THE INFLUENCE OF WATER ON THE SHEAR STRENGTH OF COAL MEASURES ROCKS AND DISCONTINUITIES IN SURFACE MINING

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ABSTRACT

The paper considers the characteristic shear strength of Coal Measures rocks and discontinuities, principally joints and bedding planes and emanates from slope stability research in British surface coal mining. Attention is given to the main factors which determine their shear strength i.e. physical and mechanical rock properties, surface roughness and weathering. The paper presents data on the particular role exerted by groundwater on these factors by reference to experimental data.

INTRODUCTION

This paper stems from a research programme at present being carried out by the Mining Engineering Department at Nottingham University into the stability of surface mine slopes operated by the National Coal Board of Britain. One aspect of this research is the study of the physical and mechanical properties of British Coal Measures rocks and their associated discontinuities. Important aims of the research are to define the influence of controlling factors on slope stability and to provide accurate strength data for stability assessment. The most important materials parameter is the shear strength of the rock discontinuities, principally joints and bedding planes. Recent studies of over one hundred British surface mine instability cases, Scoble [1] , Cobb [2], indicate that failure along discontinuities are primary contributory factors to mine slope instability. The influence of groundwater on stability analysis will be discussed in this paper with special reference to its effects on the shear strength of Coal Measures rock discontinuities.

REVIEW OF THE EFFECTS OF WATER ON ROCK MASSES

British Coal Measures strata are of Carboniferous age and consist generally of a complex combination of intact rock, faults, joints, shear zones and bedding planes. The deposits are layered and are often characterised by a general cyclothem sequence. Groundwater plays a significant role in the stability of excavated slopes in Coal Measures rock masses. Firstly, it can affect stability by reducing the normal stresses acting on a potential failure plane and secondly it can cause alteration of the mechanical properties of both intact rock and discontinuities.

The presence of water has been shown to reduce the stresses acting at a point within a rock mass. This is caused by the creation of uplifting forces and the effect is shown by the effective stress principle which states that

$$\sigma_e = \sigma_p - U$$

where σ_e = the effective stress
σ_p = the total or principal stress
U = the pore water pressure

Hence the pore water pressure should be subtracted from the normal stress to give the effective normal stress acting on a potential failure plane. This will in turn lead to reduced shear strength of discontinuities comprising the failure plane. The forces resisting movement within a slope can thus be reduced under the presence of groundwater pressure. Water can also increase the disturbing forces if tension cracks are present at the rear of a slope. The head of water in such a crack can add significantly to the forces tending to cause instability and increase promptly with mine site rainfall to precipitate failure. The combination of the above effects will reduce significantly the stability of a mine slope. It is important therefore to gain as much information about slope groundwater regimes at the initial exploratory phase of a surface mine, in order to assess the drawdown effects of excavation and the likely operative groundwater pressures in the excavated slopes.

Coal Measures rocks consist predominantly of relatively poorly-rounded and poorly-sorted quartz grains fixed in either a matrix of very fine-grained clay mineral paste or a calcareous cement. Price [3] . The clay minerals present are mainly kaolinite, illite, sericite and chlorite. It has been observed that the reactive effect of water is more pronounced with the clay matrix than the calcareous cement. The alteration of the mechanical properties of a rock mass can derive from the alteration of both intact rock and discontinuity properties.

Alteration of Intact Rock Properties

The reduction in strength of intact rock may be considered using Griffith's failure criterion for brittle materials,

$$T_o = \left(\frac{2E\Gamma}{\pi C}\right)^{\frac{1}{2}}$$

where T_o = tensile strength
E = Youngs modulus
Γ = surface energy
$2C$ = length of crack

Absorption of an aqueous phase onto the surface of a crack reduces the surface energy required to propagate the crack and therefore reduces the tensile strength of the material. This in turn causes a reduction in the compressive strength of the material. This effect is shown with chemically inert materials such as quartz, Charles [4] , as well as with rocks containing a high clay content. Price [3] has shown that the reduction in compressive strength for Coal Measures sandstone can be as much as 55% when comparing completely dry and saturated samples. Van Eeckhout [5], working on Coal Measures shales, concluded that moisture lowers the resistance to fracture and increases internal crack lengths. He also noted that expansion - contraction cycles caused by alternate wetting and drying caused crack propagation. The above theory has also been confirmed by Colback and Wiid [6].

Clay minerals tend to fill voids between grains and reduce permeability. Chemical reaction on the application of water causes clay mineral swelling and this can alter the geometry of the pores, leading to changed permeability. The process of swelling has been examined by Arscott [7] Spears and Taylor [8] and Barton [9]. It is noted that rocks with high clay content (mudstones, shales and seatearths) can swell considerably the application of water.

