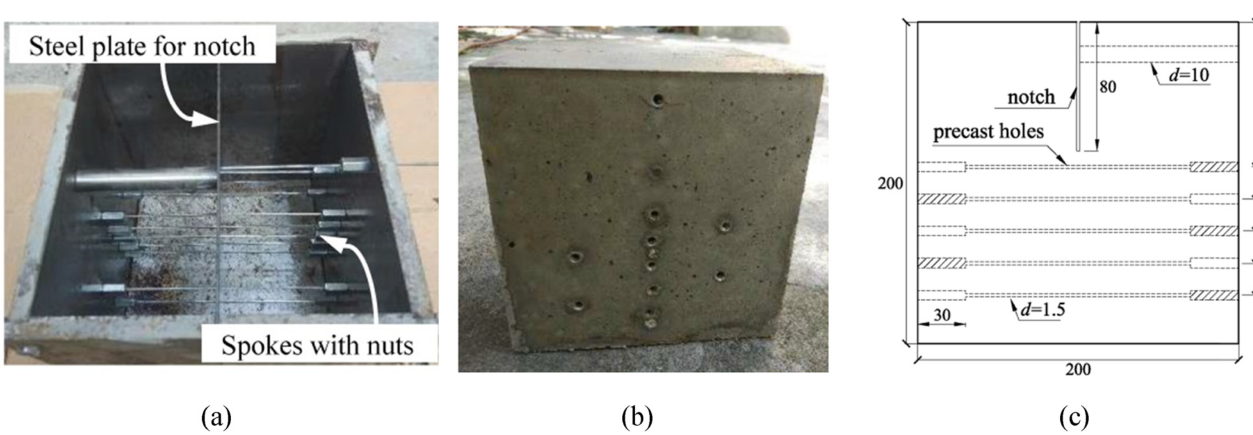

Figure 1: Configuration and casting of the test specimen (unit: mm). (a) Photograph of the mold; (b) photograph of the specimen; and (c) section view along the center.

mixture proportion in the same time. The compressive strength tests and elastic modulus tests are carried out, respectively, according to the standard [26] to provide a reference on wedge-splitting loading. The test results of the compressive strength, elastic modulus, and Poisson's ratio are given in Table 2. The results are used to provide a reference on wedge-splitting loading.

2.2 Instrumentation and test procedure

Considering the hydraulic loading using the sealing device [23], a dynamic wedge-splitting test is carried out in the laboratory to study the fracture behavior of concrete. The test is conducted on the electro-hydraulic servo dynamic testing machine, as shown in Figure 2(a). The water pressure is maintained by a water pump within the measurement range of 2.5 MPa. In order to investigate the effect of water pressure on the concrete fracture behavior, the values of load, water pressure, the CMOD, and strains along the predicted crack path are recorded during the test. Specifically, the specimen is supported by two rollers and two steel blocks are pasted on the top surfaces of the specimen on both sides of the notch. A larger splitting force is generated in horizontal direction by the wedge frame with smaller wedge angle. The load provided by the test machine is recorded by a force sensor and transmitted to the specimen face through wedge loading frame, bearing, shaft, and steel block. According to the equilibrium condition and neglecting friction, the horizontal splitting force F_h can be expressed as follows:

$$F_h = F_v/\tan\theta - F_s, \tag{1}$$

where F_v is the vertical component with the relation of $F_v = F_0/2$, and θ is the wedge angle with $\theta = 15°$. As clearly shown, the applied vertical component F_v, the specimen's gravity G, and the supporting force are in the same vertical line, thus avoiding the additional moment at the notch tip. The impact of specimen weight can be negligible.

