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Brittle – Ductile Transition of Oil Shale

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Abstract. The importance of oil shales as an economical substitute to conventional resource has increased many folds. The extraction of petroleum from these resources at a commercial level can be achieved with the help of wellbore and hydro-fracturing. The major problem occurs while excavating the wellbore are due to the very high in-situ stresses. Therefore, the selection of material model for the designing of wellbore will depend on the failure mechanism. At greater depth the failure of rocks changes from Brittle to Ductile, and hence the rheological model for brittle or ductile region will not work in semi-brittle region. Therefore in the present study, the oil shale rock from Assam is considered due to its oil bearing nature. The samples collected from the site are tested under the high confining pressure ranging from 2 to 30 MPa at different anisotropic angles. The effect of confinement and anisotropy on the strength is studied in detail. From the investigation, it is found that the material shows brittle behavior at low confinement, whereas at high confinement it shows Brittle - Ductile transition. It is also observed that the anisotropy plays a critical role in defining the brittle-ductile transition zone. It is observed that the oil shale undergoes the transition from brittle to ductile at 30 MPa of confinement for 0 and 90° anisotropy angles. Which shows that at greater depth the generalised design philosophy will not work well. Further, the transition for 30° anisotropy angle starts at 12.5 MPa of confinement pressure. Therefore, the designing of wellbore should be carried out by using nonlinear anisotropic strength criterion.

Keywords: Oil Shale; Brittle – Ductile Transition; High Pressure, Anisotropy

1 Introduction

The exploration for alternative energy sources to petroleum has increased in recent past due to increase in demand and depletion of existing petroleum reserves. The cost of import of petroleum is also increased, therefore every country wants to become self-reliant in the energy sector. The worldwide presence of oil and gas shale is immersed as an economically viable substitute. Before 80’s, it was not economical to extract oil from these reserves due to technology deficiency, but now many countries have started the extraction at a commercial level with the help of technological improvements in hydro-fracturing.

These resources are considered as unconventional oil in unconventional rocks, and the depth of deposition vary from a few meters to few thousand meters. The most common approach for oil extraction is drastically breaking the bond of the organics which involves in-situ retorting process. The three stages associated with this procedure are fracturing, injection to achieve communication and fluid migration at the underground location [1]. Hence, the Geomechanics study of shale rock is vital for the effective recovery of shale oil/gas such as wellbore instability, optimization of hydraulic fracture, etc. The failure attributes of shale are complicated and are chiefly controlled by their complex fracturing pattern and restricted transport properties such as permeability and porosity [2]. On the other hand, the fracturing behaviour of shale will depend on varying environmental factors such as temperature, water and in-situ pressure condition. Understanding the fracturing behaviour accompanying the failure scenarios of shale is imperative in the planning of stimulation operations in shale reservoirs for enhanced oil and gas recovery.

The extraction process requires the drilling of wellbore (Horizontal and Vertical) at greater depth, and with increasing depth the pressure and temperature also increase. Hence, under these extreme conditions, the rock undergoes a transition in failure mode from localized brittle fracture to nonlocalized plastic flow. This transition has important implications on problems related to wellbore stability. The existing rheological models for the lithosphere are important for a many geophysical problems, and the extrapolation of either brittle fracture or plastic flow laws into the semibrittle regime results in significant overestimation of strength [3, 4, 5, 6]. The long term stability of the underground structures depends on the time dependent behaviour of surrounding rockmass [7, 8, 9, 10]. At greater depth, the brittle and ductile zones may develop in an engineering rock mass due to tectonic stress [11, 12]. After excavation of underground opening, the creep behaviors may be observed for the surrounding rock, which is caused due to change in the applied stress. This affects the distribution and magnitude of engineering disasters, such as time delayed rockburst and deep fracturing [13, 14, 15]. The brittle and ductile properties of the rocks will also be affected by σ_3 and σ_2 simultaneously [16, 17, 18]. The value of σ_3 can increase the ductility of rocks, whereas the brittleness of rock increases with increasing σ_2. To date, research on brittle and ductile creep under true triaxial stress is rare.

