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Effect of Humidity on Tensile Strength of Rocks in Selected Underground Coal Mines in Malawi

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ABSTRACT: One of the major challenges facing coal mines in Malawi is occurrence of hanging roof falls during the rainy season. Following this, the effect of humidity on the tensile strength of coal bearing rocks, arkose sandstone and fine-grained sandstone from Mchenga underground coal mine, was studied aiming to clarify the mechanism of roof fall in the underground mines and proposing countermeasures against the roof falls. Rock samples from the mine were treated in varying humidity levels. Some specimens were oven dried at 80°C and a desiccant was used to attain low humidity. Moderate humidity was obtained using magnesium-nitrate-hexahydrate, high humidity was achieved by pure water and some specimens were vacuum saturated. Subsequently, Brazilian test was carried out to obtain indirect tensile strength along the sedimentary plane. For comparison, Neogene tuffaceous Kimachi sandstone from Japan was also tested, following the same conditions. It was confirmed that indirect tensile strength of the rocks decreased with increase in humidity. The sensitivity of indirect tensile strength to humidity for arkose and fine grained sandstones was 12% or 29% larger than that for Kimachi sandstone. The stronger sensitivity for Mchenga roof rocks would be because the rocks contain illite, whose strength is very sensitive to water, while Kimachi sandstone contains only less sensitive zeolite for clay minerals.

1. INTRODUCTION

Historically, mining has been imperative to human and social development, and the industry will continue to make investments that meet the increasing needs of society (ICMM, 2012). Moving from being an agro-based economy, Malawi has ventured into mining as its alternative economic driver towards the future. Coal offers an alternative for electrical energy in the country due to insufficient power generation from hydroelectric power stations along the Shire River in Malawi. This has put coal as the strategic commodity for the mining sector, focusing on the establishment of coal-fired power plants in the country. There are seven coalfields spread across the country, with four coalfields of bituminous coal in the Northern Region. Currently, four underground coal mining operations are running with additional two open pit mines in these coalfields.

However, coal mining operations in Malawi are ranked small scale, considering the production amounts, level of mechanisation and size of the mines. The combined coal production is at 11,000 tons per month (Malawi Annual Economic Report, 2015). One of the major challenges facing these mines is occurrence of hanging roof falls during the rainy season. Potential roof falls in underground coal mines are one of the most significant hazards for miners. Roof falls can threaten miners, damage equipment, disrupt ventilation mechanisms and block installed emergency escape routes. The hazardous nature of roof fall can be illustrated from the statistics of mine accidents recorded in November 1, 2012, where death of two miners and injury of other two was reported at Kaziwiziwi Coal Mine. On the other hand, the US mine accident statistics indicate that during the ten year period, from 1996 to 2005, 7738 miners were injured from roof falls in underground coal, metal, non- metal and stone mines (Mine Safety & Health Administration (MSHA), 2005). Coal mines showed the highest rate, that is 1.75 roof fall injuries per 200,000 h underground work. Fatal injury trends from 1996 to 2005 were equally troubling. Coal mining has the highest number that is 82 out of 100 roof fall fatalities (0.021 fatalities per 100,000 miners). The Mine Safety and Health Administration (MSHA) of the US in 2006 reported seven fatalities, 278 non-fatal-days-lost (NFDL) injuries, and 152 no-days-lost (NDL) injuries because of roof falls in US underground coal mines (MSHA, 2006).

Chugh and Missavage, 1981, studied the effect of moisture in strata control in coal mines. They summarised that moisture gain and moisture loss in mine rock is related to seasonal changes in absolute humidity of mine air. In summer, absolute humidity of surface air is high and air temperature above those of rocks underground. When the hot surface air, drawn into the mine for ventilation, is cooled by rocks the air loses its moisture on rocks (sweating). In winter, surface air temperature and humidity are lower than rocks underground and air travelling through the mine gains temperature and humidity. This causes mine rocks to lose moisture and thus has the drying effect.

In another research by Fujii et al., 2011, steel-arch removal test was carried out on a roadway at Kushiro Coal Mine, Japan in May, 2006. Several large rock falls, as large as 2 m occurred and it was estimated that the rock mass was weakened by the humid-air inflow and the large-scale roof falls were induced. Initially, there was no large roof fall, even after 15 steel arches were removed. The unsupported span reached 16 m without large roof falls, except for rather small falls of loosened rocks that were as large as tens of centimeters. A few months later, in August and September, humid summer air flowed into the site and dripping water was seen on the rock surface.

