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Deformational Behaviour of Coal Measure Rocks

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Abstract: Rock mass properties play a significant role in planning and designing of either underground, surface or in-situ gasification of coal measure rocks. The economics of exploitation is dependent up on the deformational characteristics of the associated rocks. The stress concentrated due to continuous dynamic loading or unloading interrupts the equilibrium of the rock mass. The current paper describes the deformational behaviour of shale and sandstone under varying saturation as well as loading conditions which are commonly associated with coal measure strata. This understanding will help in better planning of energy exploitation programs.

Keywords: *Shale, geomechanics, stress-strain, deformation*

1. Introduction

Deformation behaviour of shale and associated coal measure rock are unpredictable and does not follow the conventional trend like other sedimentary rocks because of its strong inherent anisotropy and heterogeneity nature.

Random orientations of weak planes/cleavages, presence of clay and silica bands and preferential alignment of platy clay minerals dictate the stress concentration path in shales and associated rock mass. There effects were studied by various researchers. The fracture modes are control by the direction of loading and orientation of minerals. If the direction of loading and orientations of minerals are parallel then the rock will fail at lower load as compared to across the loading. Many researchers have studied the deformational behaviour of shaly rock in reference to their anisotropy. Researchers [1] have explained the deformational and microstructural changes under variable confinement for an Illite rich shale. They have reported that the stress-strain behaviour of Wilcox shale showed a change from shallow linear slope to non-linear slope on yielding. Water content strongly influences the mechanical response of rock and is an irreversible phenomenon[2,4]. Majority of rocks follow the Hooke's law of linear elasticity. The deformation and stiffness are related to normalized length. Accumulation of strain tarts instantly once stress is generated in the rockmass. At low stress level effective stress controls the modulus however, rock samples developed anelastic behaviour. At initial load, weak rocks exhibit sharp increase in stiffness, due to healing and filling of micro-cracks which results into better compaction.

The porosity and permeability of shaly rocks further add to the complexity in the rock. The porosity and permeability of shale and sandstone are stress dependent. This behaviour decides the fracture and flow behaviour of these rocks. A number of researchers postulated relationship between these parameters and suggested an exponential trend [5–7]. Kwon et al [8] described that the permeability and porosity are influenced only by continuous loading but also by deep stress environment of the reservoir condition. It is suggested that the closing of micro-cracks, alignment of mineral particles while loading and crushing with confinement control the permeability [5]. Due to mechanical compaction, permeability may undergo drastic changes and different materials respond differently to this load. The sandstone samples demonstrate different type of permeability as compared to shaly rock. Permeability of shaly rock is more affected by confinement as compared to that of sandstone and silty rocks. The heterogeneity in terms of shape of pores and the abundance of micro-cracks in shale act as a driving force for the elevated stress sensitivity of permeability in these rocks [9].

It is established by researchers that some of the dynamic properties are well correlated with various static properties like P-wave velocity with UCS. Most of the researchers have reported a linear correlation between these parameters [10–12]. However, in this work such strong relationship was not established. The uniaxial compressive strength test is normally performed on shale for designing purposes however, very limited work has been done to understand the durability of shale. It is reported that the compressive strength varies with moisture content but reliable quantification has not yet been established [13].

Singh et al [14] tried to correlate Point load index with UCS for various rock types including shale. They have reported a linear correlation with coefficient of 0.82 under dry conditions. However, they have not reported any test for shale in saturated conditions which is very essential for decision making.

Elastic constants and other associated petrophysical and geomechanical properties are greatly susceptible to variable pore fluid pressure and its composition. When subjected to shearing, shale entirely changes its mechanical behaviour [15]. Preferential orientation of clay minerals existing within shale have influence on its stress-strain behaviour. Presence of clay minerals increases the water absorption of shale thus dictating the pattern of deformation leading to failure. Thus the deformation in a shaly rock can be characterized by its level of water saturation. These properties depend on the relative orientation of cleavage and loading direction however, cohesion and angle of friction are not properly correlated with degree of saturation [16]. Johnston [17] indicated that shale deformation is dominated by inelastic processes such as change in wave velocity due to creep, resistivity and pore water pressure.

Keeping in mind the potential as a future source of energy, the deformational behaviour of Indian Gondwana shale was studied. The variation of strength under dry and saturated conditions indicates lowering of strength and associated elastic constants. Very limited numbers of studies have been conducted on the effects of saturation on anisotropy and elastic constants. This study aims at bridging this knowledge gap by explaining the bearing of saturation and stress-strain behaviour on strength and deformation characteristics of shale and associated rocks. The study also tries to establish some correlation of water saturation with strength parameters.

