Evaluation of Shear Strength Parameters in Unreinforced and Shotcrete Reinforced Coal through Experimental and Numerical Methods

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Abstract
The shear strength of coal mines forms the most significant aspect in the evaluation of mining disasters. A series of direct shear strength tests were conducted on intact coal specimens and coal-shotcrete specimens to evaluate the shear strength characteristics of the coal and coal-shotcrete interface. The tests were carried out under 1, 2 and 3 MPa of normal pressure respectively. The peak shear strength in intact coal specimen reaches its maximum value of 3.96 MPa under 3MPa of normally applied pressure while the shotcrete-coal interface has an estimated peak shear strength of 0.73, 0.80 and 0.86 MPa under the normal pressure of 1, 2 and 3 MPa respectively.

Mohr-Coulomb model parameters such as adhesion strength and angle of adhesion were further determined that were used for the design and evaluation of shear strength of in situ coal mines. Numerical simulations of coal-shotcrete and intact coal specimens were performed using the Mohr-Coulomb model in Abaqus software and the numerical results obtained were found in good agreement with experimental results exhibiting peak variation of less than 15%. Further, ultrasonic pulse velocity test measurements were performed on coal specimens to evaluate the dynamic shear strength parameters and the parameters obtained were found to be enhanced compared to static strength parameters.

Keywords: Coal, shotcrete, shear strength, Mohr-Coulomb model, Abaqus.

Introduction

Coal mines predominantly experience varied loading conditions or stress states that are classified on the basis of frequency of loading and direction of loading. Based on the varied frequency of loads, the loading states in mining activities range from static loadings such as overburden pressure to impact loading conditions such as blast loading conditions[11].

Coal mines also experience different types of loads depending upon the line of action of the acting force and these loads are termed normal load and shear load as shown in fig. 1. Extraction of coal from the mines generates multiple varied loading conditions particularly shear loading conditions, thus leading to the chances of several hazards that include roof collapse, caving in, rockfall and excessive deformation.

Numerous studies reveal that there is more advancement in estimating and optimizing the energy efficiency of coal as compared to an estimation of strength parameters of coal seams that are susceptible to heavy overburden pressure and frequent dynamic loading cycles[18]. This scarcity in the availability of geo-mechanical characteristics in mines especially underground coal mines aids in the huge recurrence of accidents that results in the loss of human lives and drain of financial resources[14].

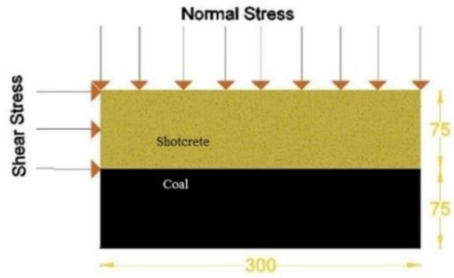

Figure 1: Stress State in Direct Shear Test

Generally, shotcrete lining is an additional structural element that is particularly used to enhance the intermittent bond strength between coal blocks, to support the overburden pressure and to act as a displacement constraint in the caving-in phenomenon of coal mines[12]. Coal being an anisotropic material is highly dependent on the direction, magnitude, intensity and duration of loading. Shear forces are imparted in numerous ways to a coal mine that primarily constitutes seismic activity and impact loads due to blasting.

Shear strength forms an important criterion in the evaluation of hazards in mines and various methods are used to evaluate the shear strength in mines such as direct shear test and indirect methods like tensile strength test and flexure tensile test. Shotcrete constitutes cement, sand and fine aggregate concrete which are applied pneumatically and compacted dynamically under high velocity. Shotcrete lining is one of the most common forms of reinforcement in the coal mining activity that is used to enhance the coal mass strength in coal mines[17].

Son[16] has produced a comparison of different test methods to study the adhesion strength at the shotcrete-rock contact and it has been found highly dependent upon the method of testing. Citing the efficiency and accuracy of the tests, it has been advised that direct test methods should be used for measuring the adhesion strength of the shotcrete–rock. Although numerous studies have been conducted in past for understanding the shotcrete-rock interface properties, this study predominantly focuses on estimating the behaviour of coal-shotcrete specimens that have not been conducted so far. Temperature-dependent curing studies are indeed an additional point of research interest but due to maintenance of temperature below flashpoint in mines, the temperatures are optimally maintained at room temperatures that correspond to the temperature maintained during the study.