This paper seeks to investigate the effect of humidity on the tensile strength of coal bearing rocks in underground coal mines in Malawi. To achieve this objective, rock samples from Mchenga underground coal mine, Malawi were studied to clarify the mechanism of the roof falls during the rainy season and to propose countermeasures against the same.

2. SITE AND INSTRUMENTATION

2.1. Mining sites

Two underground mines; Mchenga coal mine (S10°42'55", E34°9'14") and Kaziwiziwi mine (S10°42'29", E34°9'50"), are located in the target area hosting the Livingstonia coalfield. The mines use room and pillar mining method. The pillar dimensions in Mchenga mine are 10 m x 10 m while in Kaziwiziwi mine measure 12 m x 12 m. The coal seam thickness ranges from 0.7 m to 3 m in Mchenga coal mine and 1.7 m to 2.3 m in Kaziwiziwi coal mine.

Stratigraphically, the area is composed of Karroo System strata preserved in a number of N-S trending basins and down-faulted troughs that display faulted relationship to the underlying Basement complex gneisses. The basal beds of the succession consist of conglomerates and sandstones referred to the Dwyka and lower Ecca series. These are overlain by a sequence of carbonaceous shales and coal seams (Cooper and Habgood, 1959). The roof stratum mainly consists of sandstone and shale (Figure 1).

Eight coin-type data loggers (Figure 2a) were installed in mine adits of Mchenga Coal Mine at varying levels with an average depth of 130 m from the ground surface. The points had varying moisture presence to record humidity in and close to the working face. The instruments were fixed in matt packs and accessible points in rocks with a clear exposure to the surrounding atmosphere in the adits (Figure 3). The humidity levels measured in the mine adits were used as control during sample preparation in the laboratory.

In addition, three mechanical hygrometers (Figure 2b) were given to mining engineers at both Mchenga Coal Mine and Kaziwiziwi Mine to measure and record humidity and temperature once every week for a period of one year.

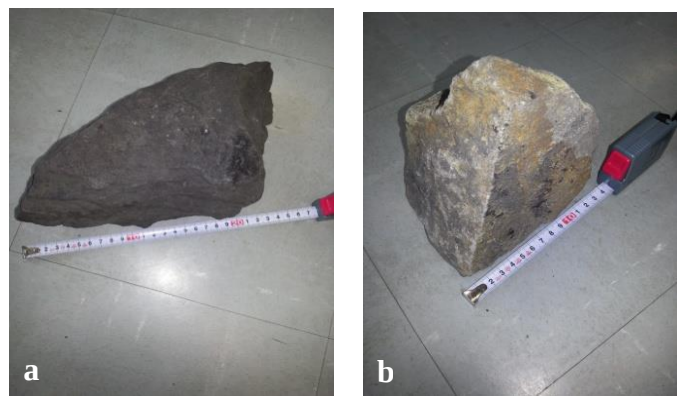


Fig. 1. Rock samples from Mchenga Coal Mine (a) Shale (b) Sandstone

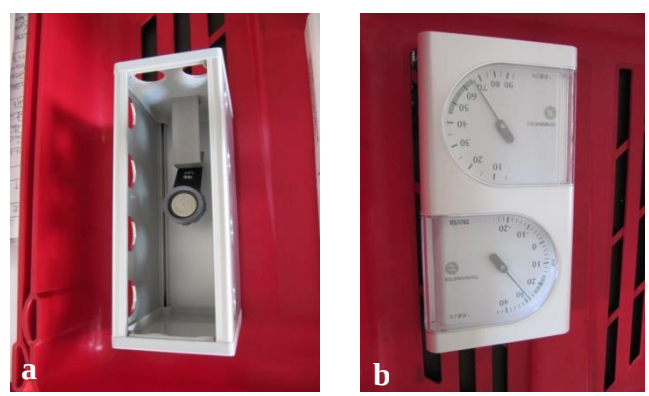


Fig. 2. (a) Coin-type data logger (b) Mechanical hygrometer

Fig. 3. (a) Lower seam adit in Mchenga Coal Mine (b) Data logger fixed in position close to the coal bearing rocks.

