COAL MEASURE ROCKS AND THEIR PROPERTIES

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ABSTRACT: Coal measure rocks tend to have anisotropic and elastically non-linear behaviour. Understanding this is a key to understanding strata behaviour in coal mines. This paper discusses which properties matter and how they can be measured. Some new test methods are introduced. The paper also discusses the relevance of geophysics in determining these properties.

INTRODUCTION

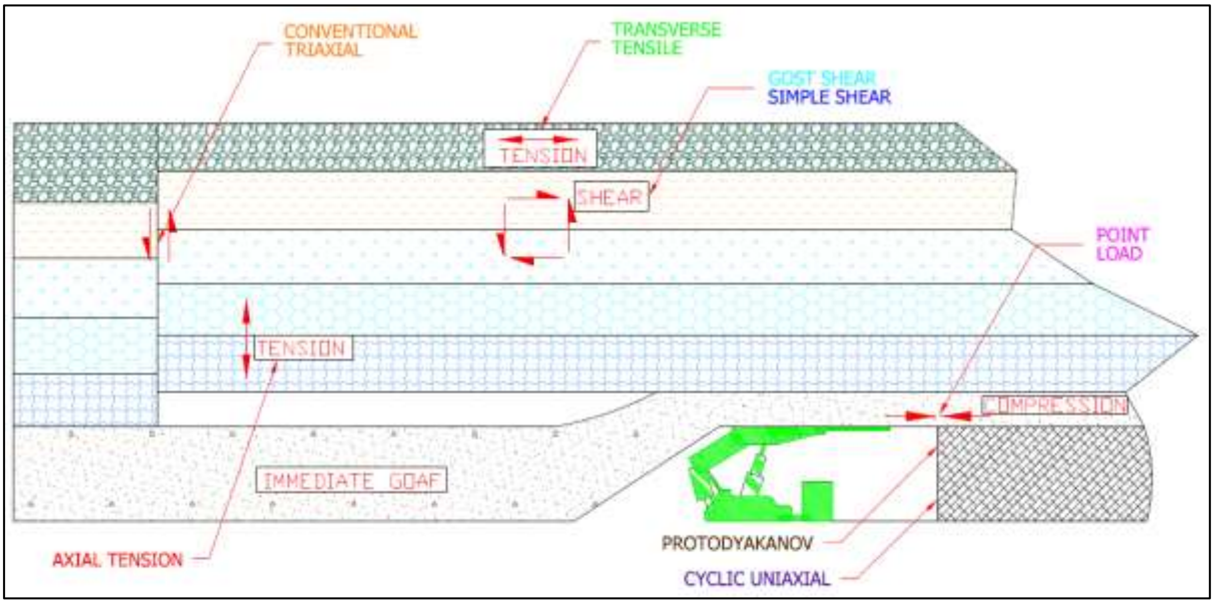

Figure 1. Schematic view of a longwall with tests that might be used to determine rock properties, (Gray, 2020).

Figure 1 shows a schematic cross section of a longwall. Above coal seam is some weak rock that collapses to form the immediate goaf. Above this there are some stronger rocks which might act as individual layers, or might act together to form a thick, strong cantilever, or if we consider three dimensions, a plate. It is possible that these plates will pull apart through the direct effect of gravity. In this case the important property is the tensile strength perpendicular to the bedding plane. The layers above will either individually, or as a group, act in bending. Bending of a plate that is acting as a cantilever will induce tensile stress in the top of the plate above the face and compression at the bottom of the plate. Rocks are normally weaker in tension than in compression and therefore the tensile strength of the rock parallel to bedding is important.

In addition to tension and compression, shear stresses will exist. These shear stresses can easily be thought of as acting perpendicular to the plates of rock, but in addition the conjugate shear stress exists along the bedding plane. It is the shear strength along the bedding planes that may control the failure of the layers. Once shearing has taken place the thinned plates have far less resistance to bending failure than the thicker unit and are likely to fail in sequence. This is the mechanism of failure which is likely in the weak rock shown as existing above the coal in this example.

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While the shear stress along the bedding plane is not necessarily the greatest shear stress within the rock mass, it is frequently the plane on which failure is most likely. If the rock is massive or the bedding planes have similar strength to the rock mass, then shear failure across the bedding planes is possible. At the coal face the situation is one of compression of the coal without confinement. The same applies to the immediate roof at the face which is likely to be in compression.

While the situation described here addresses the loads brought about by gravity there is a pre-existing loading situation within the rock mass. This comprises the pre-existing stress field within the rocks which is disturbed by mining. Mining brings about failure by sequentially unloading the stress at mined openings or around the longwall goaf. This sequential unloading can lead to major stress concentrations and in particular the shearing of the rock mass along bedding planes.