A series of direct shear tests have been performed to investigate the shear strength characteristics of coal and shotcrete-coal interface. Numerical modelling has helped in analysing a phenomenon by avoidance of cumbersome, risky and expensive experimental tests. Thus, it gets a pre-requisite for the numerical models to have validated material characteristics that may be used to calibrate the actual conditions and simulate the future conditions.

Material and Methods

Coal is predominantly found in coal seams in the earth’s crust as rock strata having black or brownish colour and is broadly divided into three categories: anthracite, bituminous and lignite coal based on the carbon content in coal. Charon et al[3] presented the composition and variation in the composition of coal that chiefly includes carbon with quantities of additional elements such as hydrogen, sulphur, oxygen and nitrogen. The coal used in the study was procured from underground coal mines in Jharkhand, India. A series of basic index property tests were performed on the procured coal sample for the identification and classification of coal as shown in table 1.

On performing the analysis, it was observed that the coal subjected to analysis was bituminous coal with bulk density =1.41 g/cm^3, dry density = 1.37 g/cm^3, specific gravity = 1.39, porosity = 12.6% and water absorption = 4.6%. Based on the suggested methods, large-box direct shear tests have been performed experimentally and numerically.

Experimental Evaluation: A large direct shear test is a common method in practice for the evaluation of the shear strength of geomaterials such as coal, basalt, soil etc. Direct shear tests are carried out as per IS 2720 part 39[6] and are in compliance with ASTM D 5607[1] during the study. Overall, six large direct shear tests were performed where three tests were performed on the intact bituminous coal specimens and three tests on shotcrete lined bituminous coal. Wet shotcrete with a mix design ratio of 1:2:3 (cement: fine aggregate: coarse aggregate) which has 100% coarse aggregate passing through a 12.5 mm sieve, has been prepared as per IS 9012[7] and sprayed over a slab of bituminous coal of 300 mm × 300mm × 75 mm.

Thus, making the specimen height increase to 150 mm and the new specimen dimensions are 300 mm × 300 mm × 150 mm with a curing period of 28 days. The weakest plane is presumed to be the centre of the specimen and in the present study, the interface element is presumed to lie in the centre of the specimen, thus constituting the height of 75 mm for the coal block.

Interface properties are generally linked to the adhesion property in the study that is confined to a very narrow region, thus interface properties are studied irrespective of the thickness of elements. Shear test was carried out in a strain-controlled test assembly with the displacement rate of 0.125 mm/min aiding the fact that low shearing rates aid in the estimation of actual shear strength parameters of a material[19]. The tests were performed under the normal pressure of 1, 2 and 3 MPa to simulate the stress state experienced by the intact coal and coal-shotcrete interface conditions as shown in Figures 2 and 3[4,13].

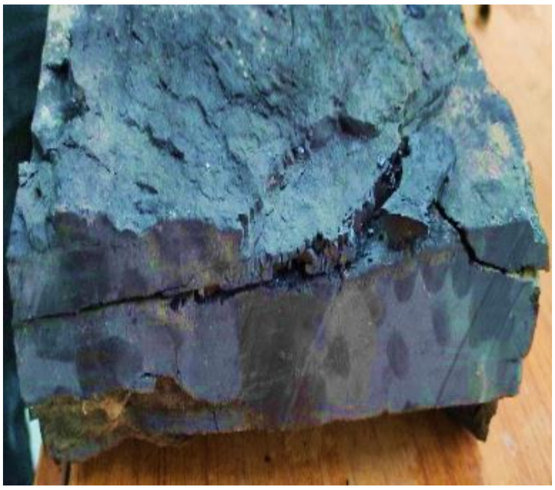

Figure 2: Failure State of Intact Coal Specimen

Table 1
Index Properties of Coal Specimen

Parameter Studied	Code of Guidance	Value Obtained
Bulk Density	IS 2386- Part III [9]	1.41 g/cc
Dry Density	IS 2386- Part III [9]	1.347 g/cc
Porosity	IS:1124-1974[8]	12.6%
Specific Gravity	IS:1124-1974[8]	1.39
Colour	-	Black
Formation	-	Layered
Water Absorption	IS:1124-1974[8]	4.6%