2. Sample Collection and Physical Description

Shale and Sandy shale samples were collected from Jamadoba coal mine which comes in the Gondwana supergroup. The sandstones collected from the area is relatively weak while the shale is hard and compact with very fine fissility. The samples were collected from variable depth. The lithological variations are repetitive in nature i.e. sandstone, shale and sandy shale with varying thickness.

3. Methodology

The selected samples were prepared for geomechanical tests as per ISRM [18–20] suggested methods. NX sized cores were prepared to test the rocks, particularly sandstone, shale and sandy shales. The rock properties determined are compressional waves, stress-strain behaviour, elastic constants, density, bulk density as well as various strength parameters under saturated as well as dry conditions.

3.1 Ultrasonic Velocity Tests

The ultrasonic velocity of a material is very important considering its implications on the material characterization. P-wave velocity of a rock can be used for the indirect estimation of its density, compressive strength and Young's Modulus. The velocity of the ultrasonic waves depends on the compactness of the solid material and its density. The denser the material more is the expected velocity. According to Kahraman [21] the ultrasonic velocity of a rock is influenced by its porosity, density, anisotropy, heterogeneity as well as the presence of discontinuities. In this work, the P-wave velocity of rocks has been determined with the help of Pundit Lab Ultrasonic Pulse Velocity tester. The samples were cylindrical cores of 54 mm diameter. Figure 1 shows a typical setup for ultrasonic testing.

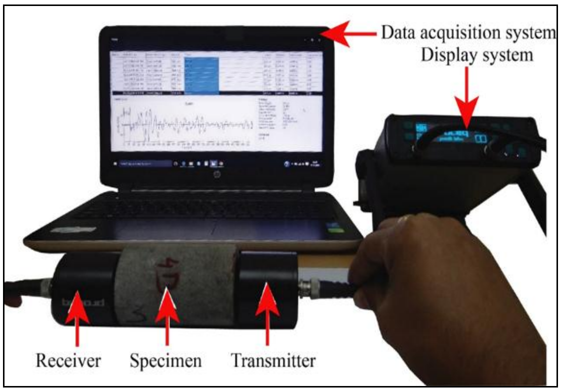

Figure 1 *A typical ultrasonic velocity set-up*

3.2 Scanning Electron Microscope Study

The geometry and alignment of clay minerals was studied using a scanning electron microscope (JSM-6390, JEOL). The procedure was undertaken at a scanning voltage acceleration of 20 kV. The samples were properly carbon coated before putting inside the SEM. The textural patterns of the group of clay minerals is observed in Figure 2.

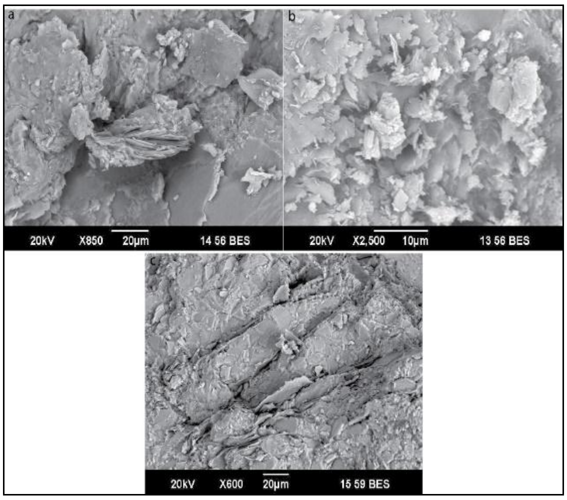

Figure 2 *SEM images of (a) sandstone showing flaky clay minerals, (b) sandy shale showing intermediate between sandstone and shale, (c) Shale showing clay minerals occupying cracks along grain boundaries*

The sandstone samples as observed under the SEM are found to be having books of clay flakes placed between quartz grains. The flakes are not oriented in a particular direction rather they are aligned in haphazard directions which leads to string anisotropic behaviour. The clay flakes often appear to be camouflaging the quartz grains. The sandy shale as suggested by the name possesses a clay orientation in between that of sandstone and shale. There are plenty of clay flakes but are not continuous neither are oriented. This haphazardness contributes to the mixed failure characteristics and influences the deformation. The clay sheets in shale display an augen type of structure in which they appear to be flowing around the quartz grains. The spaces between the quartz grains are occupied by clay minerals which contribute to the strength reduction on saturation.

3.3 Geo-Mechanical Properties

Various geo-mechanical tests like UCS, Young's Modulus, Poisson's ratio and stress-strain behaviour were performed as per ISRM suggested methods. The complete table of estimated geomechanical properties is given below.