Weathering of intact rock due to the combined action of water, carbon dioxide and oxygen can also reduce strength values by mechanical means i.e. water and temperature cycling, or by chemical dissolution i.e. removal and transportation of certain elements by water flow. Work has been carried out by Spears and Taylor [8] on weatherability and also Franklin and Chandra [10] who considered the slake durability index, which measures the resistance of rock samples to weakening and disintegration due to a standard cycle of drying and wetting.

Alteration of Discontinuity Properties

Work carried out by Horne and Deere [11] and Coulson [12] indicates that for polished surfaces, the frictional characteristics are significantly affected by the presence of water. Generally water acts as an anti-lubricant on massive structured minerals and as a lubricant on minerals with a layer-lattice crystal structure. However as surface roughness increases these effects are reduced and other factors become significant. Coulson [12] showed that, for surfaces which suffer little damage during shearing and which tend to produce polished surfaces, there was an increase in strength when water was present. However, most natural joints exhibit surface roughness and on their wet surfaces decreased crystal strength and intercrystal bonds allow a more plastic deformation. This leads to increased surface area contact and the formation of debris which allows increased absorption of water and the formation of a thick surface paste. With increased displacement this paste acts as a viscous lubricant which reduces the shear strength of the discontinuity. Jaeger [13] suggested that slickensides develop across powdered shear debris more readily when the surface is saturated. Consequently the shear strength is reduced and there is a greater curvature in the shear strength envelope. This change in behaviour, however, is absent with smooth polished surfaces which exhibit the tendency for linear shear strength envelopes.

Study of the mode of failure of rough discontinuities gives an indication of the reason for reduced shear strength due to the application of water. It is accepted that the shear strength of such discontinuities is controlled by a combination of dilatant movement and failure through intact rock asperities. These two mechanisms occur simultaneously. It can, however, generally be stated that at lower normal stresses the discontinuity will tend predominantly to dilate, whilst at higher normal stresses shearing through asperities is more dominant. Combination of these two failure modes gives rise to a curved shear strength failure envelope. The effect of water on such mechanisms is not fully understood. A rational explanation, however, is that the tensile and compressive strengths of the asperities are reduced by water, due to the reasons stated earlier, and the forces required to shear through the intact asperities are consequently reduced. This leads to decreased shear strength of the discontinuity and further surface damage and debris. It is postulated therefore that the effect of water on the frictional properties of rock discontinuities is governed significantly by surface roughness characteristics. Coulson [12] showed that for sandblasted surfaces the reduction in residual shear strength due to water was generally between 5 and 10%. Barton [14] has reported a general reduction for non-planar joints of between 5 and 30%. The effect of weathering on strength is accentuated when considering joints, due to the relatively high permeability of joint systems, which allows water easy access to joint walls. The joint walls suffer from the adverse effects of weathering before the main body of the intact rock is altered.

The influence of water on the shear strength of filled discontinuities and clay bands must be considered due to its relevance in Coal Measures slope engineering. The presence of intraformational shear zones, Salehy [15], and strata with high clay content, such as seatearths, have been responsible for a number of surface coal mine instabilities in Britain. Barton [9], in a study of filled discontinuities, stated that when a slope is excavated above a clay filled discontinuity there will be a strong tendency for negative pore pressures to develop. Reduction in the normal stress allows the clay to expand. If heavily overconsolidated, the clay also tends to expand during shear. Both mechanisms generate negative pore pressures, which cause water to be sucked into the clay. Hence the moisture content is increased and the shear strength reduced. Cullen and Donald [16] reported a reduction of 30% in residual shear strength for a clay due to an increase in moisture content from 22 to 27%.

EXPERIMENTAL DATA FOR COAL MEASURES ROCKS AND DISCONTINUITIES

Intact Rock

Table 1 summarises the results of over 2000 laboratory tests carried out on British Coal Measures rocks. Both dry and saturated samples were tested, following I.S.R.M. standards, to give mean uniaxial compressive strength (σ_c), indirect tensile strength (σ_t, Brazilian method) and Elastic Modulus (E). Also given are the percentage reductions due to saturation of the samples. Generally it can be seen that for siltstone and sandstones the percentage reduction for the three parameters ranges from 17 to 57% whilst for the generally more argillaceous rocks (i.e. the mudstones and seatearths) the reductions range from 75 to 97%. These results tend to support the theory given earlier.

The resistance of Coal Measures rocks to weathering was studied by means of the slake durability test, see figure 1. The general trend is for rocks of high strength to have high slake durability index values and for those of low strength to exhibit low durability. Slake durability is affected by clay content and was investigated by the authors as a possible index test for Coal Measures rock classification. It was thought possibly to be more appropriate than other index tests for classifying the weaker, more clay-rich rocks, which in themselves are more susceptible to strength reduction by water. Figure 1, however, indicates that Coal Measures mudrocks exhibit a wide range of slake durability index and that strength classification by this means is difficult. Work by Hassani [17] on possible index ranking of rock strength by the point load method and by Wild [18] on the shear vane method offer alternative methods of index strength classification.