Figure 3: Coal-Shotcrete Interface Failure

Numerical Evaluation: Numerical analysis studies aid in the performance of simulation studies without the use of cumbersome and time-consuming experimental studies. In this study, finite element analysis of interface effect was carried out using Mohr-Coulomb numerical model in Abaqus software[2]. Mohr-Coulomb failure aids in the determination of failure criterion in geomaterials in the form of a linear envelope that is obtained from the observed shear strength characteristics of a material under different applied pressure conditions. Cube-shaped mesh elements C3D8R: An 8-node linear brick of the size 1 × 1 × 1 mm was generated to precisely estimate the effect of shear loads on the shotcrete coal interface as shown in fig. 4. Boundary conditions in the numerical calculations were simulated to the real-time experimental conditions where displacement is allowed only in the direction of loading while all other rotations and displacements are encastered as shown in fig. 5.

Further, the displacement rate of the numerical simulation test was kept at 0.125 mm/min and the results were further calculated thereof. The finite-element size was selected as 10 mm after performing the pre-analysis. Overall, 15300 elements and 18260 nodes were used for defining the mesh of the specimens. The interaction property module defined in the Abaqus software was used to define the interaction between coal and shotcrete specimen. The friction coefficient is also defined as 0.6 on the contact surfaces because of the possible friction effects in the experimental study. Shotcrete lining 75 mm thick was modelled with a 3-dimensional element type with the 8-noded brick element (C3D8R) which is suitable for solving the quasistatic problems.

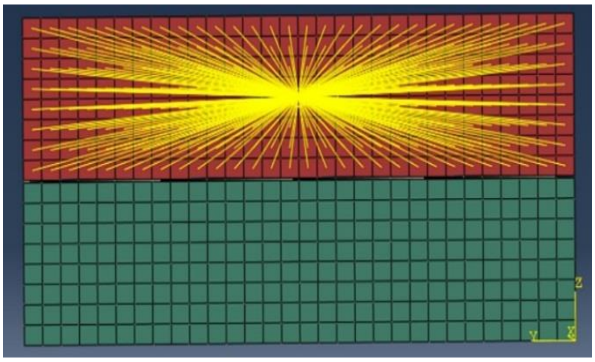

Figure 4: Numerical Model of Coal-Shotcrete Interface

Ultrasonic Pulse Velocity Measurement: Ultrasonic pulse velocity measurement setup works on the principle of generation of complex stress waves that include compressional waves, shear waves and Rayleigh waves while undergoing multiple reflections at the boundaries of different material phases within a material. The ultrasonic waves are transmitted in the form of a pulse through an electro-acoustical transducer into the material after traversing the length of the specimen at the onset of boundary, the fastest waves (longitudinal waves) are received through another transducer. UPV test is a non-destructive type of test method used for the estimation of different deformation parameters of geomaterials such as modulus of elasticity E_{dyn}, modulus of rigidity G_{dyn} and K_{dyn} bulk modulus under dynamic loading conditions[5,10].

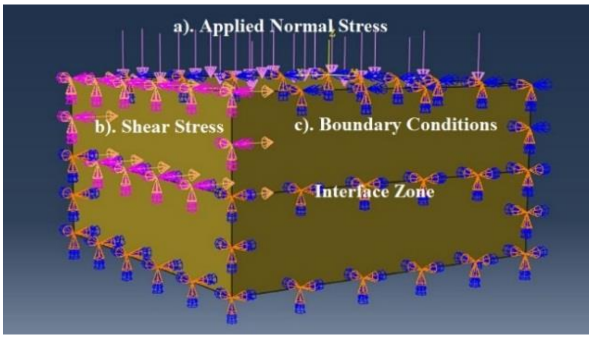

Figure 5: Depiction of a) Applied Normal Stress, b) Shear Stress and c) Boundary Conditions in Numerical Model

It was used to determine the elastic constants in coal with the consideration of anisotropy above 2% in the material considering the fact that bituminous coal is highly anisotropic in nature. The test procedure involves the determination of primary wave and shear wave velocities in addition to density and Poisson's ratio as shown in fig. 6. For anisotropy greater than 2%, the elastic constants are calculated through different empirical relations as given in the equations 1-4.

