Mechanism for mining subsidence reactivation due to groundwater recharging - the geotechnical aspect

Z. LI[1], D. J. REDDISH[2] & Y. SHENG[3]

[1] *Nottingham Centre for Geomechanics, Nottingham University. (e-mail: enxzl2@nottingham.ac.uk)*
[2] *Nottingham Centre for Geomechanics, Nottingham University. (e-mail: david.reddish@nottingham.ac.uk)*
[3] *School of Civil Engineering, University of Leeds. (e-mail: y.sheng@leeds.ac.uk)*

Abstract: Following the closure of many coal mines throughout the UK and subsequent switching off of pumps, the groundwater level has rebounded. Mining subsidence has been reported to have been reactivated due to the deteriorative effects of groundwater on the mechanical properties of rocks resulting in potential environmental hazards. This paper presents experimental studies carried out on UK Coal Measures rock samples, aimed at quantifying the effects of water on the rock properties, with particular emphasis on failed or broken rocks. The shear strength of the failed rocks is examined in detail with reference to the water content. It is observed that not only the strength of the intact rock but also the shear strength of the already existing failure surface reduces dramatically because of water. The deteriorated material properties were then introduced into a FLAC numerical model to investigate potential reactivation of subsidence caused by groundwater rebound. Numerical results clearly indicate that as the rock mass properties are reduced by the saturation with groundwater, the corresponding subsidence increase.

Résumé: Le niveau de Léau souterraine a resurgi depuis que les pompes minières ont été coupées suite à la fermeture de plusieurs mines charbonnières à lrcwers le Royaume Uni. Láffaissement minier an été réactivé en raison de la détérioration dans le comportement mécanique du rocher, causant plusieurs dangers environnements. Ce papier présente les résultats des testes laboratoires exécutes sur des échantillons de charbon du Royaume uni afin de quantifier les effets de l'eau sur les propriétés des roches, avec un accent particulier sur les roches pulvérulents la résistance au cisaillement des rochers pulvérulents est examiné an détail par rapport à l'eau. Il est observé que non seulement la résistance des rochers intacts mais aussi la résistance au cisaillement des fissures déjà existantes à la surface sont radicalement réduites. Un mécanisme réparateur pour cet effet nuisible est proposé.

Keywords: abandoned mines, discontinuities, mechanical properties, rock mechanics, subsidence, water table

INTRODUCTION

Many environmental hazards like landslides and dam collapse are caused by the penetration of water into internal voids or fractures, especially during periods of heavy rainfall (Bobet, 2003; Wen & Aydin, 2005). Under saturation conditions the bearing capacities of these fractures or joints are dramatically reduced (Ballivy et al., 1976; Baud et al., 2000; Colback & Wiid, 1965; Masuda, 2001; Zhu & Wong, 1997), resulting in serious implications to stability. The detrimental effects of water on the stability of geo-structures still remain an important topic.

Water infiltration has also been observed in the strata disturbed by various coal mining activities. Many coal mines throughout the UK and Europe have been closed down or abandoned generally as a result of the cost of mining at great depth and recoverable reserves becoming exhausted. As a result of this, water pumping used for mine drainage is usually switched off, allowing the groundwater table to recharge to its original level. Consequently, the previously drained mine workings are without doubt at risk of inundation. With consideration of the strength deterioration effects of water on rocks the subsidence of the previously stabilized strata would be reactivated bringing about further damage to the surface.

Intact rocks have been investigated to qualitatively evaluate the effects of water (Ballivy et al., 1976; Broch, 1979; Colback & Wiid, 1965; Dube & Singh, 1972; Masuda, 2001; Parate, 1973; Van Eeckhout, 1976). It is reported that 20-90% of the uniaxial compressive strength was lost after the rocks were saturated from a dry state depending on the rock type. Additionally, other parameters such as cohesive strength, Young's modulus and so on are also reduced. However, the deficiency in previous studies is a lack of comprehensive description of the development of the property parameters with the water content.