The sealing device is mainly composed of a silicon plate, a steel board, and clamps. Both sides of the silicon plates are fixed to the specimen with clamps. The steel board is employed to limit the lateral deformation of the silicon plate. The water pressure along the predicted crack is measured by five diffused silicon water pressure sensors (labeled respectively as Sensor $1^\#$ to $5^\#$) which are plugged into the ends of the precast holes. Before the measurement of the water pressure, water is continuously poured into the sealing device through the water inlet until water flows out through the air outlet. The air outlet designed on the top of the device guarantees that the water will fully fill the cavity of the sealing device. Five strain gauges of 20 mm × 2.5 mm (labeled respectively as Gauge a–e) are installed along the predicted crack path in the half-bridge to record the strain. Meanwhile, the CMOD is recorded by YHD-50 extensometer. All signals are connected to a DH5920 dynamic strain acquisition system and the computer. A brief description of the instrumentation system is presented in Figure 2(b).

3 Results and discussion

3.1 Load–CMOD curves

When the machine force is imposed on the wedge-splitting device, a larger force is generated in the horizontal direction to split the specimen. The relationship between the machine force and the splitting force can be presented using equation (1). In order to study the effect of water pressure, the hydraulic fracture test considers different outlet pressure P_0 of water pump (*viz.* 0, 0.2, and 0.4 MPa). The concrete specimen is split under the dynamic load and water pressure. The typical recorded force–CMOD curve is shown in Figure 3(a). The concrete specimens with different applied outlet pressures behave almost the same and the curves exhibited distinct elastic stage and downward section. With the increase in the applied water pressure, the critical load of concrete specimen decreases dramatically. It is clearly indicated that the water within the crack indeed affects the fracture ability of concrete. The calculated horizontal splitting force F_h vs CMOD is determined

Table 1: Compositions of the concrete specimens

Cement type	Water/cement ratio	Sand ratio	Mixture proportion (kg/m^3)				
			Water	Cement	Sand	Fine aggregate	Coarse aggregate
32.5	0.52	0.41	182	350	761	569	538

Table 2: Material properties of concrete

Nominal strength (MPa)	Compressive strength (MPa)		Elastic modulus (GPa)		Poisson's ratio	
	Sample value	Average value	Sample value	Average value	Sample value	Average value
30	30.2	29.5	35.8	33.2	0.179	0.178
	28.7		31.7		0.172	
	29.6		32.5		0.184	

and shown in Figure 3(b). The critical values of the splitting force F_h under different outlet pressures are 19.45, 14.25, and 10.60 kN, respectively. The relative decrement in critical force corresponding to the water pressure is 26.7 and 25.6%. The bearing capacity decreases as the concrete undergoes hydraulic loading.

3.2 Crack propagation analysis

In terms of the fracture behavior of concrete, the internal micro-cracks are hardly observed in the fracture test. Five waterproof strain gauges are set along the predicted macro-crack propagation path. The outlet pressure P_0 of water pump is 0.2 MPa. The typical strain values of Gauge-a, b, c, d, and e at different times are elaborated in Figure 4. Crack propagation is completed in a very short time. Until the crack reaches the nearby Gauge points, the increments are almost zero. The first recorded crack occurs at 0.064 s on the point of Gauge-a, where the strain value is larger than 100 microstrains. Then, the crack propagation takes 0.027 s to reach Gauge-b and 0.010 s to reach Gauge-c. The rest of the crack propagation occurs extremely fast and is almost instantaneous, which means that after the crack initiation and stable growth, the crack penetrates through the specimen rapidly.

In order to investigate the cracking speed during the propagation, the crack growth ratio vs time of a typical specimen is presented and fitted using an exponential function, as shown in Figure 5. The crack growth ratio denotes the ratio of the current crack length to the total path length. To obtain the relation of the cracking speed to the crack growth ratio, a differentiation is conducted on the fitting line. The speed at Gauge-a is almost zero and increases as the crack propagates early. The peak value of cracking speed is as high as 11.08 m/s. Meanwhile, the speed finally has a trend to reach a peak value,