Calculation of dynamic modulus of elasticity:

$$E_{dyn} = \frac{\left[\rho V_s^2\left(3V_p^2 - 4V_s^2\right)\right]}{\left(V_P^2 - v_s^2\right)} \tag{1}$$

Calculation of modulus of rigidity:

$$G_{dyn} = \rho V_s^2 \tag{2}$$

Calculation of Poisson’s Ratio:

$$\mu = \frac{\left(V_P^2 - 2V_s^2\right)}{\left[2\left(v_p^2 - v_s^2\right)\right]} \tag{3}$$

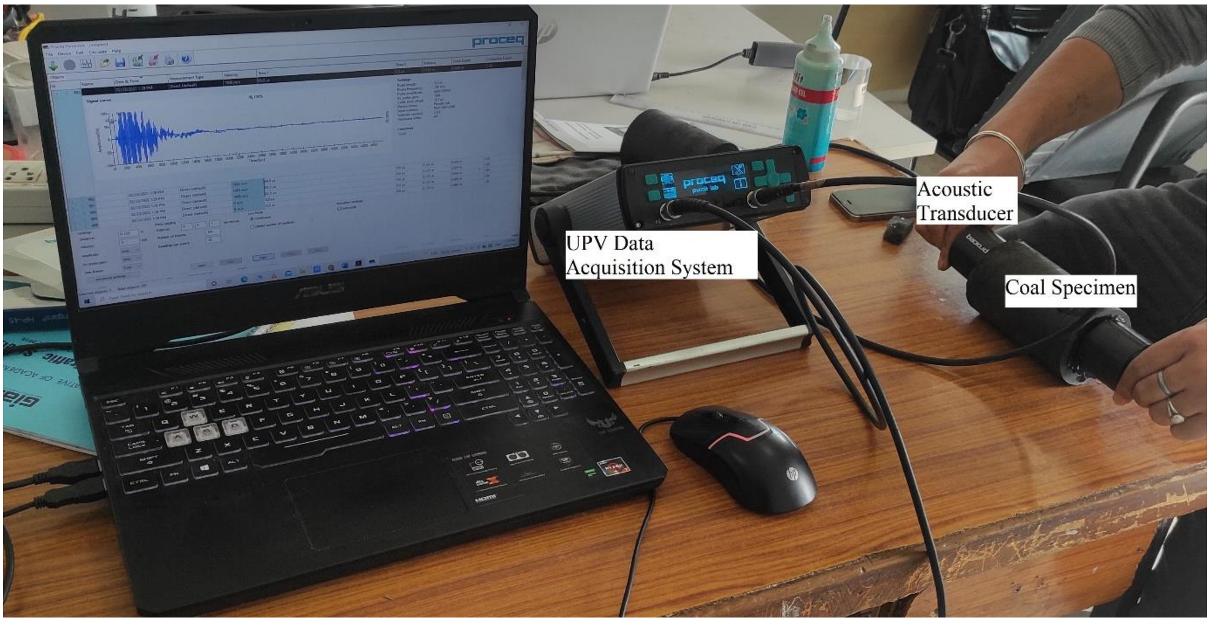

Figure 6: Ultrasonic Pulse Velocity Test

Table 2
Mohr-Coulomb Parameters from Direct Shear Test of Intact Coal Specimen

Specimen	Normal Pressure (MPa)	Peak Shear Stress (MPa)	Peak Shear Displacement (mm)	Cohesion Strength (*c*) (MPa)	Angle of Friction (*α*°)	Elasticity Modulus (*E*) (MPa)
Coal	1	3.48	0.73	16.5	36.5°	800
	2	3.64	0.72			
	3	3.96	0.66			

