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FRACTURE PROPAGATION MODE OF COAL UNDER INDIRECT TENSILE STRESSES

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ABSTRACT: This work presents the results of an investigation on the study of fracture pattern in coal under induced tensile stresses using image processing techniques. Several high-speed recordings captured at 5 kHz and above were examined, and three distinct fracture propagation modes were identified. As the coal tensile strength increases, the fracture behaviour was observed to be a spalling-like rupture in the form of a dominant tensile crack accompanied with multiple large secondary shear fractures that break the test specimen apart into several pieces. Combined localised tensile and shear cracks at intact rock bridges within a coal Brazilian sample (with pre-existing defects) was also observed, indicating a very different failure pattern from that in standard recommendations.

INTRODUCTION

Rock burst and spalling is a spontaneous and violent rock failure that occurs (within moments or seconds) commonly in high-stress deep mines in stiff and competent rocks. It produces flakes with sharp edges, flat cutting pieces, and large fragments. According to the literature, initiation and propagation of unwanted tensile cracks is responsible for such catastrophic and disastrous rock failures (Diederichs and Martin, 2010). But, rockburst is only one of the many cases in geomechanics where the rock breakage is predominantly governed by tensile (brittle) cracking. Other examples in which rock tensile fracturing plays a critical role include: (i) hydraulic fracturing, (ii) shallow tunnels where horizontal stresses are much larger than the vertical stress components, (iii) deep circular excavations where the horizontal stresses are less than one-third of the far-field vertical (gravitational) stresses - according to the Kirsch theory (Hudson and Harrison, 1997; Serati, et al., 2020), (iv) weak rock types such as lightly cemented sandstones and clay-rich rocks such as shales when lightly confined (Kaiser and Kim, 2008), and (v) in large open pit slopes and high mountain (Stead, et al., 2007). A proper estimation of rock tensile strength is therefore critical in a wide range of rock engineering applications. The coal longwall caving, in particular, requires the knowledge of rock tensile activity and its location which in turn assists in managing longwall geomechanics and associated issues in caving control.

The rock mechanics literature is almost exclusively replete with both direct and indirect testing methods to estimate rock tensile strength. Some of the widely accepted testing standards include the direct tensile test (ISRM, 1978), ring test (Serati and Williams, 2015), truncated Brazilian test (Serati, et al., 2017), Hydraulic fracturing test, block and double punch tests, pull-off test (Cacciari and Futai, 2018), the Point load strength test (Serati, et al., 2018), bullet-shaped tensile testing (Serati, et al., 2015), the flattened Brazilian disc test (Perras and Diederichs, 2014), and testing of a sphere under concentrated loads (Chau and Wei, 1999). While the direct tensile test provides the most reliable rock strength value in tension, samples often fail outside the centre at grip points in practice (i.e. premature anchorage failures). The test is also relatively more expensive compared to other alternative methods, and unwanted induced bending stresses often interfere with the test results.

The Brazilian test method was presented first in September 1943, at the 5th meeting of the Brazilian Association for Technical Rules, and has become very popular since then, mainly due to its ease of preparation and interpretation (Perras and Diederichs, 2014; Masoumi, et al., 2017). In this inexpensive test, a disc is loaded between two points across its diameter until it fails under uniformly distributed induced tensile stresses at the vicinity of the sample centre. Knowing the sample geometry (e.g. radius r and thickness t) and the load at failure (F), the material tensile strength (σ_t) can be

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calculated using Equation 1. However, according to Griffith's strength criterion, it should be noted that the test is only valid if the sample breaks into two equal haves due to the formation of a single crack initiated at the specimen centre, where the induced tensile stress is the maximum.

$$\sigma_t = \frac{F}{\pi\, r\, t} \tag{1}$$

To study the fracture mode of coal under induced tensile stresses, the Brazilian test was performed in this research work and coal samples of different strength values were tested using high-speed photography techniques.