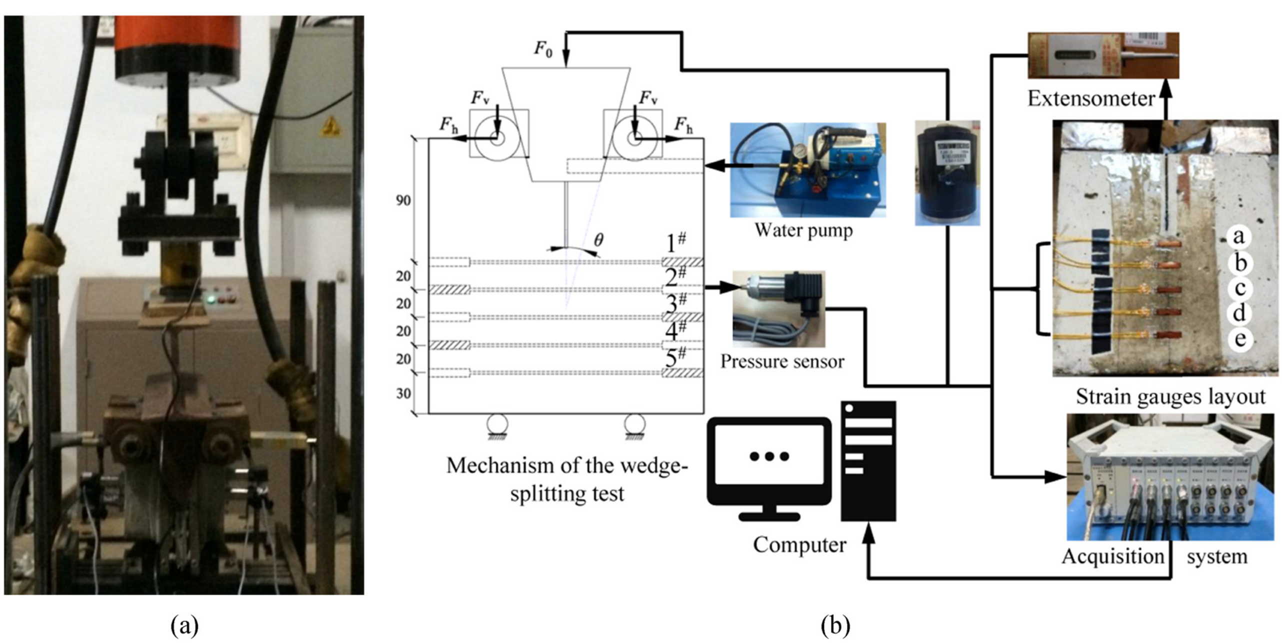

Figure 2: Hydraulic fracture test with the mechanical wedge-splitting device. (a) Test set-up and (b) wedge-splitting test instrumentation system.