Therefore, many researched developed the procedure for finding the brittle-ductile transition point. Mogi [19] divided the brittle ductile zone by a straight line on the basis of the extensive experimentation performed on different rocks. The ductile behaviour is characterized by the deformation without any decrease in the stress after yield point. The slope of the straight line defining the transition between brittle and ductile behaviour of rock is expressed in the term of strength (σ_1) and confinement (σ_3) as ($\sigma_1 - \sigma_3$) = $3.4\sigma_3$. Byrelee [20] studied the brittle ductile transition on the basis of frictional data for sliding on faults by drawing the single curved envelop. The envelop is developed by transforming the $\tau - \sigma_n$ envelop into σ_1 and σ_3 coordinates by using following equations: $\sigma_1 - \sigma_3 = 2.31r$ and $\sigma_3 = \sigma_n - 2.31r$. Barton [21] investigated the Mohr envelopes of triaxial data representing the peak shear stress reaches a point of zero gradient after crossing the critical state line having a gradient of $\tau/\sigma_n = 0.5$. The failure at critical state is represented by the ratio $\sigma_1 = 3\sigma_3$. Ramamurthy [22] and Behrestaghi [23] suggested that the brittle - ductile transition for intact and jointed rocks occurs when $\sigma_1/\sigma_3 = B_{i,j} + 1$, where $B_{i,j}$ is a material constant which depends on material response to stress state and material quality. It is also found that the transition will occur when σ_1/σ_3 approaches to unity, and at this point $(\sigma_1 - \sigma_3)/\sigma_3$ becomes equal to $B_{i,j}$. Whereas, other propositions considered in the present does not account the material properties of the rocks. These procedures depends only on the single constant ratio of σ_1/σ_3 for all type of rocks.

Nygard et al. [24] and Gutierrez and Nygard [25] experimentally studied the brittle–ductile transition, in shale and mudrock. The experimental study is based on triaxial tests on different mudrock and shale from North Sea reservoirs and adjacent areas sheared at different effective confining stresses. The deformation can be brittle or ductile depending on the properties of the mudrock and the effective confining stress level. The ductile behaviour is characterized by contractive response and gradual deformation to failure. Whereas, brittle deformation is characterized by dilative response and sudden failure at a well-defined peak shear strength followed by strain softening down to residual shear strength. Hence, the selection of the proper rheological model for the designing of the wellbore will depend on the brittle ductile transition boundary.

Therefore, in the present study, an attempt is made to understand brittle ductile behaviour of oil shale rock by considering the effect of anisotropy. The favourable characteristics of Assam coal for conversion to liquid fuels have been known for a long time. Studies have indicated that these coals and carbonaceous shale constitute the principal source rocks that have generated the hydrocarbons produced from the region. The detailed investigation is carried out to understand the strength behaviour of these anisotropic rocks under uniaxial and triaxle loading condition. The anisotropy angles considered in the present study are 0, 30, 45, 60, and 90°, respectively. The brittle ductile transition zone for the oil shale rock is found out for different anisotropic angles.

2 Geology and Sample preparation

The samples are collected from the tikka parbat of the Makum coal field. The Makum coalfield is the largest coalfields of North Eastern region of India, as shown in figure 1 (a) and (b). It falls between latitudes 27°15’ and 27°25’ N and longitudes 95°40’ and 96°5” E. The rock formation of the Makum coalfield belongs to Tertiary age, and are exposed in a narrow SW belt of imbricate thrust, flanking the Naga-Patki hills, and extended from Haflong in the southwest to Mio Bum in the northeast. The shale/oil shale and sandstone of Tikak Parbat are interbedded with the coal, and the coal and carbonaceous shale of the location is considered as the principal source rocks of the hydrocarbons produced from the region [26, 27].

(a) (b)

Fig. 1. Site for sample collection (a) Tikak Parbat and (b) Blasted material

The specimen for the testing are prepared as per the ISRM suggested method [28], the experimentation is performed on the cylindrical specimens of length to diameter ratios of 2. These cylindrical specimens are prepared by drilling operation on parent rock sample in laboratory or at site using portable core drilling machine. The coring (44 mm diameter) is performed for different angles with respect to coring direction (0^o, 30^o, 45^o, 60^o and 90^o), as shown in figure 2 (a) and (b). While coring, the water was used in controlled manner to avoid the core damage.

3 Mineralogy and Physical Properties

The mineral composition of oil shale rock is carried out through X-ray diffraction analysis. The mineral identification is carried out using JCPDS-ICDD 2002 (International Centre for Diffraction Data) database through search and match technique. The qualitative investigation shows that the oil shale predominantly consists of quartz (Q) and general clay (kaolinite + illite), whereas small traces of plagioclase (Pl), K feldspar (F), pyrite (P), calcite (C), and other metal sulfides (S) are also present.

Further, the physical properties of oil shale are determined in accordance with IS: 13030 [29] and ISRM [28]. The density of all the oven-dried oil shale samples shows the variation between 2.40 to 2.80 g/cc, whereas the average dry and saturated densities are 2.52 and 2.56 g/cc. The specific gravity value obtained from the experimental investigation is 2.6. The sonic wave velocity of oil shale rock at 0^o and 90^o anisotropy angle is 3614 and 1506 m/s. The porosity value obtained from the experimentation is 9.27 % and 4.82 % at 0^o and 90^o anisotropy angles, respectively.