EXPERIMENTAL SETUP

A total of 15 different coal samples were prepared and tested according to the American Society for Testing and Materials (ASTM) or International Society for Rock Mechanics (ISRM) standards (ISRM, 1978; ASTM, 2016). For the ASTM tests, samples were tested in direct contact with load frame platens under a continuously increasing compressive load until failure. To record the fracture propagation pattern, a Phantom v2012 camera was utilised. The camera is capable of recording at up to 1,000,000 frames per second (fps) at reduced resolution or 22.5 kHz at a full resolution of 1280 x 800 pixels (Phantom, 2020). Our previous investigations (Serati and Williams, 2015; Serati, et al., 2018; Xu, et al., 2018; Bahaaddini, et al., 2019) suggest that such capabilities make the camera system a very suitable gear for monitoring cracking processes in brittle solids. To identify the type of fracture pattern, each video recording was then carefully examined frame by frame using Phantom Camera Control (PCC) image processing software to identify the frame position in which the first macro crack became visible and then the last frame in which the specimen was fully disintegrated. In some cases, the edge Sobel vertical (i.e. Sobel operator), the edge Prewitt vertical or Laplacian filters were used to ease the monitoring of tensile crack propagation pattern (Phantom, 2020). For each test, the load at failure, frame number at which the first crack was identified (and its corresponding force and deformations), and the sample's tensile strength; were recorded. All tests were conducted at 450 N/sec.

It is well understood that the presence of water in water-sensitive soft rocks can soften its textures, loosening its structure and increasing its deformability leading to an overall reduction in the material's strength (Joseph et al., 2009; Brady and Brown, 2004). After the completion of all Brazilian tests, it was therefore decided to further measure the moisture content for each tested coal sample by calculating the ratio of the bulk mass of the tested specimen to its dry mass after being dried in an oven for at least 24 hrs. However, due to the flammability of coal, the oven temperature was kept at 60 °C. In addition, bulk, saturated, dry weight density and porosity (n) were also measured using Equations 2 and 3.

$$n = \frac{100\, V_v}{V}\ \% \tag{2}$$

$$V_v = \frac{M_{sat} - M_s}{\rho_w} \tag{3}$$

In the above equations, V_v is the pore volume measured as a ratio of saturated mass (M_{sat}) subtracted by solid (dry) mass to the water density (ρ_w). To measure the rock porosity, the coal samples were saturated for 24 hrs by using a vacuum chamber and then dried in an oven for another 24 hrs (Paul WJ, 2002; Kacy M, 2013). Table 1 and Figure 1 summarise the obtained results, but for consistency, only the test performed by the ASTM method are presented and discussed in this report.

After careful examination of all high-speed recordings, three distinct fracture types were identified (see also Figure 1):

Type I: in samples exhibiting Type I fracture mode, a single straight tensile crack is initiated at the middle of the sample and propagates radially in both directions towards the outside of the specimen along the axis of diametral compressive loading. This is the accepted fracture pattern for standard Brazilian tests based on Griffith fracture criterion, where a single crack splits the sample into two halves (see Figure 1a).

Table 1: Summary of the test results

Sample	Moisture content [%]	Dry density [kN/m^3]	Porosity [%]	Tensile Strength [MPa]	Observed Fracture Pattern (see also Fig. 1)
S-01	0.7	10.29	2.16	2.89	Multiple cracking
S-02	1.5	11.90	11.53	1.35	Multiple cracking
S-03	1.0	12.33	7.33	0.83	A single straight crack
S-04	3.2	12.08	12.20	0.47	Cracking through rock bridges
S-05	1.7	12.21	8.37	0.52	A single straight crack
S-06	0.9	11.51	4.82	0.17	Cracking through rock bridges
S-07	0.8	11.91	7.13	1.87	Multiple cracking
S-08	1.5	12.11	9.84	0.38	Cracking through rock bridges
S-09	1.8	11.81	11.45	0.28	Cracking through rock bridges

Type II: in this fracturing mode, the central tensile crack propagates outwards in either direction to the edges of the specimen along the axis of diametral loading. But, unlike Type 1 above, when the tensile fracture has fully propagated to the outside of the sample boundary, moderate-sized inverse shear conical plugs are formed in the vicinity of contact points. The shear fractures then propagate back towards the centre of the sample (see also Figure 1b). However, it was observed that the secondary induced shear cracks do not necessarily propagate fully through the sample diameter and either terminate inside the intact material or join the central tensile crack. From the results in Table 1 and Figure 1 combined, it can be deduced that Type II cracking mode is mostly observed in specimens with the highest tensile strength. That is, the more brittle and the stronger the coal sample in tension, the higher the possibility of observing multiple cracking in the coal Brazilian testing; hence deviating from the standard recommendations.