2.2. Weather conditions in the Northern Region

Malawi has two distinct seasons. The period from November to April is the warm-wet season during which 95% of the annual precipitation takes place. A cool-dry winter is evident from May to August, with a short hot-dry patch lasting from September to October. Temperatures vary from 25°C to 37°C while humidity ranges from 50% to 87% from the drier months to wetter months respectively. End of October marks the beginning of the rainfall season in the country, with the main rains arriving from mid-November in the southern region and progressively spreading northwards. During this period, the main rain bearing systems that influence weather over Malawi include the Inter-Tropical Convergence Zone (ITCZ), Congo air mass, Easterly Waves and Tropical Cyclones (Malawi Meteorological Services Bulletin, March 2015).

During sampling period of January to March 2015, the air over Malawi was fairly moist and unstable. The daily relative humidity values had ranged from 62% to 85% at Mzuzu in the Northern region (Weather and Agro-meteorological Bulletin-Malawi, 2015). This was triggered by moderate to heavy rainfall ranging from 88 mm/d to 110 mm/d, confined to very few areas in the north and south areas of Malawi. This led to flooding in some areas in the Northern region. In addition to that, recorded air temperatures hovered across the region with a minimum range of 20°C to 25°C and a maximum range of 30°C to 35°C. (Figure 4)

However, following the monitoring and measurements of humidity by the mechanical hygrometers close to the working face, it was found that recorded humidity inside the mine was higher than the regional average humidity levels as shown in Figure 5 below.

The same trend was observed with measurements for temperature. Recorded temperature inside the mine remained higher than the regional average temperature as illustrated in Figure 6 below.

3. ROCK SAMPLES

Medium to coarse-grained arkose sandstone (arkose sandstone) and ultra-fine to fine-grained sandstone (fine-grained sandstone) from Mchenga coal mine were used for the experiments, together with Neogene-tuffaceous Kimachi sandstone from Japan for comparison.

From the analysis of the thin-sections (Figure 7), both rock samples from the coal mine showed no cementing minerals. The arkose sandstone showed a rich content of carbonate minerals and biotite. The matrix minerals included illite, cryptocrystalline siliceous minerals and carbonate minerals.

On the other hand, the fine-grained sandstone showed an argillaceous part lamination, a conspicuous black thick band. The matrix minerals included illite, goethite, coaly substances and opac minerals.

Scanned images of the arkose sandstone showed no obvious open pore spaces (Figure 8). The surface exhibited a uniform colour and texture. As for the fine-grained sandstone, there were patches of different colours which could indicate different textures.

Kimachi sandstone which was sampled at the Shimane prefecture, Japan was used for the experiments. It is a relatively well-sorted medium-hard clastic rock with a typical grain size in the range 0.4–1.0 mm. It consists mostly of rock fragments of andesite and crystal fragments of plagioclase, pyroxene, hornblende, biotite, and quartz, as well as calcium carbonate, iron oxides, and matrix zeolite (Dhakal et al., 2012).

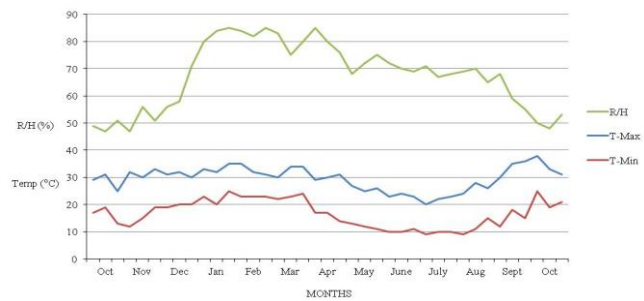


Fig. 4. Relative Humidity and Temperature in the Northern Region, 2014-2015 season (Weather and Agro-meteorological Bulletin-Malawi, March 2015)