4 Uniaxial and Triaxial Testing Equipment

The UCS and Triaxial tests are carried out in a 1000 kN loading frame by applying a constant rate (0.01 mm/sec) of deformation with an accuracy of ± 0.002 mm, as per ISRM test procedure [28]. To achieve the uniform stress distribution and to minimize end friction, the Teflon sheets of 0.5 mm thickness are placed between the loading platen and specimen at both ends. The Servo controlled triaxial setup is shown in figure 3.

5 Results and Discussions

5.1 Strength Behaviour

The effect of confinement on the failure strength of oil shale rock is investigated by testing the specimens in high pressure triaxial cell at different anisotropy angle (β) and confining pressure or minor principal stress (σ_3). The values of failure stress or major principal stress (σ_1) obtained from the experimentation at different confining pressures for different anisotropic angles is presented in table 1. The variation of σ_1 with σ_3 at different β angles for oil shale rock is shown in figure 4. The plots are drawn by taking the average experimental results into consideration. It is observed from the figures that the curves between σ_1 and σ_3 shows nonlinear behaviour for all the cases. It is noted that the failure strength at $\beta = 90^o$ is maximum, and the minimum strength is obtained at $\beta = 30^o$. It is also found that the failure strength under 10 MPa pressure at $\beta = 0^o$ and 90^o are 1.6 times the failure strength at unconfined state. Further, the failure strength at $\beta = 30^o$ under 10 MPa confinement stress is 2.6 times more than that at unconfined stress state. It is also found that the increase in strength is more at $\beta = 30^o$ as compared to the other orientation angles.

5.2 Brittle – Ductile Transition

In the past many researchers investigated the brittle – ductile transition zone by dividing the $(\sigma_1 - \sigma_3)/\sigma_3$ verses σ_3 plot into brittle and ductile region by a straight line. Mogi [19] divided the brittle and ductile region by using straight line with slope defined by $(\sigma_1 - \sigma_3) = 3.4\sigma_3$. Mogi observed that the brittle – ductile transition boundary is curved by studding the weaker marbles and limestone. Byrelee [20] studied six different rocks, and the brittle-ductile transition is investigated by plotting σ_1 verses σ_3 curves. It is found that, envelop is curved up to 100 MPa of confining pressure, after which it becomes straight line. The brittle and ductile region are separated by a straight line having relation $(\sigma_1 - \sigma_3) = 2.8\sigma_3$. Further, Barton [21] observed that the brittle-ductile transition occurs when $(\sigma_1 - \sigma_3) = 2.0\sigma_3$. Ramamurthy [22] and Behrestaghi [23] suggested that the brittle - ductile transition for intact and jointed rocks occurs when $\sigma_1/\sigma_3 = Bi,j +1$, where Bi,j is a material constant which depends on material response to stress state and material quality. It is also found that the transition will occur when σ_1/σ_3 approaches to unity, and at this point $(\sigma_1 - \sigma_3)/\sigma_3$ becomes equal to Bi,j. These procedures depends only on the single constant ratio of σ_1/σ_3 for all type of rocks. Therefore, in the present study, the investigation on brittle – ductile transition behaviour of oil shale rock is carried out to understand the effect of anisotropy angle on the brittle – ductile nature of such rocks. The comparison of brittle-ductile boundary lines suggested by Mogi [19], Byrelee [20], Barton [21], Ramamurthy [22] and Behrestaghi [23] for oil shale rock is shown in figure 5. The brittle- ductile transition by Ramamurthy's approach is evaluated by considering the Bi,j = 2.2, on the bases of the triaxial test data. It is observed that, above 12.5 MPa of confining pressure only one orientation angles i.e $\beta = 30°$ falls in the ductile region, whereas all other anisotropic angles falls in the brittle zone of failure. The studies related to the Mogi's approach revels that the oil shale rock falls in ductile region above 27.5, 7, 13, 24 and 30 MPa of confining pressure at 0, 30, 45, 60 and 90° anisotropic angles. Similarly, the studies related to Byrelee's approach suggests that only one angle i.e. $\beta = 30°$ fall in the ductile region for pressure above 9 MPa, and all other orientation falls in the brittle region. Whereas, Barton's approach showed the similar type of results for transition as observed from Ramamurthy's approach, because the value of Bi,j considered is close to 2.

(a) (b)

Fig. 2. In situ coring of the specimen (a) portable coring equipment and (b) preserved samples

(b) Data Accusation System

(a) Compression Frame

Fig. 3. Complete triaxial setup for UCS and triaxial testing (a) loading frame, (b) data accusation system

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Table 1. Failure strength of oil shale rock.