The measurement of rock stress is described by Gray, 2018. The way in which this stress is redistributed is dependent on the shape of the mine openings and the stress-strain behaviour of the rock. The nonlinear and anisotropic pre-failure stress strain behaviour is described in some detail by Gray, Zhao and Liu, 2018.This paper looks in more detail at measuring the failure properties of the rock.

All too frequently, testing has become a rote process of taking representative samples of each lithology and sending them off for uniaxial compressive testing, interspersed with the occasional triaxial test, to determine failure properties. The problem with this approach is that the failure mode in these tests is by shearing at an acute angle to the sample axis which, in vertical holes, is generally across the bedding planes. Furthermore, the only pre-failure parameters measured are the axial Young's modulus and associated Poisson's ratio. As most laminated rocks have quite different mechanical properties depending on the direction, this is very limiting. Not only are most coal measure rocks anisotropic, but they frequently display quite significant non-linearity prior to failure. The test process, therefore, needs to be thought about carefully.

ROCK STRUCTURE

Where jointing exists, it is likely to have a major effect on rock behaviour. This is because the presence of an un-cemented joint will destroy all tensile strength across it and will remove the cohesive component of the Mohr-Coulomb strength. Therefore any jointing needs to be measured. The best way to do this is as part of the core logging process. Core logging enables the lithology to be determined and the joints to be measured in terms of orientation and the nature of the joint. The joints can then be aligned with information from the acoustic televiewer scan of the hole. The acoustic televiewer can never do the same job as having the core available because it does not look inside the joint to determine to what degree it is open, nor can it provide information on joint infill. If joints are filled then thought must be given to measuring their strength.

Another structural feature that frequently dominates the behaviour of sedimentary strata is bedding. This is not only because lithology changes across the bedding, but because the bedding planes have quite different properties to the rock on either side of them. This variation may be apparent on clearly visible bedding surfaces or may be hidden in the rock mass itself. An example of this is where mica is deposited parallel to the bedding, with the results that the rock is extremely weak in tension across the bedding, strong in tension parallel to bedding and has a shear strength on the bedding plane that is a fraction of that across it. This highly anisotropic behaviour extends to the rock's elastic behaviour also. Proper core logging enables observations for inhomogeneity and the choice of samples, and how they should be geotechnically tested.

In the case of coal its cleating frequently controls the behaviour of the coal. It does this in a similar manner to larger joints but frequently at a much higher frequency. The presence of cleating and its spacing will determine whether the coal has cohesion and strength, or at the extreme end of the spectrum behaves as a granular mass. In the latter case the coal will need confinement to have any strength. Coal without cleating will tend to be of high strength and will therefore if highly stressed be prone to coal bursts. Coal that is highly cleated will, if gassy, be prone to outbursts (Gray & Wood, 2022).

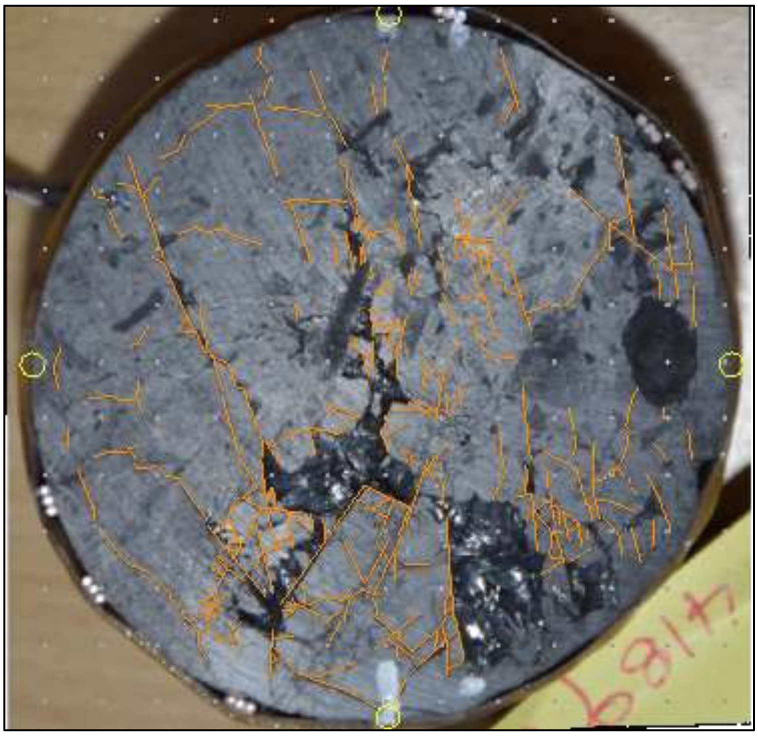

Figure 2: Coal core with significant fracturing marked in orange

Figure 3: Coal core without any fracturing

Figure 2 shows a section of core with significant fracturing that is unlikely to coal burst, but may, if gassy, outburst. In this the fracturing is highlighted with orange. Figure 3 shows a section of core without fractures which will not outburst but by the nature of its high strength, and in this specific case lower modulus, might be prone to coal bursting.