With respect to jointed rocks, little attention has been paid to the consideration of the presence of water even though they are common in the subsidence strata. Few investigations have been undertaken either from the laboratory testing point of view or from the theoretical side. Due to coal mining extraction, a great number of ubiquitous rock joints are produced in the overburden because of the redistribution of the stress field, and these provide a good flow channel for water. Accordingly, hydro-mechanical coupling analysis is usually conducted to assess the influence of water flow on the rock deformation. The action of water is herein carried out as an equivalent load that only applies to the solid matrix. The deterioration of the physical properties due to water is, however, not considered.

In addition, compared to intact rocks, jointed rocks could contain more water because of the additional failure surfaces produced (Li & Reddish, 2004). A corresponding primary investigation (Li et al., 2005) showed that rock

© The Geological Society of London 2006

joints were more sensitive to water than intact rock. A small amount of water could cause much strength loss of a rock joint because of the high water sensitivity of the residual friction angle. In view of the above, this paper puts more emphases on the performance of jointed rocks especially with reference to water. It also involves numerical simulations with FLAC to study the reactivation of ground subsidence due to groundwater rebound.

EXPERIMENTAL TECHNIQUE AND RESULT

Experimental technique

Multistage triaxial compression tests were conducted in this study. 3 stages were allocated to the intact sample and 7 stages to the fractured sample. The intact sample was compressed in 3 stages until a full failure state occurred followed by the production of rock fracture. After that, further shearing was performed on the failure surface with displacement servo controlled unloading. In this study we define the peak and finally stable axial stress as peak and residual strengths respectively at each stage. Corresponding friction angles are peak and residual friction angle. The detailed testing methodology is coved by Li et al. (2005).

Two rock types were employed in this research, i.e. coarse grained sandstone and siltstone, which were collected from the Arkwright opencast site in Derbyshire, East Midlands, UK. The sandstone consists mainly of quartz and feldspar grains whilst the siltstone is predominately made up of calcite, dolomite and orthoclase minerals. Related mechanical and physical parameters are listed in Table 1

Table 1. Summary of geotechnical parameters

Parameter	Sandstone	Siltstone
Dry density (kg/m^3)	2277	2393
Porosity (%)	13.0	7.4
Dry uniaxial compressive strength (MPa)	68.1	87.1

Samples were conditioned to a chosen level of saturation with a new method. Specimens were firstly immerged into water with a constant vacuum, 1kPa to reach a full saturation state followed by air drying to a chosen weight and then were shelf conditioned for 1-2 weeks in an air tight container with some water at the bottom. This method was confirmed as a powerful way to obtain an even water distribution throughout sample since the evenness of water distribution can strongly influence the testing results (Barlett & MacGregor, 1993; Poon et al., 2004). Figure 1 demonstrates the comparison between the two different conditioning methods in terms of the uneven rate of water distribution obtained by breaking and analysing the samples for water content.

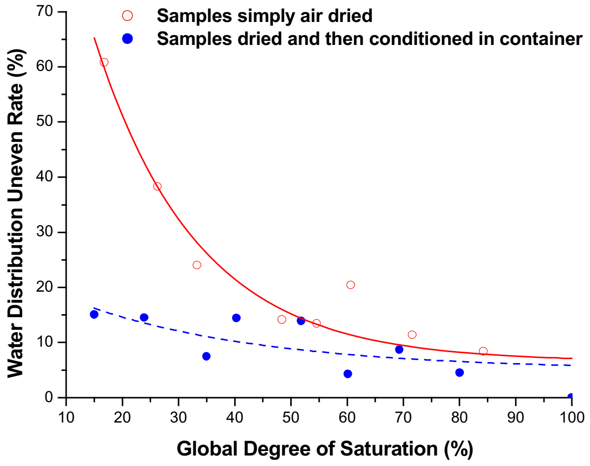

Figure 1. Variation in water distribution between conditioned and air dried samples

Testing result

Rock samples were tested with various degrees of saturation. A continuous variation with saturation was obtained for each deformation parameter. Since the cohesive strength, internal friction angle and Young's modulus are crucial in rock deformation these three parameters were monitored for both the sandstone and the siltstone. Related testing values are tabulated in Table 2 and Table 3 for sandstone and siltstone respectively together with the reduction ratio from dry to a saturated state.