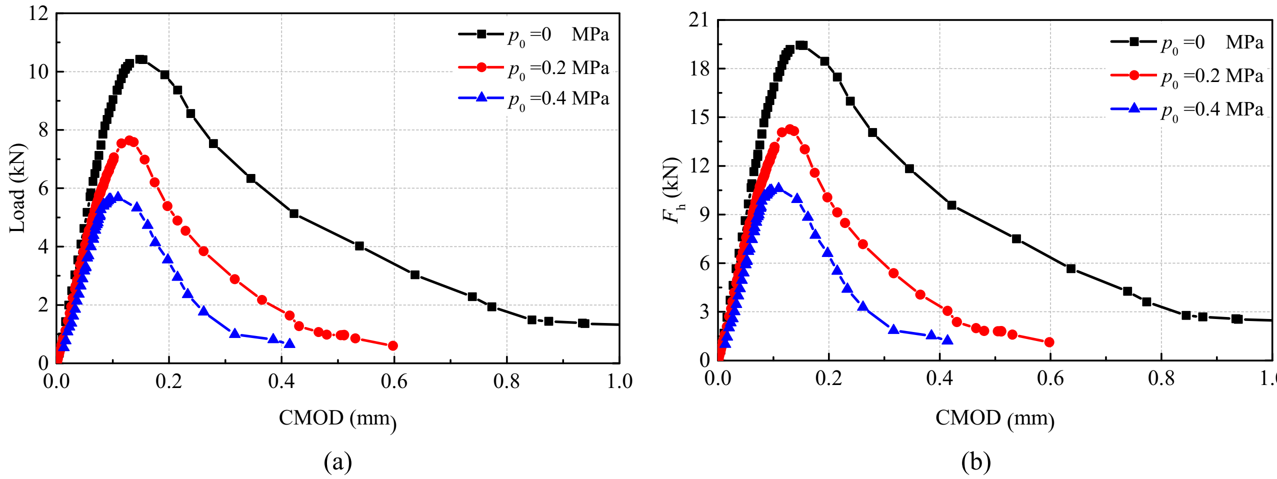

Figure 3: Load–CMOD curves with different outlet water pressures. (a) Measured initial force F_0 and (b) calculated horizontal splitting force F_h.

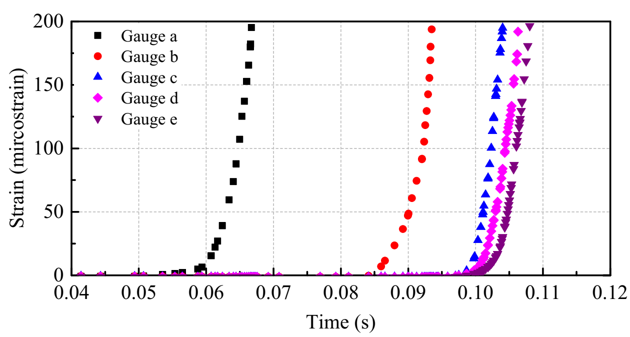

Figure 4: Strain–time curves at outlet water pressure of 0.2 MPa.

as shown in Figure 6. This phenomenon reveals the quasi-brittle property of concrete.

4 Determination of water pressure distribution

During the fracture test, five diffused silicon water pressure sensors are employed to record the variations in the water pressure in the precast holes. Fortunately, four sensors are operative and the time history curves of measured water pressure are detailed in Figure 7. Take the value of Sensor $1^{\#}$, for example, the value of water pressure increases with the crack propagation in the early stage and then reaches a peak value. The maximum value of the measured pressure is 50.98 kPa. Subsequently, the water pressure value decreases as a result of crack tip moving forward. The main reason is that the water may experience a back-flow phenomenon in the precast hole due to the fast cracking. On the other hand, the peak values of Sensor $1^{\#}$–$4^{\#}$ are different and appear to gradually decline relative to time, as shown in Figure 8. The main reason is that the crack propagation is too fast under dynamic load and the cracking speed increases rapidly, as shown in Figure 6. Correspondingly, the value of water surface tension increases with crack opening speed. The descent rate is about 1.078 MPa/s. The comparison of the crack growth ratio between the strain cracking points and water pressure sensor points is shown in Figure 9. The two time history curves experience the same varying trend and both of them are fitted well with the exponential functions. However, the variation in water peak pressure is later than the variation in strain.

In the terms of hydraulic fracture behavior of the concrete, the internal water pressure plays an important

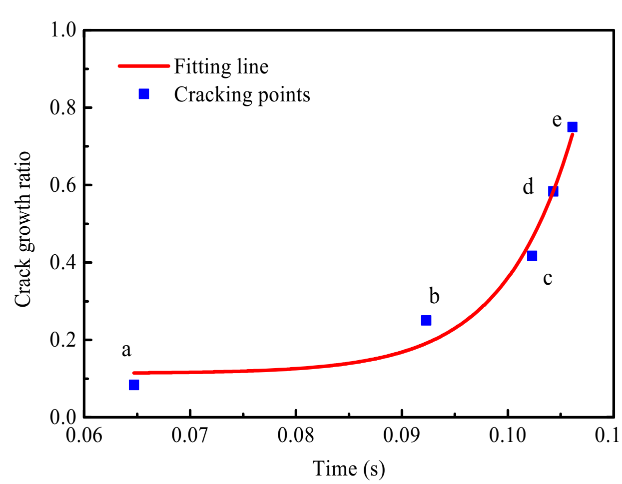

Figure 5: Crack growth ratio.