The coal shown in Figure 3 is not the sort of material that will outburst in a coal storm event as these are associated with fine fault gouge, but is rather the material that is associated with failure which leads to dilation and pressurisation of the void space caused by this dilation. This pressurisation may take place if the desorption rate of the coal is adequate to pressurise the voids without leakage through the face. If the fractures were parallel so that little fracturing existed perpendicular to them then the potential for a blocky outburst is more likely. Figure 2 also enables a sizing of the potential fragments that may form with dilation. This is important in assessing the characteristic particle size ranges that may form on dilation. These sizes affect the rate of diffusion. Equation 1 describes the key dimensionless time parameter determining how diffusion behaves from spheres (Crank, 1975).

$$\boldsymbol{fn(t) = \sqrt{\frac{Dt}{a^2}} = \frac{2}{d}\sqrt{Dt}} \tag{1}$$

Where	D	is the diffusion coefficient (m^2/s)
	a	is the characteristic lump radius (m)
	d	is the characteristic lump diameter (m)
	t	is the time (s)

From Equation 1 it can be seen that the square root of the diffusion coefficient of diffusion and the inverse of the particle size control the rate of diffusion.

ROCK TESTING

Rock testing can be divided into those tests that measure the elastic parameters of the rock and those that measure the failure strengths. Few measurements are made of post failure behaviour because the transition to this involves such a rapid loss of strength that special test equipment is required to record it. This means very stiff testing systems which have rapidly responding servo control. These are therefore beyond the reach of most testing programmes. Undertaking a number of different tests of relevant parameters is still possible.

The normal tests that are conducted as part of exploration and geotechnical evaluation are uniaxial compressive tests, a few triaxial tests and some point load tests. These tests are relevant but miss much of the information that should be gained. As vertical core holes are predominantly drilled across the bedding planes the shearing that occurs in a triaxial test is through these. Unless tensile splitting of the specimen occurs, this is also the case for uniaxial tests.

Point Load Tests

In the point load test is the core is loaded to failure both axially and across the diameter. The resulting value is normalised to a 50 mm diameter core. This test gives a difference in strength of the rock to loading in different directions. The index is just that though, because the test imposes a complex loading situation on the core. Failure may be by local crushing but is usually by some mixture of shear and tensile stress. If a core containing bedding plane weakness is tested across its diameter, then the probable failure mode is predominantly by tensile stress across the bedding. If a lump of core is point load tested coincident with the core axis then the result is more of a measurement of tensile strength parallel to the bedding. These are useful measurements but they are not precise, as the stress situation around the spherical points causes complex local stresses. Correlations between point load tests and the uniaxial compressive strength of rock are not helpful where the rock is anisotropic. In practice, one of the problems with the use of the point load test is ensuring that a representative sample is taken and not just the stronger material which it is easier to test.

ROCK STRENGTH TESTS

Uniaxial Compressive Tests

To be really useful uniaxial compressive tests should be conducted with some means of axial and circumferential strain measurement. From these it is possible to determine the axial Young's modulus and the Poisson's ratio that is associated with it. If the test is conducted in cycles of loading it is also possible to determine the component of plastic offset after each loading cycle. The plastic component may be very large and is normally missed in conventional uniaxial testing where the load is increased to failure. It is also important in rock behaviour. Figure 4 shows the results from uniaxial testing on a fairly non-linear sandstone while Figure 5 shows the permanent offset associated with each cyclic load. The latter shows a not uncommon feature where the circumferential offset is greater than the axial.

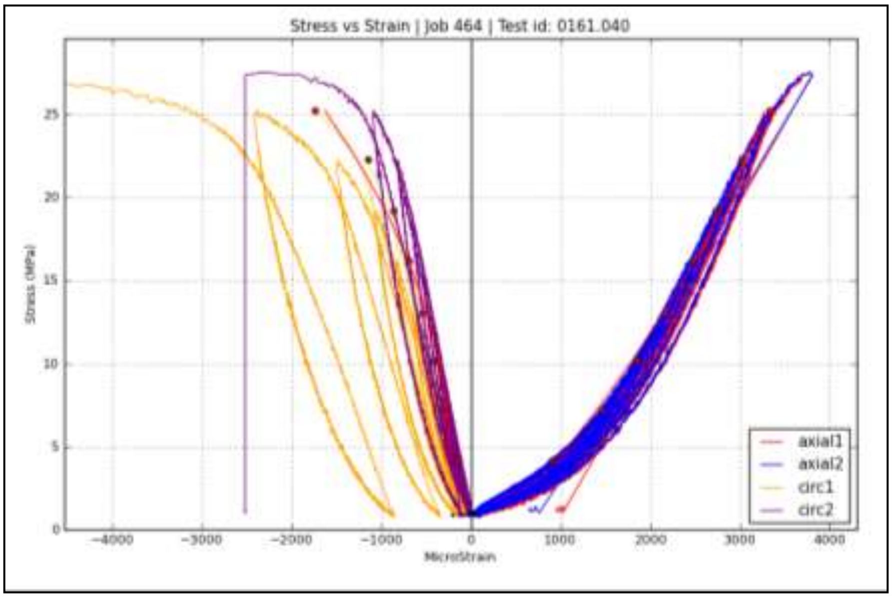

Figure 4. Example of cyclic uniaxial test results on a sandstone.