Table 1: *Various geomechanical properties of the tested rock samples*

Sample no	Type	Young's modulus (GPa)	Poisson's ratio	Bulk Density
2	shale	2.14	0.19	2.27
3	sandy shale	5.84	0.18	2.63
4	sandstone	10.16	0.19	3.16
5	sandy shale	5.61	0.18	2.47
8 (a)	sandy shale	5.41	0.21	2.54
8	sandy shale	5.23	0.19	2.60

4. Results and Discussion

The compressional wave velocity under dry conditions varies from 5410 m/s to 2953 m/s whereas under saturated condition the values are lower except in one case (Table 2). The reduction in P-wave velocity due to saturation has been observed up to 40.6%. This can be attributed to the presence of high percentage of clay minerals in the shaly rock. The effect of water saturation and opening of cracks can be seen on figure 3.

Table 2: *Change in P-wave velocity under saturation*

Sample	P-wave velocity (dry) m/s	P-wave velocity (saturated) m/s	Percentage reduction %
2	2953	1753	40.6
3	3689	3175	14
4	5410	3941	27
5	4192	2567	38.7

The S-wave velocity also follows a similar trend of value reduction under saturated conditions as compared to dry conditions. The maximum reduction witnessed was up to a maximum of 36.54% starting from 12.56% (Table 3). The variation in percentage reduction is due to variation in clay mineral content in the shaly samples. Higher the percentage of clay minerals more is the reduction in ultrasonic velocity of the samples.

Table 3: *Change in S-wave velocity under saturation*

Sample	S-wave velocity (dry) m/s	S-wave velocity (saturated) m/s	Percentage reduction %
2	1708	1461	32.56
3	2179	1906	12.56
4	3164	2365	25.79
5	2477	1571	36.54

Figure 3 *A water saturated shale sample exhibiting extension cracks along clay layers*

The Uniaxial compressive strength of core samples was determined using Universal testing machine. The rate of loading was kept constant for all the tests. The samples were tested under both dry and saturated conditions. The higher UCS was observed for dry samples as compared to saturated samples. Most of the failures were along the pre-existing micro-cracks which are widened and propagated further. The results are given in table 4.

Table 4 *Change in UCS under saturation*

Sample	UCS (dry) MPa	UCS (saturated) MPa	Percentage reduction
1	9.11	-	-
2	18.45	15.60	15.12
3	29.00	20.90	12.56
8	24.90	21.18	14.96
4	41.50	38.60	6.9

Sample 1 was very fragile after saturation with water, so compression test after saturation was not possible to conduct. It is evident that the reduction is not fully dependent on depth but is dictated by the clay content of the sample.

The samples were tested under constant slow loading rate. The strain gauges were properly pasted on the cylindrical rock samples on axial and lateral direction. The tests were conducted for both dry and saturated samples. Figure 4 demonstrates the behaviour of stress-strain of shale sample under dry as well as saturated conditions. The general trend is identical for both lateral and axial mode. The dry sample does not show any linearity prior to yielding, but under elastic zone it exhibits linearity and follows Hooke's law.

Following the elastic zone, a flat top indicates stress accumulation during loading which further indicates strain hardening probably due to the presence of clay material followed by sudden failure. This also exhibits time dependent stress behaviour of the material as well as swelling characteristics. The transition from brittle to ductile phase change is crucial where geomechanical material goes from reversible to non-reversible strain conditions. However, under the saturated condition material behaviour has slightly changed and shows more linearity than its dry counterpart. This may be due to filling up of voids or build-up of hydrostatic stress within the voids. This may also be attributed to the possible swelling of the material which closes the voids and makes it apparently homogeneous as compared to dry condition.

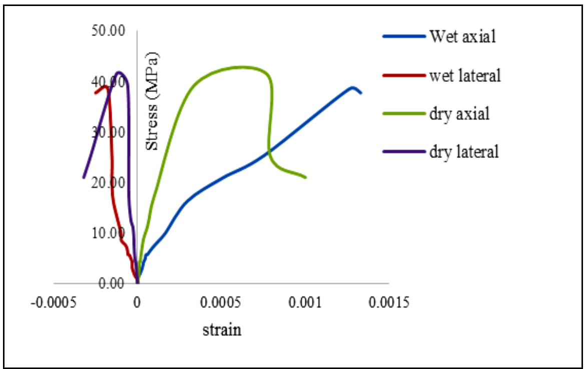

Figure 4 *Stress-Strain behaviour of Shale under dry as well as saturated condition*

The failure mode is more towards the brittle nature than ductile till it reaches the nominal failure stress. The peak stress recorded is 38.60 MPa (saturated) whereas 41.51 MPa for dry samples whereas residual stress indicates sharp decrease from 41.51 MPa to 25.16 MPa, roughly a 40% decrease. The strain continued to increase from 0.000771 to 0.00792. This clearly suggests permanent damage to the rock and extensive cracking under shear mode. This trend was not observed in saturated rock samples. The residual stress was very high in case of saturated rocks up to 37.78 MPa. This evidently demonstrates that the shaly rock behaviour is entirely different under dry and saturated condition.