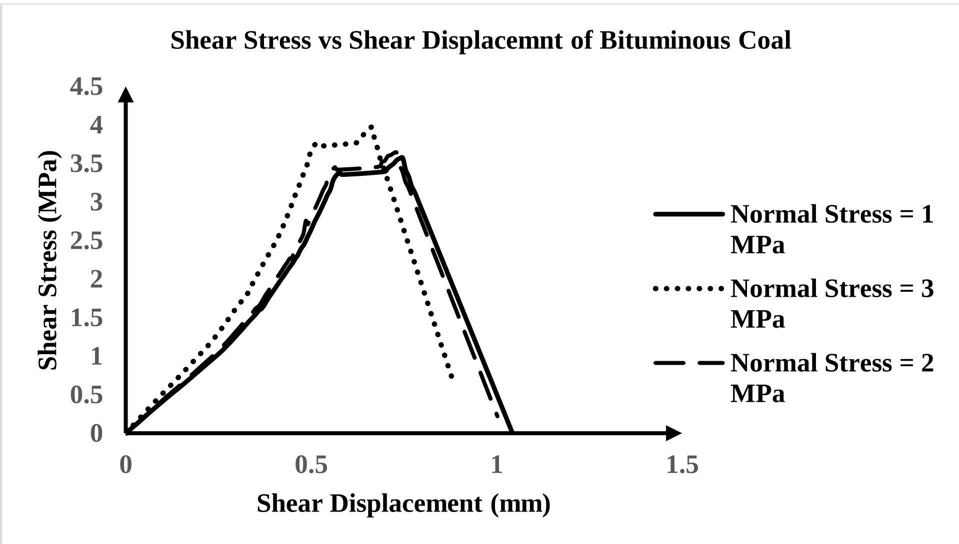

Figure 7: Shear Stress Vs Shear Displacement of Intact Coal Specimens

Calculation of bulk modulus:

$$k_{dyn} = \frac{\rho\left(3v_p^2 - 4v_s^2\right)}{3} \quad (4)$$

where E_{dyn} is the dynamic modulus of elasticity, *r* is density, v_s is shear wave velocity, v_p is compressional wave velocity, G_{dyn} is the dynamic modulus of rigidity, μ is Poisson's ratio and K_{dyn} is the dynamic bulk modulus.

Results and Discussion

It was observed from the experimental tests that the peak shear strength of the intact bituminous coal specimen was 3.48, 3.64 and 3.96 MPa under the enactment of normal pressure of 1, 2 and 3 MPa respectively and shear displacements observed at peak shear values are 0.73, 0.72, 0.66 mm respectively and the results are presented as in fig. 7. Coal being an anisotropic geomaterial has a layery formation that entraps some other minerals such as kaolin between the intermittent layers. This layery formation leads to the low shear strength values in coal as compared to the compressive strength.

Thus, on the enactment of shear forces in coal blocks, fractures are readily seen although the coal possesses remarkably high values of compressive strength. The results obtained from direct shear tests are used to evaluate other derived parameters such as cohesion, modulus of elasticity and internal angle of friction as shown in table 2.

On application of Shotcrete as per the aforementioned techniques, the cracks or surface fractures in coal blocks are filled by shotcrete and in addition, the formation of a new interfacial bond between the surfaces takes place. For conducting the simulations on the designs of mines, it gets a pre-requisite to estimate the interface parameters of coal and shotcrete layers. The shotcrete and coal interface material depicted peak shear strength of 0.73, 0.80 and 0.86 MPa under 1, 2 and 3 MPa respectively and shear displacements at peak shear values are 1.85, 1.90 and 2 mm respectively and the same are presented in fig. 8.

Based on the shear strength and normal stress parameters, Mohr-Coulomb model was used to evaluate the other derived characteristics of coal–shotcrete interfaces such as the adhesion strength of the coal-shotcrete interface and angle of adhesion as shown in fig. 9. Several other parameters such as adhesion strength, angle of adhesion and elastic modulus that are used for numerical modelling in the Mohr-Coulomb model were obtained from the shear tests and these parameters are shown in table 3.

Numerical analysis of the direct shear test using the Mohr-Coulomb model was observed to be in good agreement with the experimental results. It was observed that peak shear stress in the bituminous coal was observed to be 3.33, 3.61 and 3.90 MPa under 1, 2 and 3 MPa respectively. The difference observed in peak shear strength characteristics of intact coal specimens through experimental and numerical results was observed as 4.2%, 0.82% and 1.5% respectively.

Table 3
Mohr-Coulomb Parameters from Direct Shear Test of Coal- Shotcrete Interface in Specimen

Specimen	Normal Pressure (MPa)	Peak Shear Stress (MPa)	Peak Shear Displacement (mm)	Adhesion Strength (c_a) (MPa)	Angle of Adhesion(α°)	Elasticity Modulus (E) (MPa)
Coal-Shotcrete	1	0.73	1.85	0.61	20˚	466
	2	0.80	1.9			
	3	0.86	2.0			