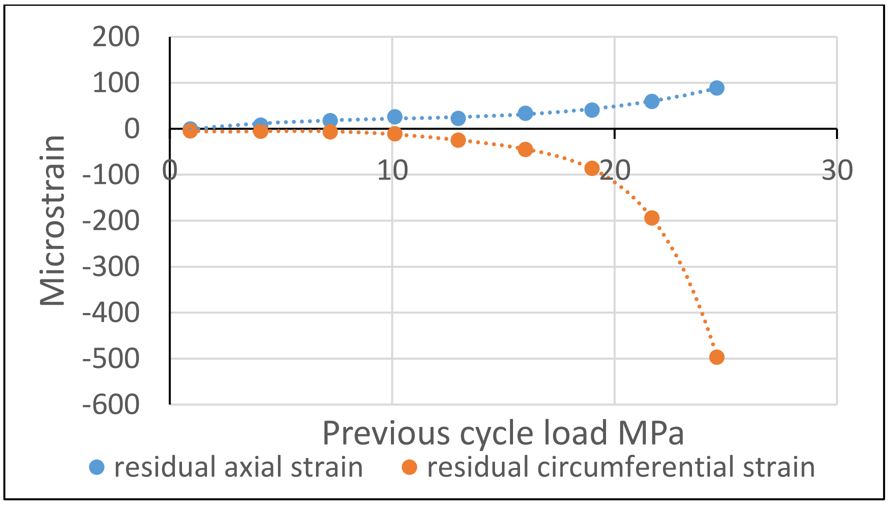

Figure 5. Example of permanent strain offset on a sandstone.

Tensile Testing

Because of the importance of the tensile strength in rock behaviour this is an important measurement that needs to be taken seriously. The conventional approach is to use the Brazilian test where a section of core is loaded across its diameter. Like the point load test this is really an index test as the loading process uses line load compression to generate tensile stress through the shape of the sample. Failure is by a combination of local compression, shear and tensile stress. The basis of determining the tensile strength comes from a theoretical calculation of the tensile stress generated in an elastically linear sample. A lot of sedimentary rock is however highly non-linear. The tensile stress calculated from the Brazilian test is usually that of failure perpendicular the bedding. Figure 6 shows Brazilian test apparatus that is suitable for field use.

Figure 6: Site Brazilian test equipment – test cylinder with hand operated pump

A better way to determine the true tensile strength of rock is to cut a biscuit of core and to glue it in side plates and to stretch it to failure. Typically an HQ-3 core of 61 mm diameter is cut into a disc of 15 mm width and glued to side plates. The sample is then loaded in tension until failure. The tensile strength and stiffness can be measured by this method. Figure 7 shows a biscuit of core that is ready to be glued in place while Figure 8 shows a core biscuit between the glued on plates that has been loaded to failure.

The use of axial tensile testing is more conventional. It involves gluing core in end holders and stretching it axially to failure. This test provides a direct measurement of the tensile strength resisting delamination. The Brazilian test does not do this and the point load test across the diameter of the core gives some approximation to tensile strength in this direction.

Figure 7: Prepared sample disc

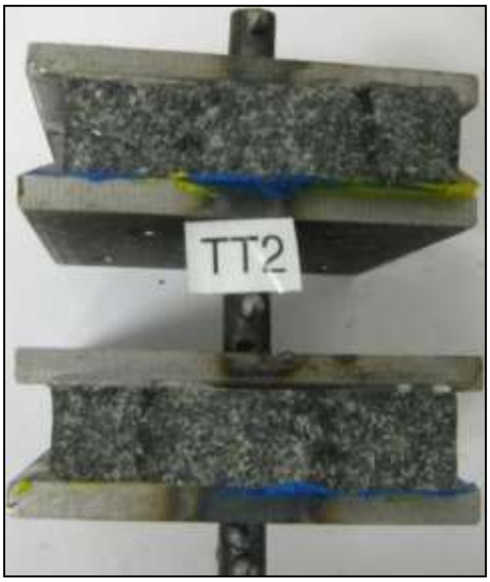

Figure 8: Failed transverse tensile test disc between glued on plates.