Sandstone samples were subjected to loading and their stress-strain plot is shown in Figure 5. The trend of the graph is almost linear prior to ultimate stress level (29.44 MPa) with axial strain of 0.000797 and lateral strain of 0.000032. Sandstone sample shows a more brittle nature and failed abruptly. The residual stress recorded is about 50% of the peak load. The Young's modulus increases in linear manner and shows 39 GPa with a Poisson's ration of 0.13. These behaviour was not observed in shaly rock. Figure 5 clearly indicates that the material failed under brittle but hardly any transformation from brittle to ductile mode prior to failure under the shear mode.

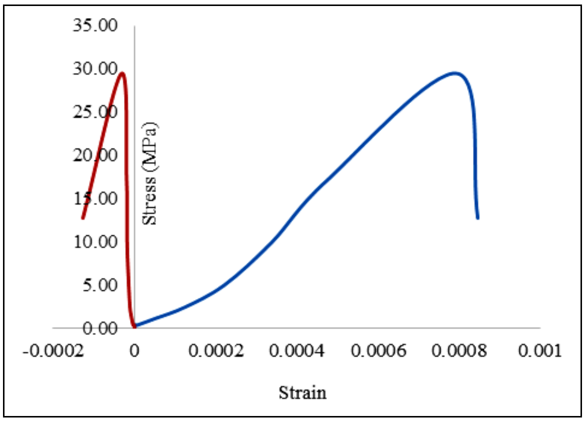

Figure 5 *Stress-Strain behaviour of sandstone*

The sandy shale sample was tested to know its behaviour because it is partially sandstone and partially shale. A typical stress-strain plot is shown in figure 6. The UCS is calculated to be 18.45 MPa, which is lower than both shale and sandstone individually. The lateral stress path is also different from other coal measure rocks. The accumulation of lateral strain is due to preferential orientation and alignment of platy clay minerals with respect to loading direction. This addresses to the observed changes in its behaviour. The peak load observed is about 32 kN with a peak stress of 18.45 MPa. The axial and lateral strain recorded at this stage are $0.687*10^{-3}$ and $0.264*10^{-3}$ respectively.

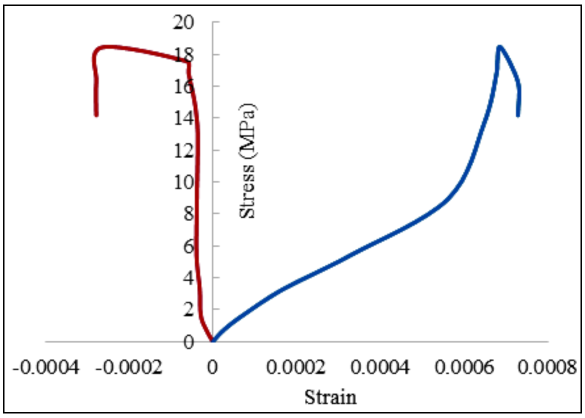

Figure 6 *Stress-Strain behaviour of sandy shale*

5. Conclusion

This study provides useful information related to the deformability of coal measure rocks under dry as well as saturated conditions. The geomechanical behaviour of shale and sandy shale is entirely different from that of sandstone. The saturated uniaxial compressive strength is lower as compared to that under dry condition irrespective of rock type however, drastic drop was recorded for shale samples. Sandy shale shows lower value of elastic constant than that of pure shale and sandstone. The percentage reduction of compressional P-wave velocity under saturated condition was up to 40.6% whereas that of S-wave velocity was 36.54%. The UCS was reduced maximum up to 15-12%. Rocks of high UCS value show lower reduction of strength on reduction. The behaviour of stress-strain for shale exhibits strain hardening under brittle to ductile field whereas sandstone sample indicates mostly linear Hookian behaviour. The sandy shale demonstrates mix mode behaviour.

This information are vital for designing and planning of fracturing activity in shale or deep underground excavation. This advance knowledge of the rock type makes the strata more predictable and reliable for exploitation of natural resources.

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