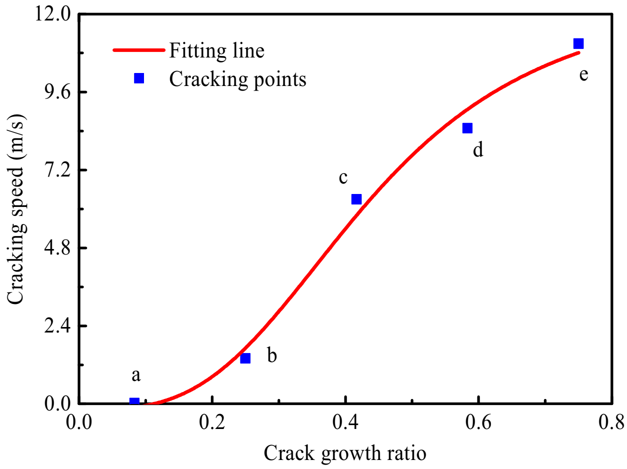

Figure 6: Cracking speed during propagation.

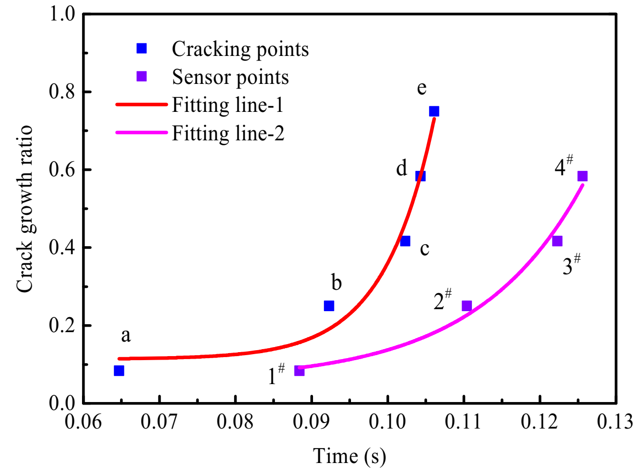

Figure 9: Comparison of crack growth ratio.

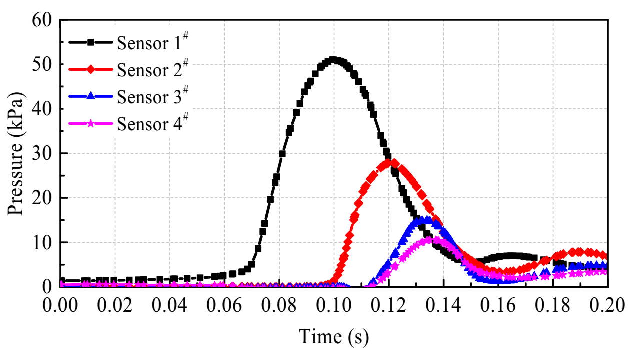

Figure 7: Time history curves of measured water pressure.

role to induce the crack. In order to investigate water pressure distribution along the crack face, the values of the diffused silicon water pressure transducers have been drawn out at the same time from Figure 7. Several water pressure values on the crack path at different times are detailed in Figure 10. Meanwhile, the distributions along the crack surface are predicted using polynomial functions. The water pressure can be expressed as follows:

$$\sigma_w = a_0 x^2 + b_0 x + c_0, \tag{2}$$

where σ_w denotes the water pressure, x is the distance of the water front, a_0, b_0, and c_0 are the fitted coefficients. Here $a_0 = -0.056$, $b_0 = 0.085$, and $c_0 = 54.45$ ($t = 0.1038$ s).