Shear Testing

The shear strength of rock against failure along the bedding plane is extremely important in sedimentary rock. As already discussed, the triaxial and uniaxial test processes do not measure strength in this orientation. The conventional approach to obtain this strength is to cement a core sample in a shear box and load it laterally. This is a slow and comparatively costly operation.

The authors have developed a quicker process which is called the simple shear test. In this a section of core is loaded in a saddle placed on a spherical self-aligning mounting within a universal test machine. The sample is loaded to failure in simple shear. Almost invariably the sample fails at one end and the failure stress is calculated as being half the load divided by the core area. The calculated shear strength does not precisely correlate with the Mohr-Coulomb cohesion term because of the nature of the loading. It is however a very quick test to perform and gain a statistical understanding of the variability of shear strength transverse to the core. Figure 9 shows a core sample sitting in the testing saddle before vertical load is applied to the upper element by a universal test machine.

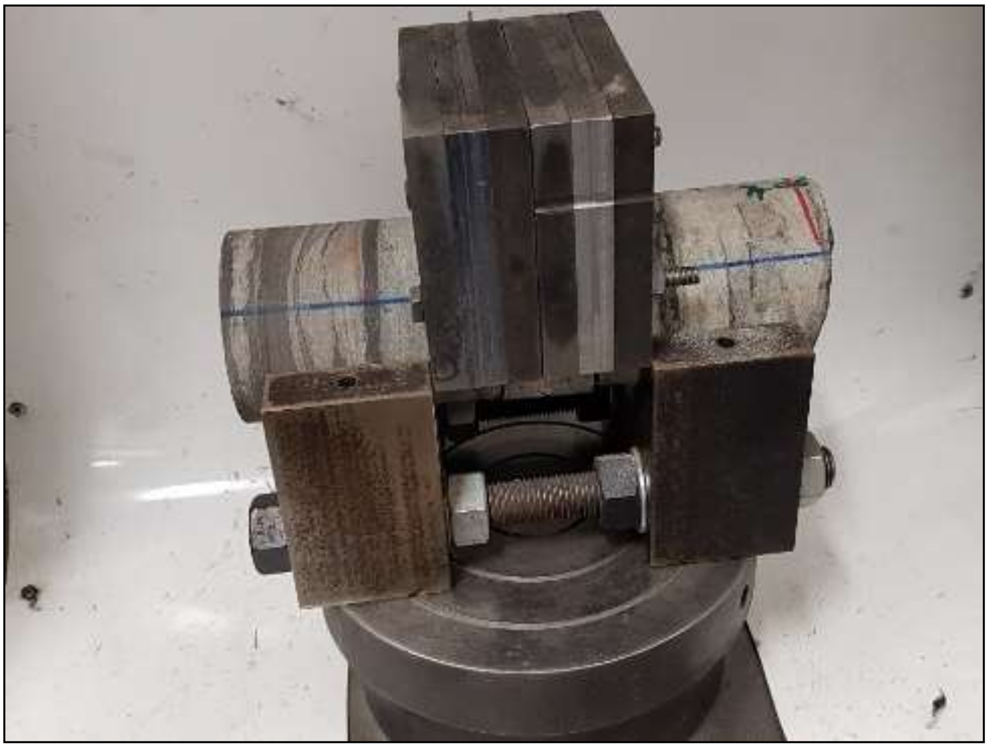

Figure 9. Direct shear test of core.

The authors have also modified a Russian test process – the GOST (ГОСТ, 1988). This is particularly suitable for measuring the shear strength of rock in terms of the Mohr-Coulomb failure criteria. The equipment used for this purpose is shown schematically in Figure 10**Error! Reference source not found.**. In this the core is placed within cylindrical restraints in a split test cylinder. The angle of the split cylinder is then adjusted and the specimen is loaded to failure. This process can be repeated to measure failure on adjacent planes at different angles of loading. These different angles create differing ratios of normal to shear stress. Several test results can be used to create a Mohr-Coulomb failure envelope as shown in Figure 11.

Protodyakanov Index Test

This is a test on lumps coal (or other weaker rock), with measurement of the coal size reduction. The process involves four weighed sets of coal consisting of 5 subsamples each with size range 20 to 30 mm and weight 40-60 g. The subsample is placed in an apparatus comprising a drop hammer of 2.4 kg weight with a 600 mm travel as shown in Figure 12. The diameter of the hammer is 66 mm and the tube it falls within is 76 mm. The number of hammer blows depends on coal strength and is determined experimentally. The volume of fines of less than 0.5 mm diameter is measured in a measuring cylinder (a tube of 23 mm diameter). The height of fines in the measuring tube after crushing of one set (5 subsamples) should be in the range of 20 – 100 mm, otherwise the number of blows should be adjusted experimentally. For the coal usually one blow is enough, but for some strong coals 2-3 blows are required.