Type III: this fracture growth involves an interesting pattern of smaller-scale tensile and/or shear cracks happening simultaneously at local points through intact rock bridges (i.e. non-persistent pre-existing flaws) inside the Brazilian test domain. Given that rock bridges are distributed randomly in different directions with various scales, the final rupture surface was reported with different directions in each sample; instead of a single straight central crack (see also Fig. 1c, d, e, f). Figure 2 illustrates the time-lapses of a typical Type III fracture pattern in which highlighted areas represent points where rock bridge failures were first identified at each stress level.

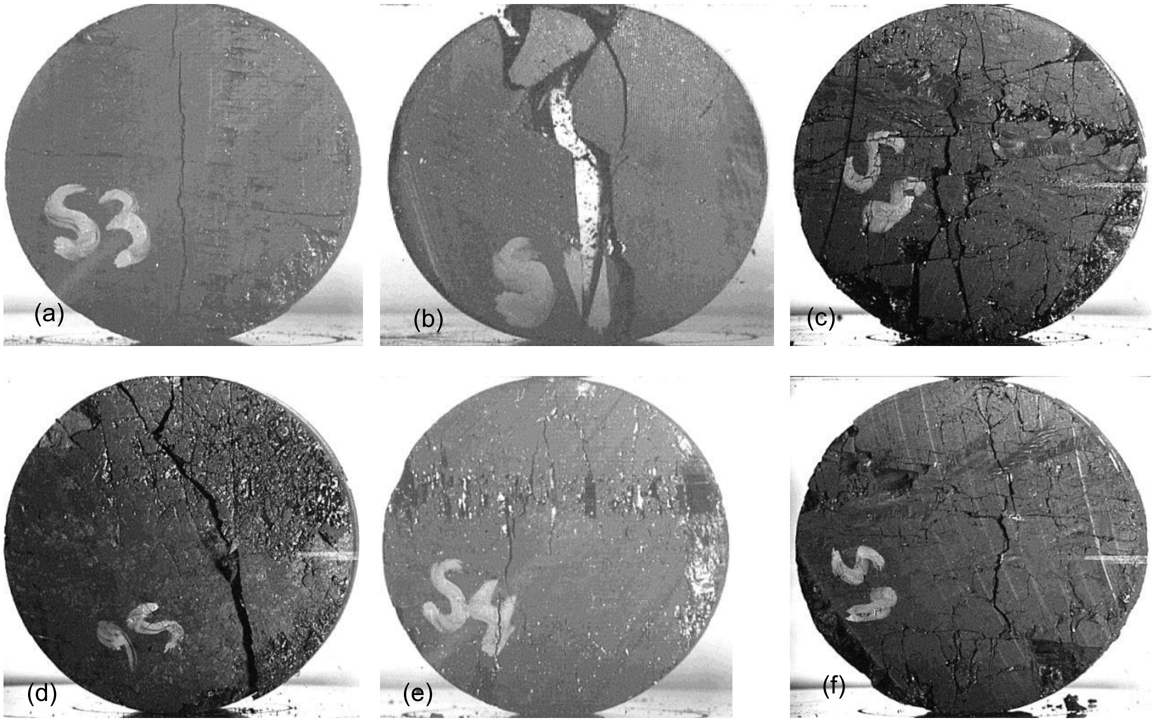
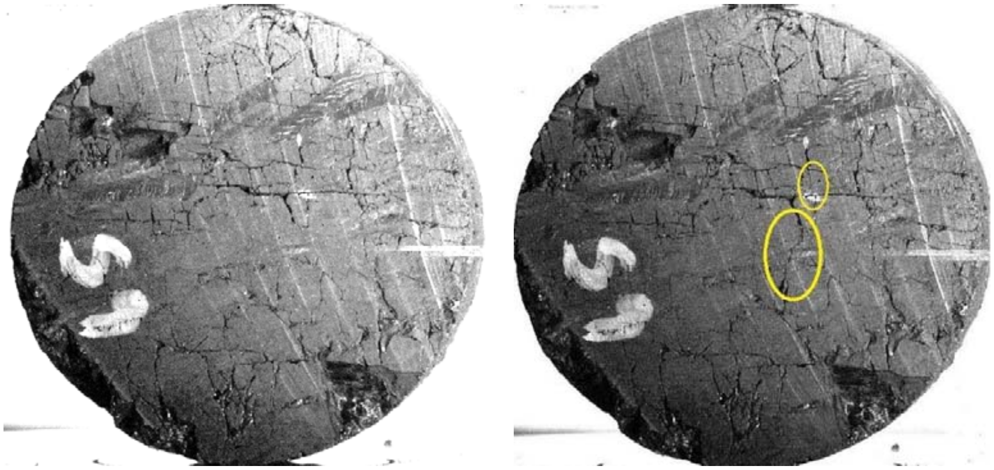