As shown in Figure 7, the water distribution is regarded as a linear relation at the beginning ($t = 0.0762$ s). Later, the water pressure presents a parabolic curve distribution along the crack path. Compared with the water pressure under quasi-static loading in previous work [21], the magnitude of water pressure within the crack decreased dramatically from the outlet water pressure. Meanwhile, the peak value of the measured water pressure gradually decreases with the crack propagation and the slope of the water pressure distribution curve decreases with the increase in the crack length. The main reason is that the crack propagation is too

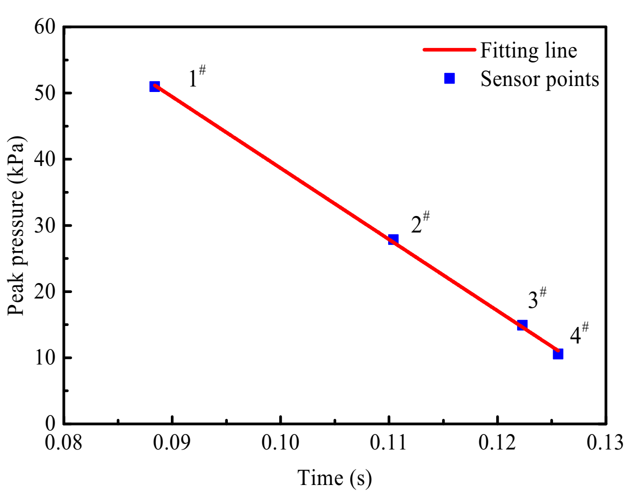

Figure 8: Peak pressure vs time.

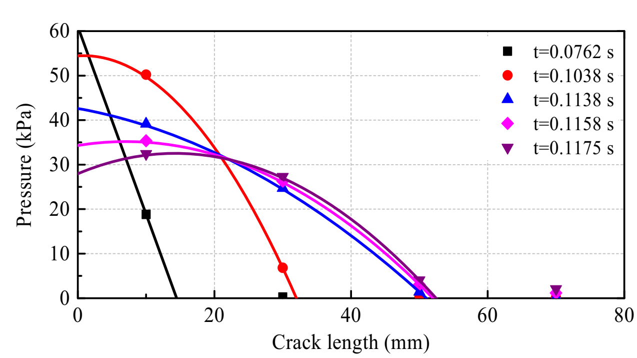

Figure 10: Typical water pressure distributions along the crack face.

fast under dynamic loading and the water fails to fill the crack. The trapped water flows into the crack and imposes on the crack faces. There was only a small amount of water continuing to go into the crack before the failure of the concrete specimen. The loading rate greatly affects the water pressure distribution and crack propagation.

5 Conclusion

The hydraulic fracture test of concrete specimen under dynamic loading has been studied to investigate the water influence on crack propagating properties. The strain varying along the crack path has been observed by the preset five water proof strain gauges. Four silicon water pressure sensors successfully measured the water pressure value on the concrete face. Based on the obtained experimental results, the hydraulic fracture behavior of the concrete has been analyzed and discussed. The water pressure distribution model along the crack surface with respect to the applied water pressure and the crack length was introduced. The following conclusions are drawn:

(1) A simple but useful hydraulic fracture test is established with a wedge-splitting device. According to the measured load–CMOD curves, the crack propagation of concrete is accelerated by the water pressure on the crack faces. The critical values of the splitting force decrease by 26.7 and 25.6%, respectively, with the external applied water pressure of 0.2 and 0.4 MPa.

(2) During the concrete splitting test, the hydraulic crack propagation presents a quasi-brittle fracture process and the speed is not a constant. The speed increases as the crack propagates until it reaches a peak value and the peak value is as high as 11.08 m/s.

(3) Under dynamic loading, the water fails to fill the crack and only a small amount of water pressure continues to impose on the crack faces during crack propagation. The water pressure is mainly a parabolic curve distribution along the crack path and the peak value decreases with the increase in the crack length.

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Conflict of interest: We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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