Confining Pressure, σ_3, MPa	Failure Strength, σ_1, MPa					
	$\beta = 0^o$	15^o	30^o	45^o	60^o	90^o
0	39.67	21.4	13.71	26.73	44.10	50.91
2	44.02	-	17.75	31.97	49.04	55.08
5	53.86	32.31	24.31	40.35	59.57	70.11
10	65.73	47.17	36.26	51.78	73.32	84.43
15	84.23	-	47.08	61.86	85.44	95.12
20	97.89	69.11	-	-	94.73	108.02
30	118.31	-	-	-	112.32	132.54

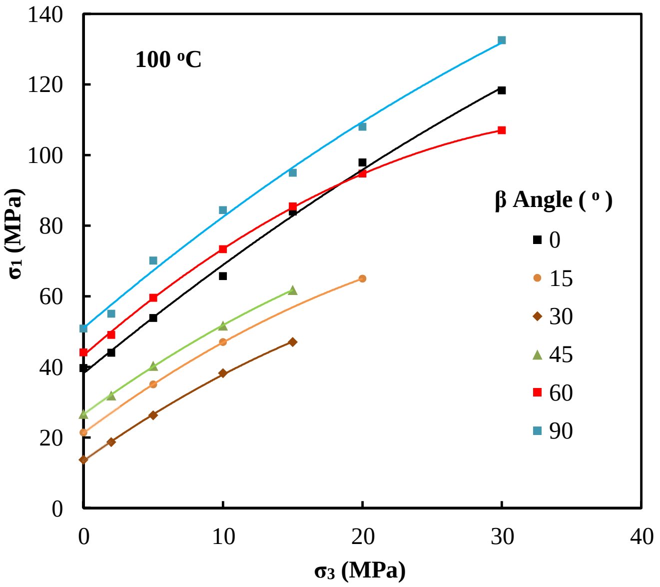

Fig. 4. Variation of σ_1 with σ_3 at different β angle

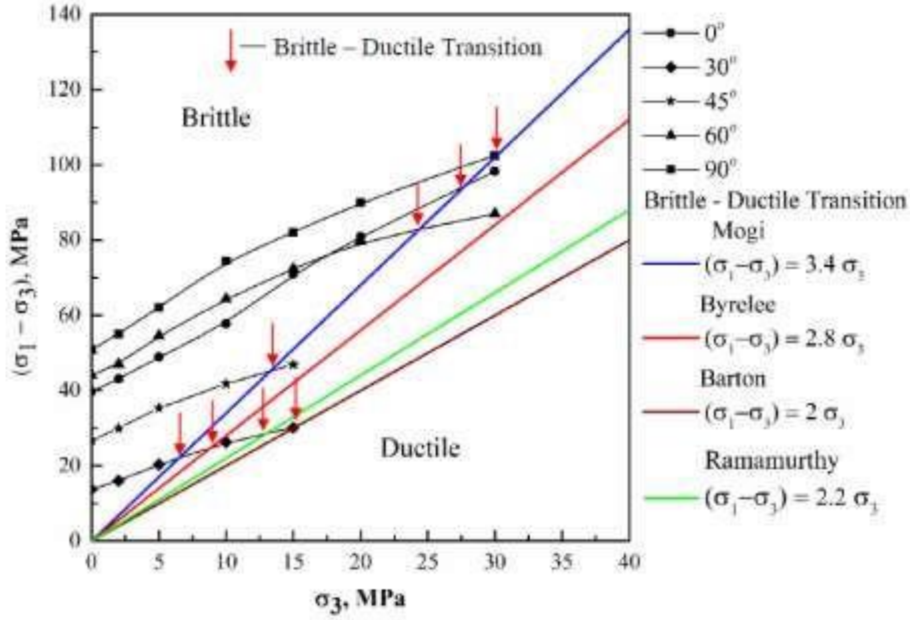

Fig. 5. Brittle – ductile transition of oil shale rock.

6 Conclusions

In the present study, the investigation is carried out to understand the effect of confinement and anisotropy angle on the brittle – ductile nature of oil shale rocks. The comparison of brittle-ductile boundary lines suggested by Mogi (1965), Byrelee (1968), Barton (1976), Ramamurthy (1986) and Behrestaghi (1992) for oil shale rock is carried out. The brittle- ductile transition by Ramamurthy's approach is evaluated by considering the Bi,j = 2.2 on the bases of the triaxial test data. It is observed that only one orientation angles for 100 ºC case i.e $\beta = 30°$, falls in the ductile region above 10 MPa of confining pressure, whereas all other anisotropic angles falls in the brittle zone of failure. It is observed that the oil shale undergoes the transition from brittle to ductile at 30 MPa of confinement for 0 and 90^o anisotropy angles. Which shows that at greater depth the generalised design philosophy will not work well. Further, the transition for 30^o anisotropy angle starts at 12.5 MPa of confinement pressure. Therefore, the designing of wellbore should be carried out by using nonlinear anisotropic strength criterion.

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