Table 2. Testing values of the rock deformation parameters under various degrees of saturation, sandstone

Degree of saturation (%)	Cohesive strength (MPa)	Friction angle (°)	Young's modulus (GPa)
0	13.3	47.4	20.5
5.6	12.3	47.3	16.4
16.1	11.5	46.0	15.1
56.6	11.2	45.3	17.0
100	10.4	46.6	14.2
Total Reduction (%)	22*	1.7*	30.7*

*Reduction rate between the dry and saturated testing values for each deformation parameter

Table 3. Testing values of the rock deformation parameters under various degrees of saturation, siltstone

Degree of saturation (%)	Cohesive strength (MPa)	Friction angle (°)	Young's modulus (GPa)
0	19.7	42.1	12.2
10.8	14.4	40.4	10.4
16.7	12.6	39.1	9.1
41.1	10.5	39.0	7.9
100	8.5	39.0	6.6
Total Reduction (%)	56.9*	7.4*	45.9*

*Reduction rate between the dry and saturated testing values for each deformation parameter

It is observed from the above data that water definitely has detrimental effects on the rock deformation parameters. Additionally, the siltstone is more sensitive to the presence of water. A bigger reduction happens on the deformation properties for the siltstone than the sandstone when the samples are fully saturated, probably because of the presence of more water sensitive minerals in the siltstone.

Fractured rocks were also examined with reference to the saturation rate. Strength envelopes are outlined in Figure 2 and Figure 3 for sandstone and siltstone respectively based on the testing results of the shear strength measured at related normal stress levels. The strength envelopes of the saturated rocks are underneath the ones for dry samples, which implies that the shear strength is always reduced by water.

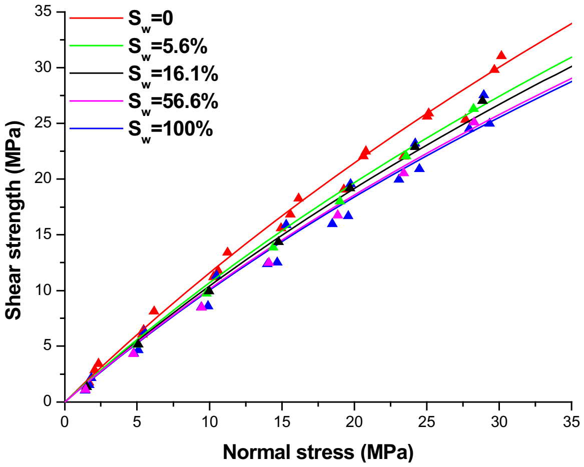

Figure 2. Strength envelopes of coarse grained sandstone under various saturation conditions

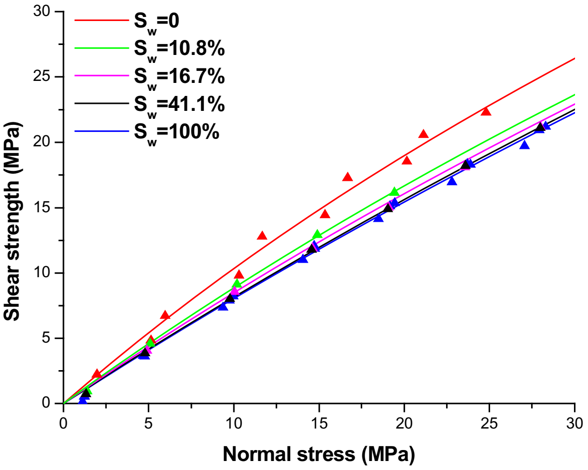

Figure 3. Strength envelopes of siltstone under various saturation conditions

NUMERICAL INVESTIGATION OF THE REACTIVATION OF GROUND SUBSIDENCE

A simplified model was established in FLAC to numerically study the reactivation of ground subsidence as groundwater rebounds. As demonstrated in Figure 4, this model is of a shallow horizontal coal seam 2m thick excavated using the longwall coal mining method. The corresponding depth is approximately 155m. The caved zone over the longwall is assumed to be 3.5 times the height of the coal seam, i.e. 7.0m. A total of 5 adjacent panels are retreated with a working width of 40m each. It should be noted that this model is employed only for the purpose of demonstrating the tendency for the reactivation of ground subsidence. More detailed information on strata properties, geological and hydrological conditions should be acquired before any quantitative evaluation can be done by this model. Ground subsidence is examined on the top surface with the material properties listed in Table 4. Related subsidence profiles are displayed in Figure 6. It is observed that the ground subsidence increases with the sequence of the excavation, which in general agrees with the theory of deformation and the site observations.