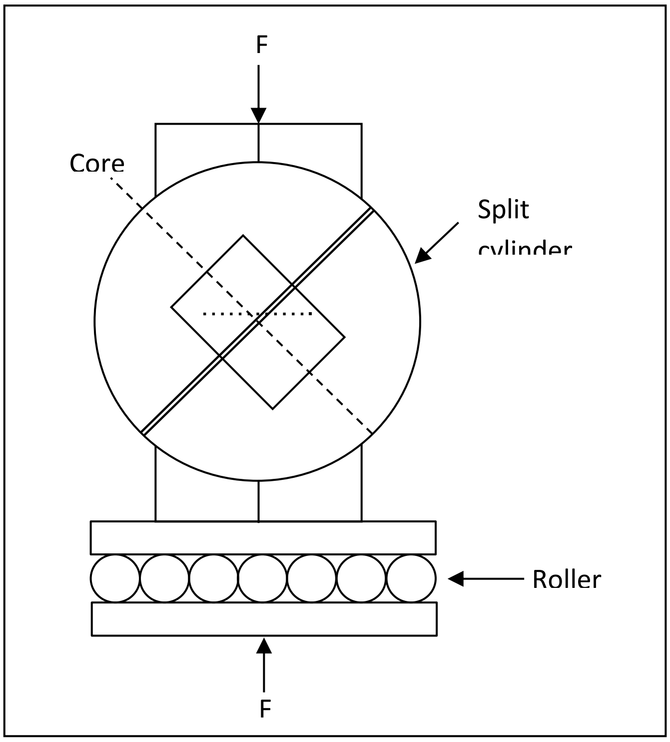

Figure 10: Schematic diagram of modified GOST Shear Test Apparatus

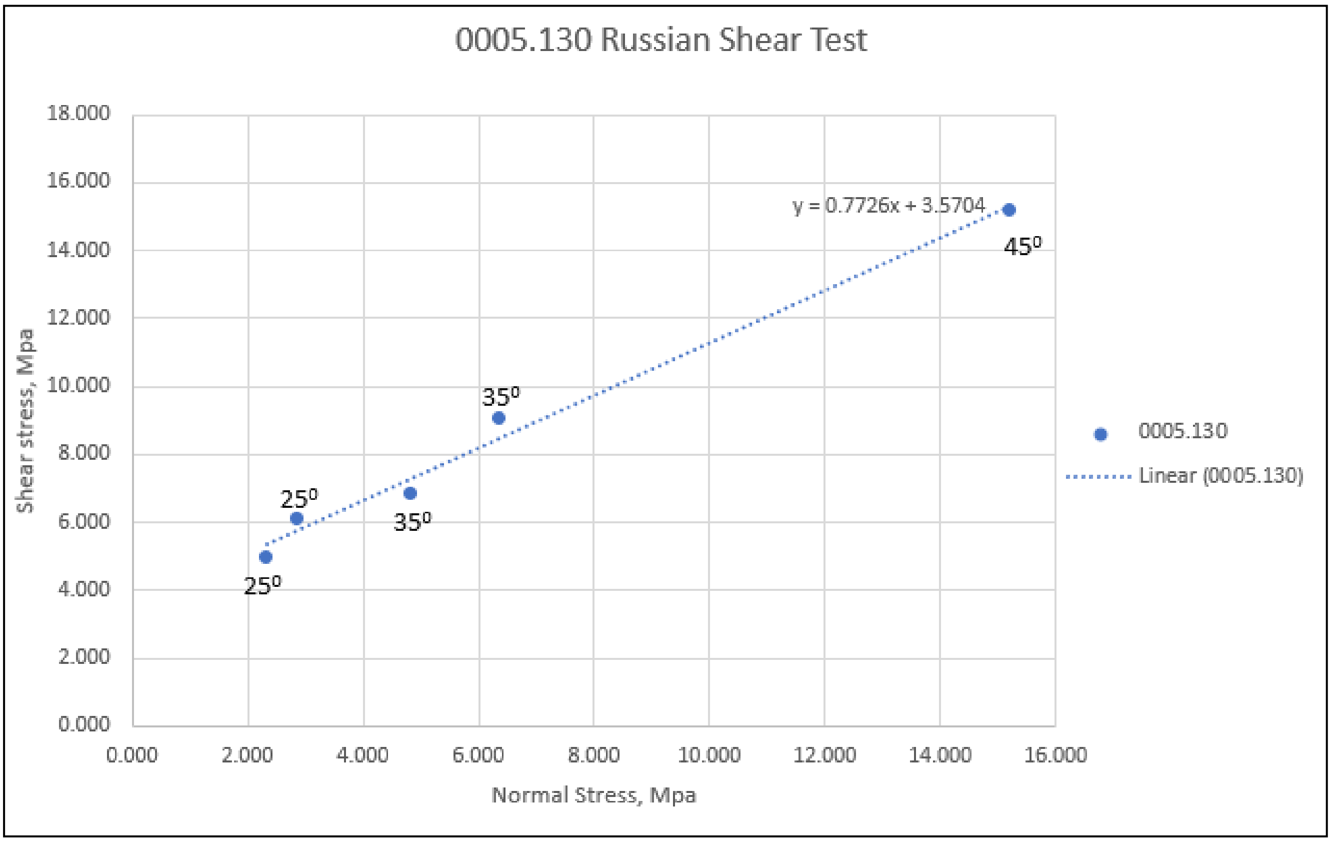

Figure 11. Modified GOST shear test results with fitted Mohr-Coulomb failure envelope.