Discontinuities

Shear strength testing on discontinuities was carried out using a purpose built, constant strain direct shear rig, Hassani and Cassapi [19]. The shear box accommodates samples up to 150 x 150 mm and provides a range of strain rates, down to 0.01 mm/min. Table 2 shows the results of direct shear testing on over 500 saw-cut Coal Measures discontinuities. The shear strength data has been analysed using geometric regression to give a power law of the form,

$$\tau = A\,\sigma_n^{B}$$

where τ = the shear strength (kN/m^2)
σ_n = the acting normal stress (kN/m^2)
A and B are index values

To allow comparison of wet and dry test data the value of index B has been set at 0.930. The value of index A is used to indicate the relative shear strengths of the discontinuities. The percentage reductions in shear strengths are also shown. The results for the saw-cut surfaces show a reduction in shear strength, due to the application of water, which ranges from 4.6 to 12.1%. Generally, the more argillaceous rocks show larger reductions. The results show good agreement with Coulson [12] who reported reductions of between 5 and 10% on planar surfaces.

Table 3 shows the results of tests carried out on wet and dry natural Coal Measures discontinuities. To allow comparison of the data, index value B was set at an average value for each set of wet and dry data. As in the previous section index A was then used to define the magnitude of the discontinuity shear strength reduction. The data for natural discontinuities indicates reductions in shear strength of approximately 40%. This again agrees favourably with the theory given in earlier sections and is due to reduced strength of the asperities. Extended shear testing of natural Coal Measures rock discontinuities is currently underway to define further this significant influence on shear strength.

Generally for all discontinuities, both saw-cut and natural, there is a reduction in index value B on the applications of water. This means that the shear strength envelope has increased curvature and is considered to result from intensified surface damage as suggested by Jaeger [13].

CONCLUSION

The paper summarises prior studies of strength reduction resulting from the influence of water on rocks and their discontinuities. The effect of water on Coal Measures discontinuities has received little attention in the past, yet the resultant reduction in discontinuity shear strength significantly affects any analysis of slopestability. Assessment of the influence of groundwater on mine slope stability is hindered in practice by a general lack of knowledge of groundwater conditions prevalent in slopes and limited experimental shear strength data.

Laboratory testing of Coal Measures rocks and their discontinuities shows that strength reductions for intact rock ranges from 17 to 97% and for discontinuities form 5.0 to 30 % when considering the influence of water. These ranges appear to be determined by the following inter-dependent factors, namely, intact rock mineralogy, permeability and state of weathering and discontinuity surface roughness and permeability.

It is suggested that close consideration be given to strength reduction due to water when selecting appropriate shear strength input for slope design in surface mine planning. Discontinuity shear strength is an important input parameter for mine slope stability analysis. The significant influence of water on Coal Measures discontinuity shear strength and a lack of prior research justifies extended laboratory and field studies of the mechanism and controlling factors by which strength reduction occurs. This is aimed to improve the simulation of mine slope behaviour and increase the efficiency and safety of surface mine operations.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance provided by the National Coal Board Opencast Executive in the support of this research work. The views expressed in this paper are those of the authors and not necessarily the N.C.B..

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FIG 1 SLAKE DURABILITY INDEX DIAGRAM