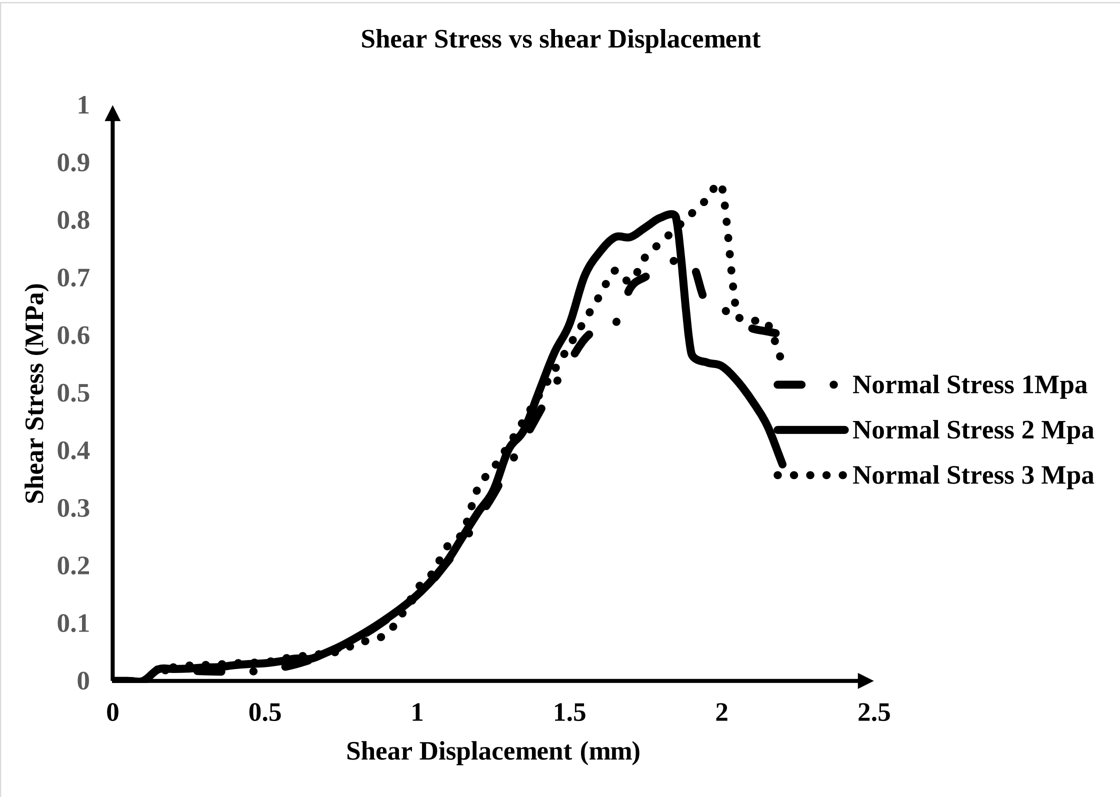

Figure 8: Shear Stress Vs Shear Displacement of Coal-Shotcrete Specimens

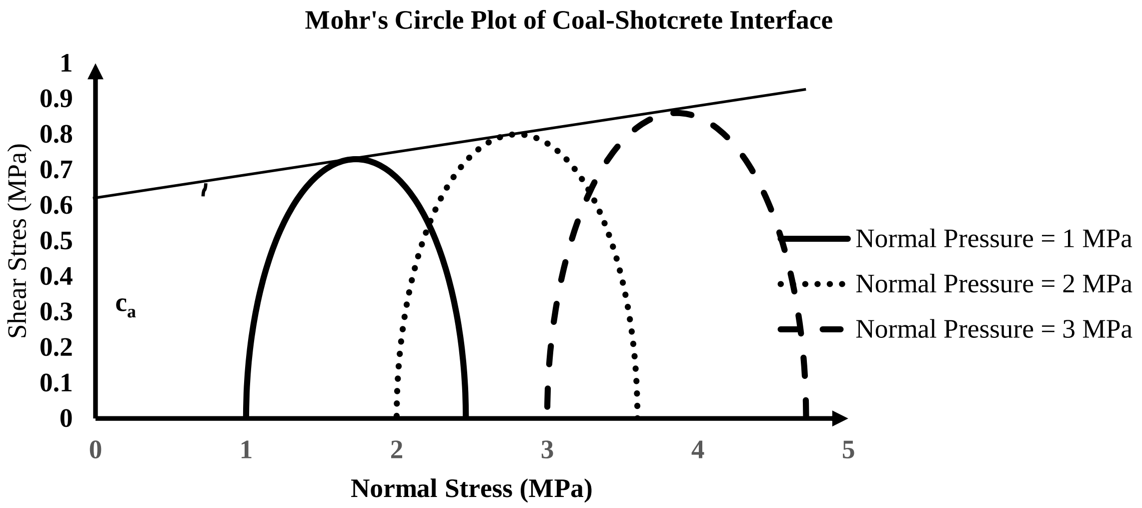