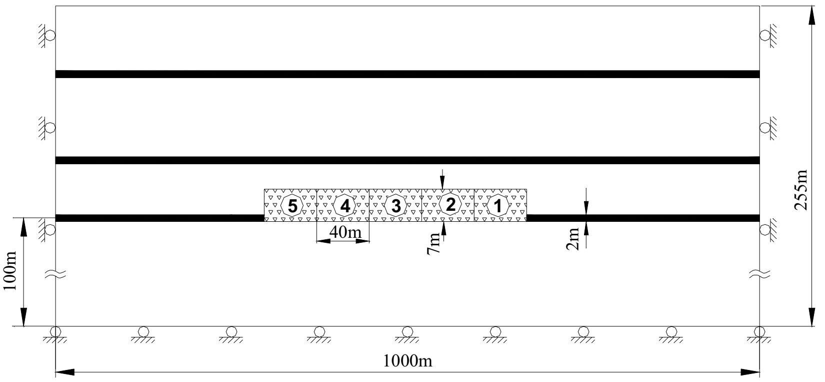

Figure 4. Diagrammatic sketch of the model used in numerical simulation

Table 4. Property parameters used for numerical modelling (Whittles et al., 2001)

	Siltstone	Coal	Sandstone	Goaf
Bulk modulus (GPa)	5.52	3.80	5.04	0.406
Shear modulus (GPa)	3.31	0.81	3.03	0.187
Cohesion (MPa)	8.13	3.36	9.19	*
Friction angle (°)	32.40	20.0	33.50	30
Tensile strength (MPa)	1.0	1.0	1.0	0

*Cohesive strength of goaf follows a strain hardening law, as demonstrated in Figure 5.

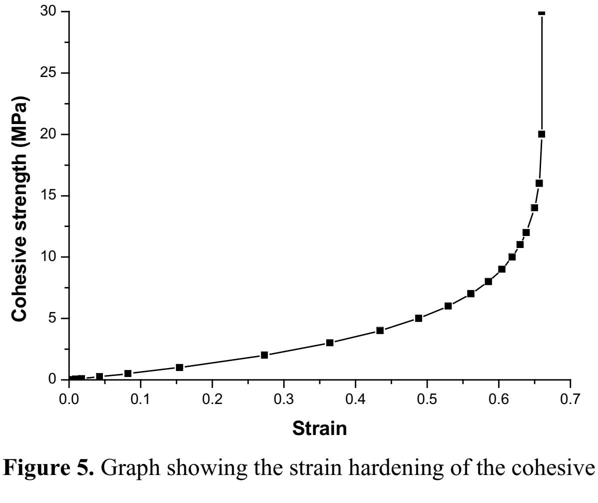

Figure 5. Graph showing the strain hardening of the cohesive strength of goaf (Whittles et al., 2001)

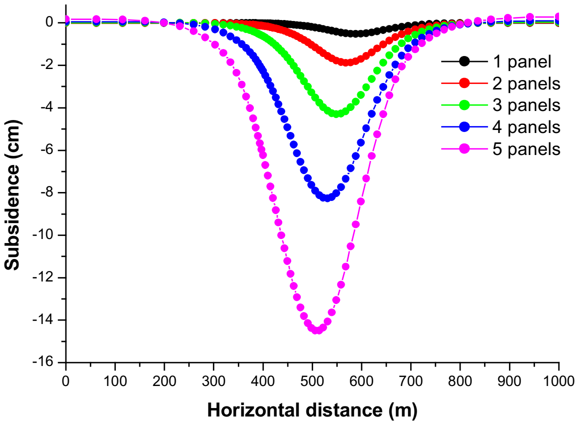

Figure 6. Subsidence profiles with 5 panels being excavated

Influence of the rock property deterioration

It is assumed in this study that the coal mine was closed down after the retreat of five panels. The groundwater table would consequently rise following the switching off of the drainage pumping. The additional rock deformation caused by water flow along with the groundwater rebound is too small to be considered. No hydro-mechanical coupling analysis was conducted. Nevertheless, the pore water pressure was included, and the change of rock properties arising from the groundwater recharge was introduced in the model.