Figure 12. Drop hammer equipment – measuring cylinder with scale and tube with drop hammer.

The *f* coefficient for the Protodyakanov Index is defined by Equation 2:

$$f_{20-30} = \frac{20*n}{h} \qquad (2)$$

Where f_{20-30} is the toughness index (for 20 to 30 mm size range)

n is the number of hammer blows

h is the scale measurement in the cylinder after 5 subsample tests (mm).

The final result is an average of 4 measurements.

The general threshold *f* value less than 0.5 is indicative of outburst proneness.

An extension to the test method for fine coal where it is not possible to obtain 20 to 30 mm lumps is to sieve the sample for the 1 to 3 mm range. This is then hammered three times and the size reduction noted by a measurement in the fines cylinder.

In this case, if $f_{1-3} > 0.25$ using Equation 3 with $n = 3$

then the equivalent $f_{20-30} = 1.57 \times f_{1-3} - 0.14;$ (3)

otherwise if $f_{1-3} \leq 0.25$ then

the equivalent $f_{20-30} \equiv f_{1-3}$

Summary of Rock Tests

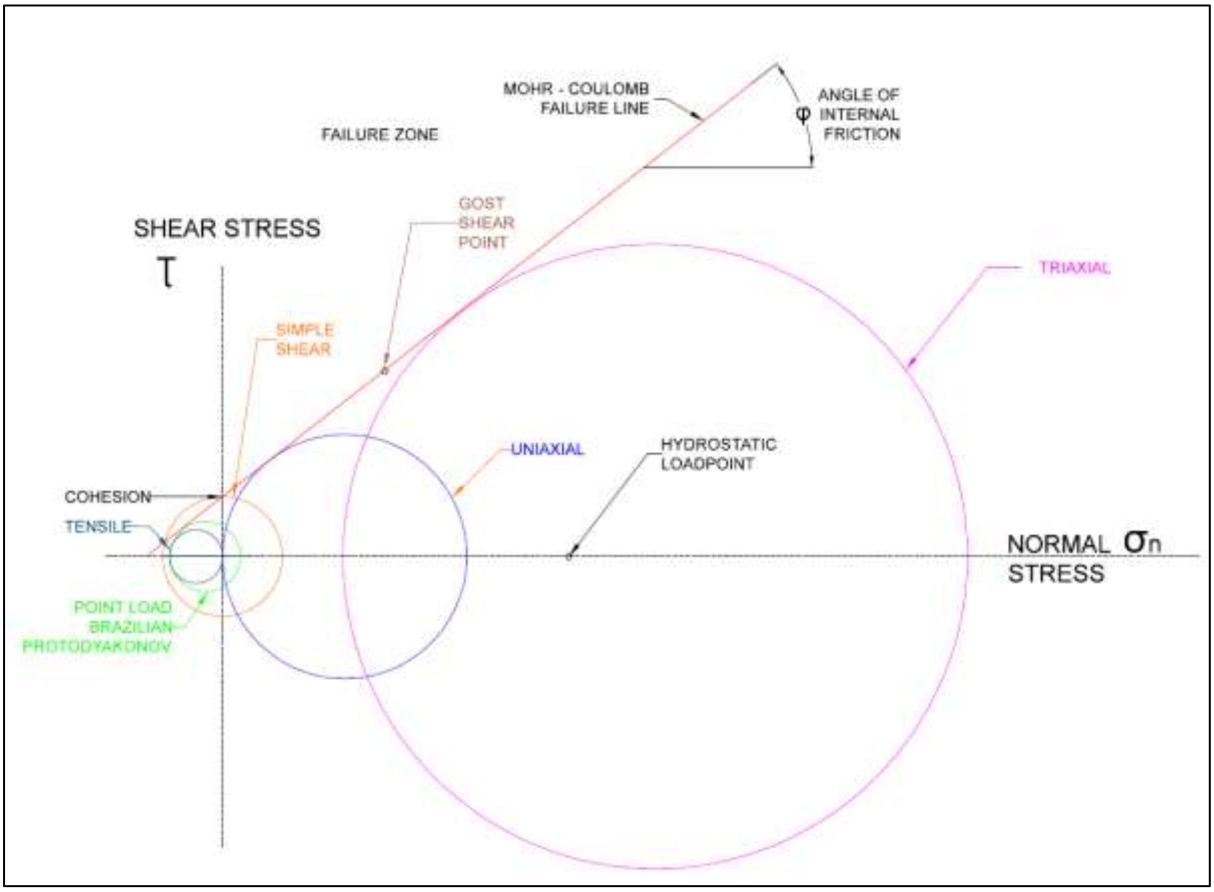

Figure 13.Stress loadings imposed by various rock tests, Gray, 2020.