Figure 1: Three distinct fracture formation patterns observed during Brazilian testing of coal at 3,500 fps including: (a) formation of a single straight crack at the sample centre, (b) multiple cracking, and (c, d, e, f) cracking through intact rock bridges

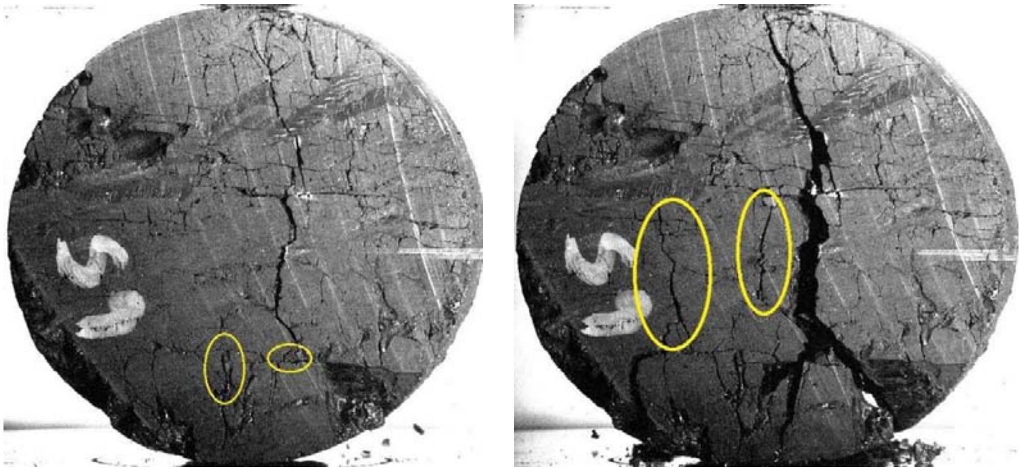
RESULTS AND DISCUSSIONS

As shown in Figure 2, if the fracture mode is governed by breaking through rock bridges in tension (or shear), visible macro cracks are always formed prior to the sample reaching its peak strength in the Brazilian test. The force of failure then provides an overestimation of the sample’s tensile strength if used and plugged into Equation 1. Alternative testing techniques should then be adopted instead, or an adjustment factor is to be applied to the test results to compensate for the overestimation of material’s tensile strength. It is therefore concluded that extreme precautions should be taken when the Brazilian test is utilised for testing of coal samples with pre-existing defects; otherwise, the fracturing process will be governed by the rupture of rock bridges thus making the test invalid and erroneous. The same applies when testing high strength brittle coal specimens in which multiple cracking becomes the dominate rupture mode, hence making the test results invalid. The key question raised form this investigation is that how a proper adjustment factor can be introduced for Brazilian testing of highly fractured or very brittle coal samples to make the test results reliable for design purposes. To answer this key question, further research and more tests are planned and are underway, which will be the subject for future studies.



(a) 5% of the maximum failure force

(b) 30% of the maximum failure force



(c) 80% of the maximum failure force

(d) 95% of the maximum failure force

Figure 2: High-speed time-lapses of Type III fracture pattern captured at 2,600 fps

CONCLUSIONS

Using high speed image processing techniques, different coal types with various strength properties were tested under Brazilian indirect loading conditions to study fracture propagation mode of coal under induced tensile stresses. Three distinct cracking patterns were observed, including: (i) a single central tensile crack, (ii) multiple cracking, and (iii) progressive failure of intact rock bridges that were often initiated well below the sample's ultimate Brazilian strength. From the results, it is suggested that extreme precautions should be taken when the Brazilian test is utilised for testing a highly fractured or a brittle coal with relatively high tensile strength for which the standard recommendations are difficult to be followed entirely. That is, for coal samples in which the Brazilian fracture mode is not a valid single crack, it is seems a significant leap to utilise such results to deduce the coal tensile strength correctly.

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