Figure 7 shows the change of the subsidence profile after the groundwater rebound with no property deterioration being considered. It is observed that the maximum subsidence value is smaller because of the buoyant force of groundwater. However, the subsidence trough is getting broader.

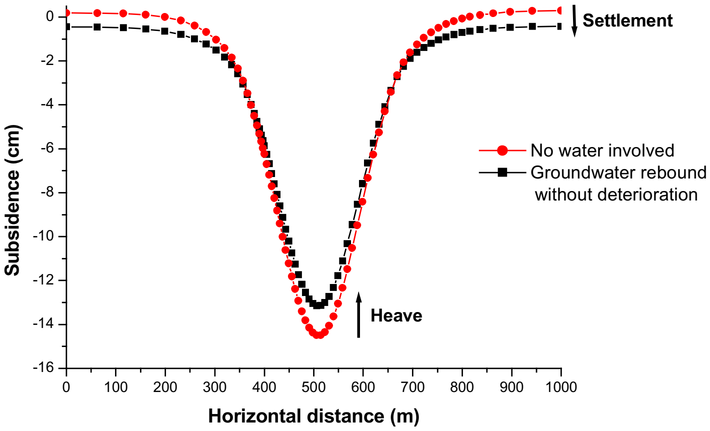

Figure 7. Changing of the subsidence profile due to the groundwater rebound

On the other hand, as revealed in the laboratory testing the rock properties are inevitably weakened if water invades the rock mass. This property reduction is therefore not negligible in the numerical simulation in order to obtain the correct trend of ground subsidence under the condition of the ground water rebound.

Corresponding subsidence profiles are plotted in Figure 8 with consideration of various property reduction rates. As expected the ground subsidence increases with the property reduction rate, whilst the profile shape and subsidence range remain almost the same. Related maximum subsidence values are also used to sketch the variation with the reduction rate, which is outlined in Figure 9. It is found that the maximum subsidence rises with the rock property deterioration rate. As also indicated in Figure 7 the maximum subsidence will reduce once groundwater rebounds if the rock property deterioration is not considered. Accordingly, there exists a threshold value of the rock property deterioration rate, at which the maximum subsidence values is equal to the one prior to groundwater rebound. This value is given in Figure 9 as approximately 45% at the cross point of the dashed line and fitted curve. This indicates that beyond this point, the deteriorative effect has taken over from the buoyant force of groundwater, and causes the reactivation of the ground subsidence.