Figure 9: Mohr's Circle Plot of Coal-Shotcrete Interface

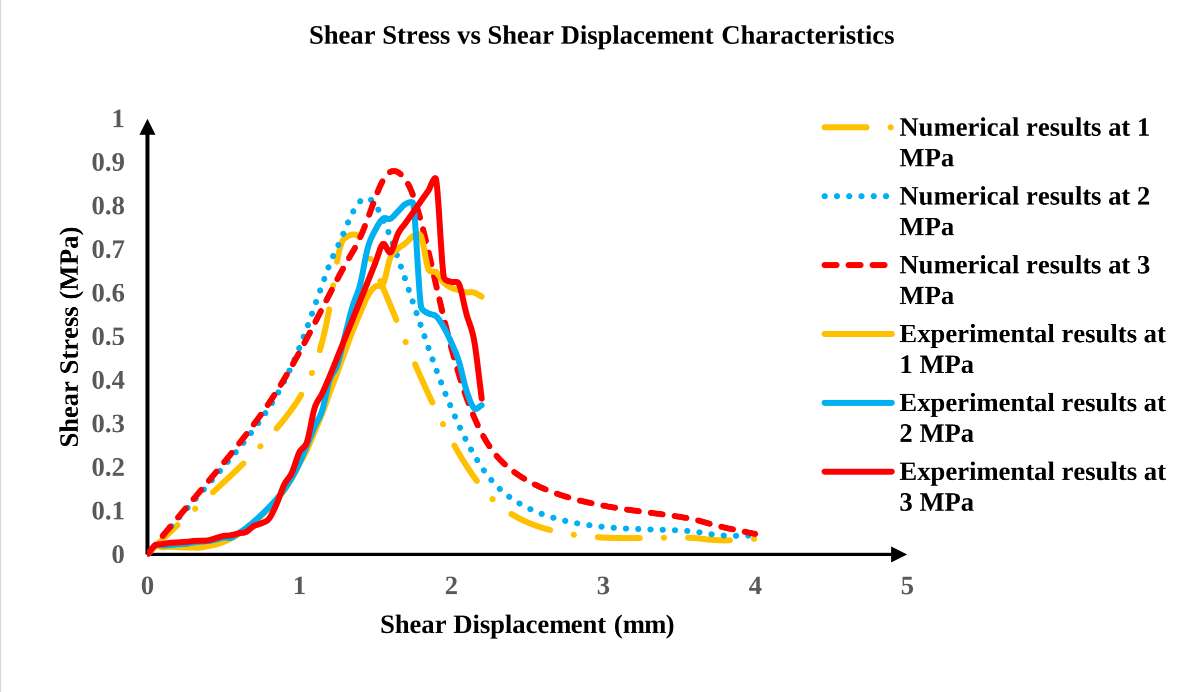

Figure 10: Experimental and Numerical Results of Shear Stress Vs Shear Displacement of Coal-Shotcrete Interface