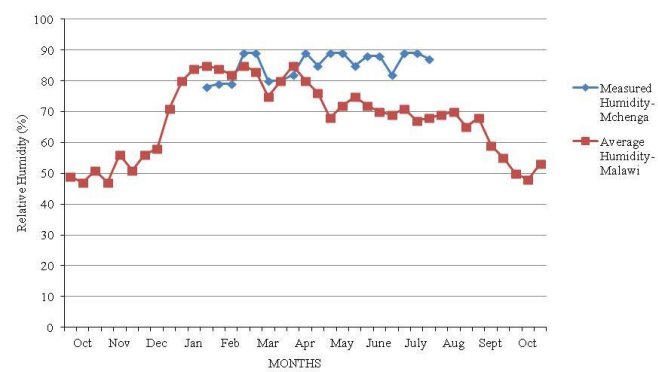


Fig. 5. Humidity variation: inside mine and regional readings

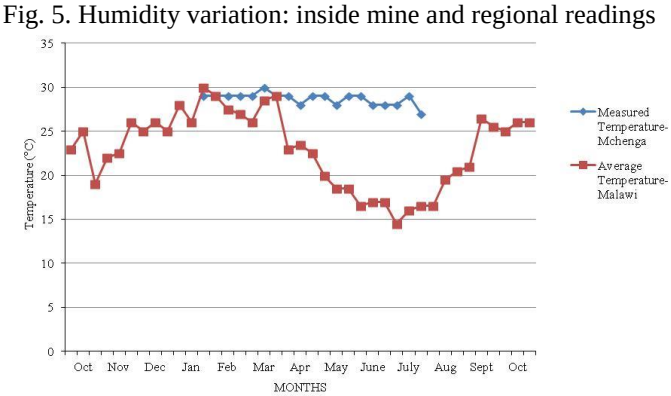
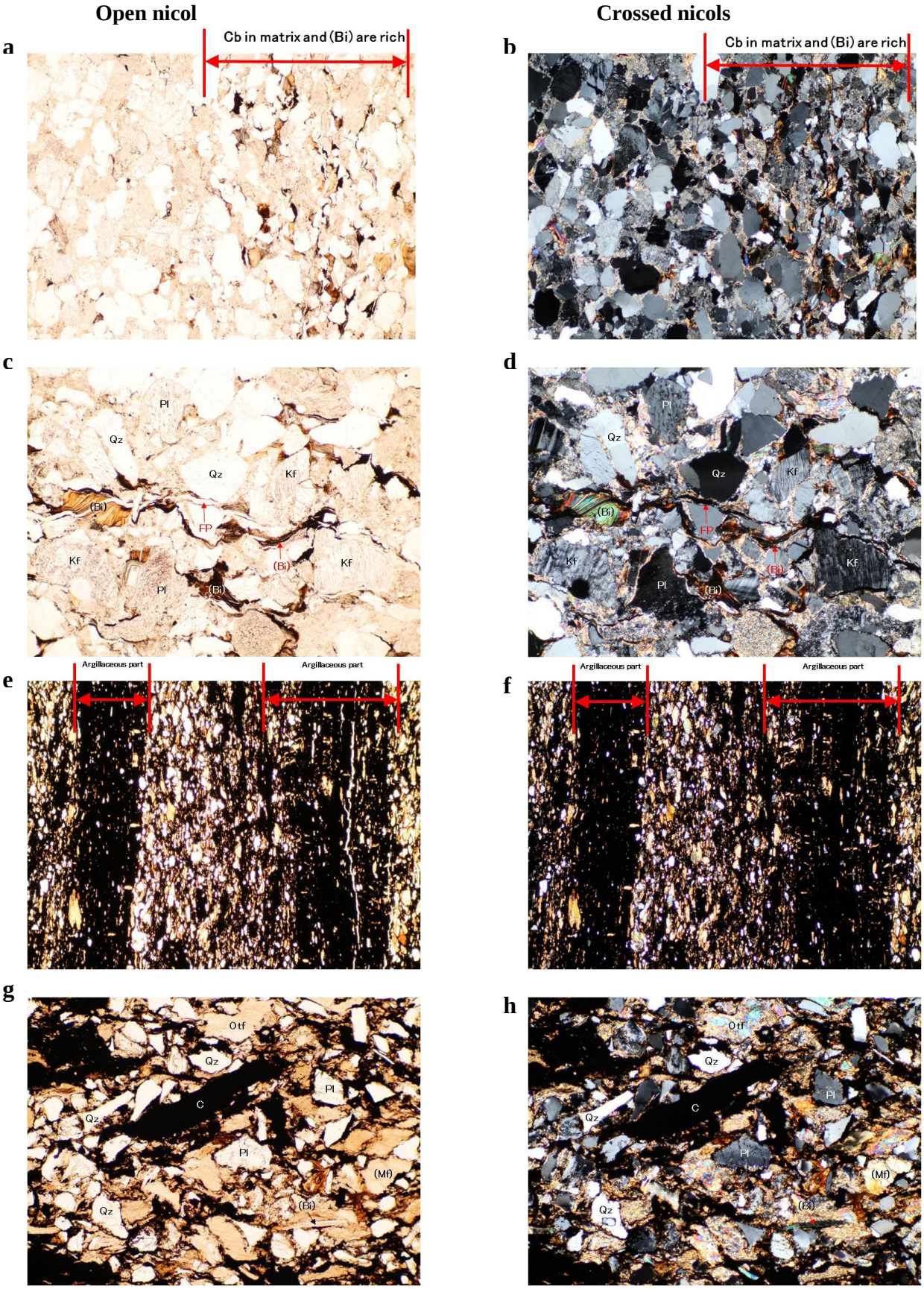