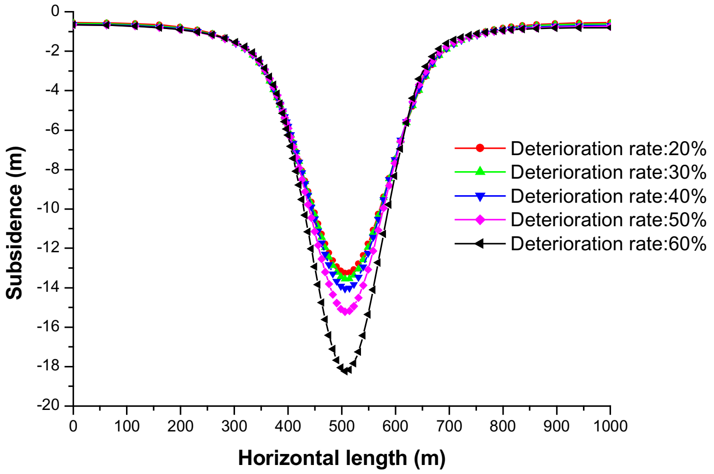

Figure 8. Subsidence profiles with various property deterioration rates

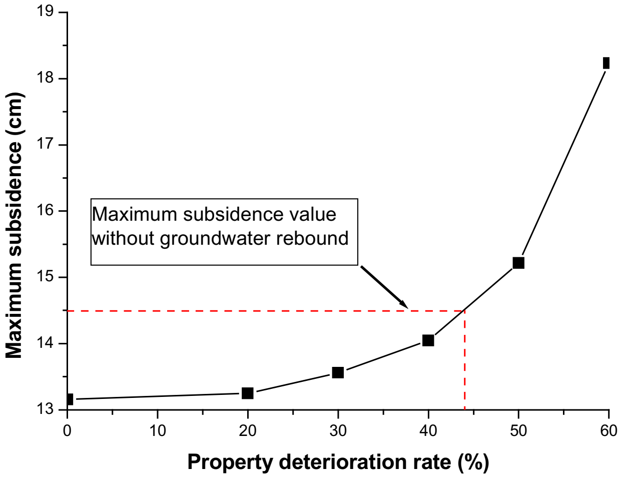

Figure 9. Variation of the maximum subsidence with the property deterioration rate

Effect of water table depth

Along with the rock property deterioration caused by groundwater rebound, the water table depth is another influential factor, which is in fact a reflection of the pore water pressure. For the sake of simplification, this factor is investigated in this study without consideration of the rock property deterioration. Ground subsidence is recorded on the surface with various rebounded water table levels, as illustrated in Figure 10. It implies that the ground subsidence increases with the rebounded groundwater level. An approximately linear relationship is shown in Figure 11 between the maximum subsidence and rebounded groundwater table depth.

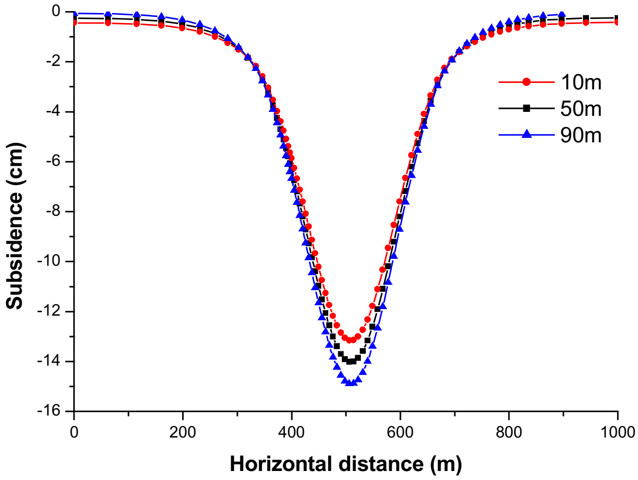

Figure 10. Subsidence profiles with representative different water table depth

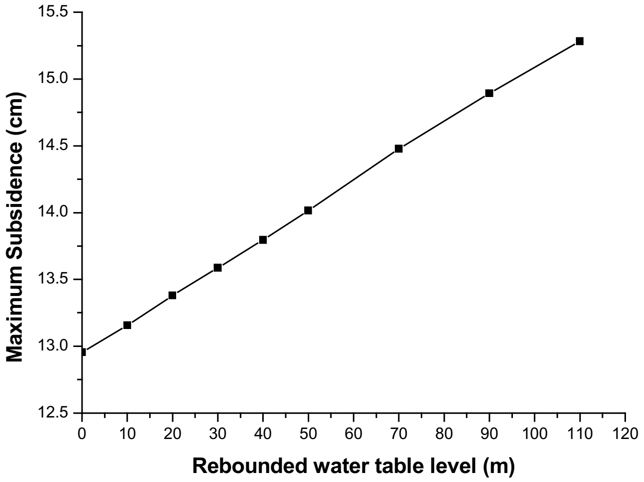

Figure 11. Development of the maximum subsidence with rebounded water table level

CONCLUDING REMARKS

Detrimental effects of water are confirmed through laboratory testing on both intact and fractured rocks. Continuous relationships for the mechanical parameters of rocks are obtained with different degrees of saturation. Apart from the water content, the specific reduction magnitude also strongly depends upon the rock type, i.e. the amount of minerals that are sensitive to water.