Figure 13 shows the Mohr's circles of failure for the various strength tests along with the Mohr –Coulomb failure envelope. The three index tests of point load, Brazilian test and Protodyakanov Index are shown in an area of compression, tension and shear which reflect their complex loading. The uniaxial test is shown with one side of Mohr's circle being in compression while the other carries no stress. The triaxial test has both sides of the Mohr's circle in compression. The GOST test shear is shown as a point though it could equally well be shown with a Mohr's circle passing through it. The hydrostatic test is described by Gray, Zhao and Liu (2018); it is not a test to failure.

What must be kept in mind when looking at Figure 13 is that the Mohr-Coulomb failure envelope will vary with the orientation of potential failure with respect to the rock anisotropy. A number of different failure envelopes may apply to the same rock.

GEOPHYSICS FOR ROCK PROPERTIES

Borehole geophysics gives some indication of lithology types and more particular changes in lithology. From a geotechnical viewpoint sonic logs and acoustic televiewer images are particularly useful. Full waveform sonic logs can be interpreted in terms of the dynamic Young's modulus and Poisson's ratio. The interpretation is, however, invariably given in terms of isotropic rock behaviour and therefore information on anisotropy cannot be obtained. The use of correlations between the Young's modulus determined from the sonic log and laboratory determined moduli can be useful. Taking this further into trying to assess rock strength from the sonic log is tenuous.

The use of oilfield tools with rotating dipoles would permit the determination of fast and slow shear waves and with them an indication of anisotropy. This technology has not yet been adopted in coal mining.

The use of the acoustic televiewer is immensely valuable in determining structural features and bedding plane orientation from the borehole image. It does not remove the need to log core to see the structural features and examine their physical state. However, by reconciliation of the core log and that of the acoustic televiewer image, it is possible to orientate the core, and thus save on the complications of obtaining orientated core by other more complex means. The acoustic televiewer image also enables the borehole wall to be examined for breakout or tensile fracturing. These features are a function of stress at the borehole wall caused by concentration of the rock stress by the borehole. In dry holes where acoustic televiewers cannot be used, optical televiewers may be used.

Hatherly et al (2009) take the use of borehole geophysics even further with the development of the Geophysical Strength Rating. Borehole geophysics alone cannot, however, make up for having some core to look at and test. The properties of sedimentary rocks are too complex to determine from geophysics alone. The process should be one of using the geophysics to assist in the interpolation of properties from point measurements.

CONCLUSIONS

This paper emphasises the need to consider the anisotropy of rock behaviour and in doing so the use of the appropriate test techniques to measure rock properties. Core testing is still needed and the test method needs to suit the stresses to which the rock may be subject. Referring to Figure 1, the picture of the longwall, we can consider what testing might advantageously be undertaken. Starting at the face we might test the coal using the Protodyakanov Index to find out its outburst and coal burst proneness. In addition, we should have certainly considered the coal structure by examining the core and measuring the cleating and other fractures. Testing the coal by cyclic loading may also be useful as it will show up any inelasticity and also give a compressive strength. Both of these are fundamental to the stability of the face and the propensity of the face to a coal burst. If we look at the immediate roof then point load testing will give an indication of its proneness to delaminate. Getting the horizontal compressive strength out of a vertical exploration core is difficult as it requires sub sampling of the core.

It is also necessary to consider the shear strength both on the bedding planes and across them. The simple shear and the modified GOST shear are appropriate and economic test processes for the former. More conventional uniaxial and triaxial testing may be used for shear across the bedding.

Tensile strength is important both in terms of direct delamination across the bedding planes and in terms of the strength of rock beams or plates. Whilst a point load test across the diameter of a core will give an indication of the strength of the core to resist bedding plane delamination, this is much better done using a direct axial tensile test on a core. A similar comment may be made about the preferability of using direct transverse tensile testing of a biscuit of core compared to Brazilian testing.

While borehole geophysics is well suited to determining similar rock types it is not ideal for use in determining rock properties where the rocks are anisotropic. The equations used to derive properties from sonic logs are on the basis of isotropic material and there are no direct means to derive anisotropic behaviour. While the acoustic televiewer is of great value in structural analysis and the determination of breakout as a stress indicator, it still cannot provide information on what infill exists within a joint.

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