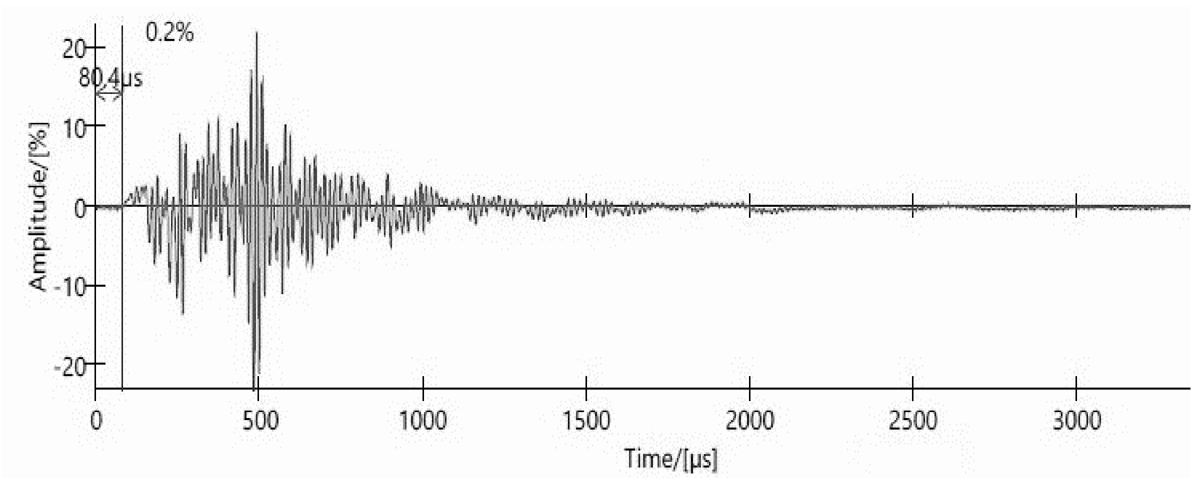

Figure 11: Ultrasonic Pulse Velocity Waveform Transmission

Table 4
Mechanical Characteristics of Coal Derived from Ultrasonic Pulse Velocity Test

Specimen	Ultrasonic Frequency	Specimen Length (mm)	Primary Wave velocity (m/s)	Shear Wave velocity (m/s)	Bulk Modulus (G_{dyn}) (GPa)	Elasticity Modulus (E_{dyn}) (GPa)	Modulus of Rigidity (G_{dyn})	Poisson's Ratio (μ_{dyn})
Coal	54-200kHz	125	2010	1210	2.44	5.13	2.10	0.22

In the numerical analysis of the shotcrete-coal interface using the Mohr-Coulomb model, the peak shear strength was observed to be 0.78, 0.81 and 0.88 MPa under 1, 2 and 3 MPa respectively as shown in fig. 10.

On comparing the peak shear strength results observed through experimental and numerical tests, it was observed that the difference in experimental and numerical results of peak shear is 0.05 MPa under 1 Mpa normal pressure and accounts for the difference of less than 5% while the variation of 0.01 and 0.02 MPa has been observed under 2 and 3 Mpa respectively as shown in fig. 10.

Ultrasonic pulse velocity measurements with a frequency range of 54 kHz to 200 kHz were performed to evaluate the primary wave velocity and shear wave velocity characteristics in the coal sample of length 125 mm and diameter of 50 mm as shown in fig. 11. The obtained values of primary wave velocity were observed to be 2010 m/s with a shear wave velocity of 1210 m/s. The modulus of elasticity or Young's modulus (E_{dyn}) when analysed through the ultrasonic pulse velocity measurement was observed to be 5.13Gpa. Poisson's ratio was reduced to 0.22 on analysis through ultrasonic pulse velocity measurements which are attributed to the fact that dynamic enactment of loads leads to the increase in brittle characteristics in a geomaterial. Mechanical properties like bulk modulus and modulus of rigidity evaluated through ultrasonic pulse velocity measurements are shown in table 4.

Conclusion

This study investigates the effect of shear strength characteristics of intact coal specimen and shotcrete–coal interface in coal mines, a series of direct shear tests were performed to evaluate the peak shear strength, shear displacement and other shear strength parameters such as adhesion strength, angle oaf adhesion and elastic modulus under varying normal stress conditions ranging from 1-3 MPa. Validation of shear strength parameters with numerical simulations with precise proficiency helps in carrying the numerical simulations with high precision, thus avoiding the cumbersome experimental procedures.

Peak shear strength characteristics show a considerable increase of 17.8% on an increase of normal pressure on shotcrete lining that in turn aids in enhanced stability of coal mines against shear stresses caused due to seismic activities or blast activities. Mohr-Coulomb model characteristics of the coal-shotcrete interface show the peak adhesion strength of 0.61 MPa and angle of adhesion of 20^0, thus indicating the productive bond strength of the coal-shotcrete composite.

Shear strength characteristics of coal shotcrete attained through the study may be used for conducting future research pertinent to the material. Shear strength parameters exhibited by one of the important reinforcement elements in mines indicate that reinforcement's additional requirements are required to ensure stability as the magnitude of shear stresses encountered in mines is high as reported in past studies[15].

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