Testing results were introduced into a numerical simulation to examine the reactivation of ground subsidence under the condition of groundwater rebound. It was observed that the ground subsidence increases not only with the property deterioration rate but also with the rebounded groundwater table level.

Acknowledgements: Special thanks are given to Mr. Mark Dale for his laboratory help, and Dr. David Whittles for the supply of the modelling input data. We also acknowledge financial support from ECSC (grant No. 7220-PR-136).

Corresponding author: Mr Zhendong Li, Nottingham Centre for Geomechanics, School of Civil Engineering, Nottingham University, Nottingham, Nottinghamshire, NG7 2RD, United Kingdom. Tel: +44-115-8466055. Email: enxzl2@nottingham.ac.uk.

REFERENCES

BALLIVY, G., LADANYI, B., & GILL, D.E. 1976. Effect of water saturation history on the strength of low-porosity rocks. *Soil Specimen Preparation for Laboratory Testing, ASTM STP*, 599, 4-20

BARLETT, F.M. & MACGREGOR, J.M. 1993. Effect of moisture condition on concrete core strengths. *ACI Material Journal*, **9**(3), 227-236

BAUD, P., ZHU, W. & WONG, T. 2000. Failure mode and weakening effect of water on sandstone. *J. Geophys. Res.*, **105**(B7), 16371-16389

BOBET, A. 2003. Effect of pore water pressure on tunnel support during static and seismic loading. *Tunnelling and Underground Space Technology*, **18**(4), 377-393

BROCH, E. 1979. Changes in rock strength by water. *Proc. 4th Int. Soc. Rock Mech.*, Montreux, **1**, 71-75

COLBACK, P.S. & WIID, B.S. 1965. The influence of moisture content on the compressive strength of rocks. *Proc. 3rd Canadian Symposium on Rock Mech.*, Toronto, 65-83

DUBE, A.K. & SINGH, B. 1972. Effect of humidity on tensile strength of sandstone. *J. Mines, metals and fuels*, **20**(1), 8-10

LI, Z. & REDDISH, D.J. 2004. The effect of groundwater recharge on broken rocks. *Int. J. Rock Mech. Min. Sci.*, **41**(3), 1B14

LI, Z., SHENG, Y. & REDDISH, D.J. 2005. Rock strength reduction and its potential environmental consequences as a result of groundwater rebound. *Proc. 9th Int. Mine Water Association Congress*, Oviedo, Spain. 513-519

MASUDA, K. 2001. Effects of water on rock strength in a brittle regime. *J. Structural Geology*, **23**(11), 1653-1657

PARATE, N.S. 1973. Influence of water on the strength of limestone. *Transaction of Society of Mining Engineers, AIME*. **254**, 127-131

POON, C.S., SHUI, Z.H., LAM, L., FOK, H. & KOU, S.C. 2004. Influence if moisture states of natural and recycled aggregates on the slump and compressive strength of concrete. *Cement and Concrete Research*, **34**, 31-36

WEN, B.P. & AYDIN, A. 2005. Mechanism of a rainfall-induced slide-debris flow: constraints from microstructure of its slip zone. *Engineering Geology*, **78**(1-2), 69-88

WHITTLES, D.N., REDDISH, D.J., & REN, T.X. 2001. Finite Difference Continuum Modelling of the Progressive Redistribution of Stresses, Displacements and Shear Plant Development around an Active Coal Mine Longwall Panel. *2nd International FLAC Symposium on Numerical Modelling Methods in Geomechanics*, Lyon, France.

VAN EECKHOUT, E.M. 1976. The mechanism of strength reduction due to moisture in coal mine shales. *Int. J. Rock Mech. Min. Sci. and Geomech. Abstr.*, **13**, 61-67

ZHU, W. & WONG, T. F. 1997. Shear-enhanced compaction in sandstone under nominally dry and water-saturated conditions. *Int. J. Rock Mech. & Min. Sci.* **34**(3-4), paper No. 364