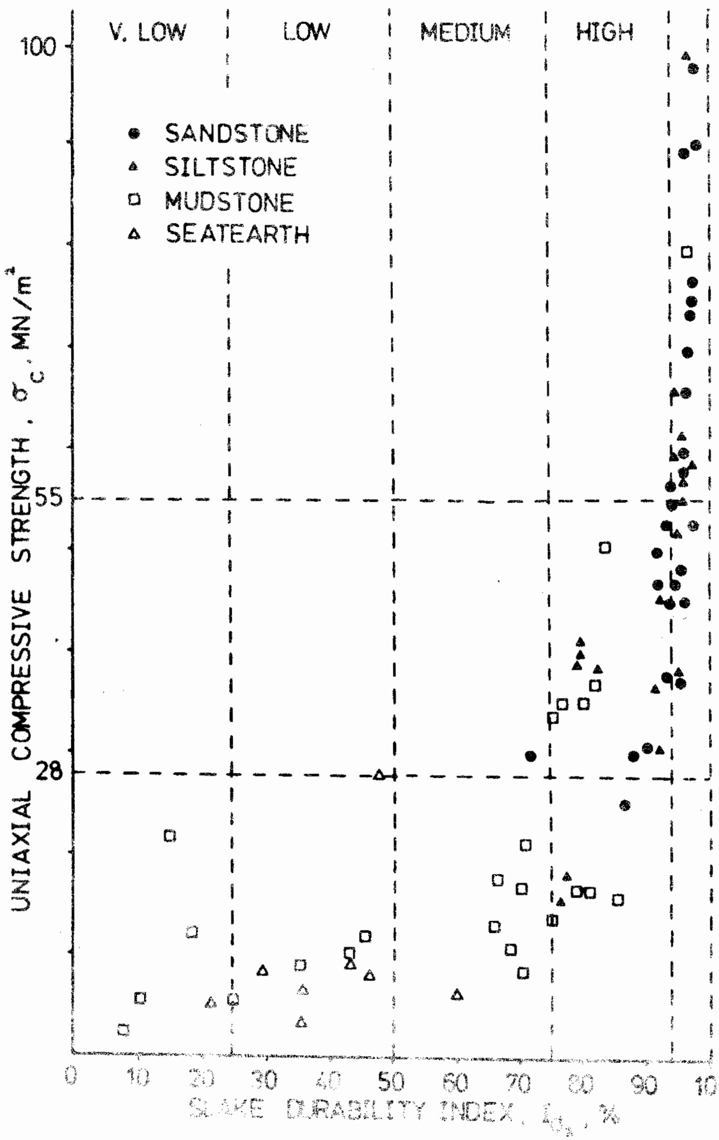

TABLE 1 SUMMARY OF UNCONFINED MECHANICAL PROPERTIES FOR INTACT COAL MEASURES ROCKS

ROCK TYPE	UNIAXIAL COMPRESSIVE STRENGTH			TENSILE STRENGTH			YOUNGS MODULUS		
	DRY (MN/m^2) $\sigma_c \pm SD$	SAT (MN/m^2) $\sigma_c \pm SD$	PERCENTAGE REDUCTION	DRY (MN/m^2) $\sigma_t \pm SD$	SAT (MN/m^2) $\sigma_t \pm SD$	PERCENTAGE REDUCTION	DRY (MN/m^2) $E \pm SD$	SAT $MN/m^2)$ $E \pm SD$	PERCENTAGE REDUCTION
MUDSTONE	39± 8	5±[illegible]	87	4±1	0.6±0.2	85	5000±3000	1000± 500	80
SEATEARTH	27± 7	1±0.2	96	3±0.5	0.1±0.04	97	4000±1000	1000± 500	75
SILTSTONE	63 ± 7	45±4	29	8±1	4±1	50	6000±3000	3000± 500	50
FINE GRAINED SANDSTONE	163±89	112±65	31	12±7	9±5	25	14000±6000	10000±5000	29
MEDIUM GRAINED SANDSTONE	64±11	50±16	22	6±2	5±1	17	9000±4000	4000±2000	56
COARSE GRAINED SANDSTONE	36± 5	24±6	33	3±0.5	1.5±0.1	50	7000±3000	3000±1000	57

TABLE 2 SAW CUT SURFACE POWER LAW ANALYSIS

ROCK TYPE	$\tau = A\sigma^{B}$				CORRECTED $\tau = A\sigma^{0.930}$		PERCENTAGE REDUCTION
	DRY		WET		DRY	WET	
	A	B	A	B	A	A	
MUDSTONE	0.870	0.929	0.854	0.914	0.863	0.759	12.1
SEATEARTH	0.906	0.921	0.847	0.913	0.848	0.748	11.8
SILTSTONE	0.918	0.933	0.987	0.913	0.938	0.871	7.1
FINE GRAINED SANDSTONE	0.934	0.960	0.971	0.944	1.165	1.076	7.6
MEDIUM GRAINED SANDSTONE	1.034	0.937	1.108	0.916	1.089	1.000	8.2
COARSE GRAINED SANDSTONE	0.774	0.947	0.875	0.924	0.877	0.837	4.6
ALL SANDSTONE	0.933	0.944	0.991	0.926	1.034	0.962	7.0

TABLE 3 NATURAL DISCONTINUITIES POWER LAW ANALYSIS

ROCK TYPE	MOISTURE CONTENT	$\tau = A\sigma_n^B$		CORRECTED $\tau = A\sigma_n^B$		PERCENTAGE REDUCTION DUE TO WATER
		A	B	A	B	
MUDSTONE DISCONTINUITIES	DRY	0.891	0.925	1.017	0.907	40.3
	WET	0.693	0.889	0.607	0.907	
WEATHERED SANDSTONE JOINTS	DRY	0.865	0.843	1.071	0.814	39.6
	WET	0.801	0.785	0.647	0.814	