Fig. 6.Temperature variations: inside mine and regional readings



Scale: 0.5mm

Fig. 7. Microscope images of arkose sandstone (a, b, c, d) and fine-grained sandstone (e, f, g, h).
[Qz: quartz, Bi: biotite, Kf: Orthoclase, Pl: Plageoclase, Mf: mafic minerals, Otf: microfossils, C: coaly substance, Cb: carbonate mineral, FP: fracture, Illite, Silliceous minerals (cryptocrystalline)]

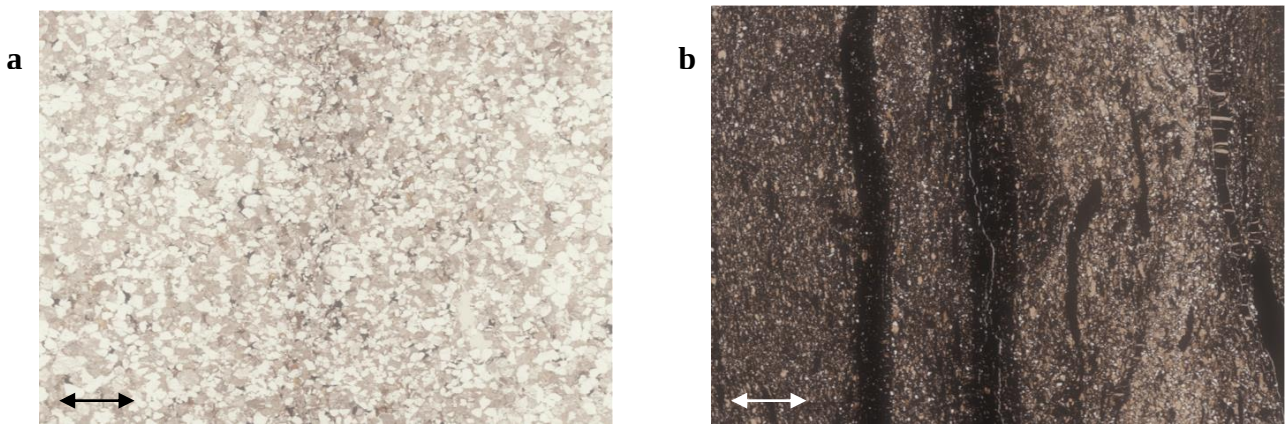


Fig. 8. Scanned images of specimens (a) arkose sandstone (b) fine-grained sandstone. The arrow length is 2mm.

4. METHOD

Three sets of 25 cylindrical rock specimens (i.e. 75 specimens in total); measuring 30 mm in both length and diameter, were cut from blocks of the three types of rocks. The specimen ends were polished to a parallelism of 0.01°.

4.1. Experimental setup

Some specimens were oven dried at 80°C. Air-tight containers were used to maintain the applied humidity levels. To attain low humidity (2%), 400 ml of dry-up compact desiccant were used. Moderate humidity (58%) was obtained using saturated magnesium-nitrate-hexahydrate [Mg $(NO_3)_2.6H_2O$] solution, while high humidity (98%) was achieved by pure water poured in the container. Finally, some specimens were vacuum saturated using pure water as shown in Figure 9 below.

These varied humidity conditions were maintained in isothermal condition of 22°C in the laboratory. In addition to that, weight of the specimens was measured and recorded using a 0.001 g accuracy balance on a daily basis. The specimens were treated in five varying humidity levels for a period of 30 days.

4.2. Porosity

The porosity of 5 dry specimens was calculated prior to mechanical testing. Specimen dimensions were measured i.e. length, width and diameter.

The specimens were oven dried for two days and the weight measured and recorded as dry weight of specimen. This was followed by vacuum saturation of the specimens for two days and the weight was measured and recorded as saturated weight of specimen.

The effective porosity (n) of the solid-cylindrical sandstone specimens was obtained by the expression:

$$n = \left[\frac{W_s - W_d}{\rho_w \times V} \right] \times 100\% \qquad (1)$$

Here measured values of weight of saturated specimen (W_s, kg), weight of dry specimen (W_d, kg), water density (ρ_w, 1000 kg/m^3) and calculated volume of the specimen (V, m^3) were used.

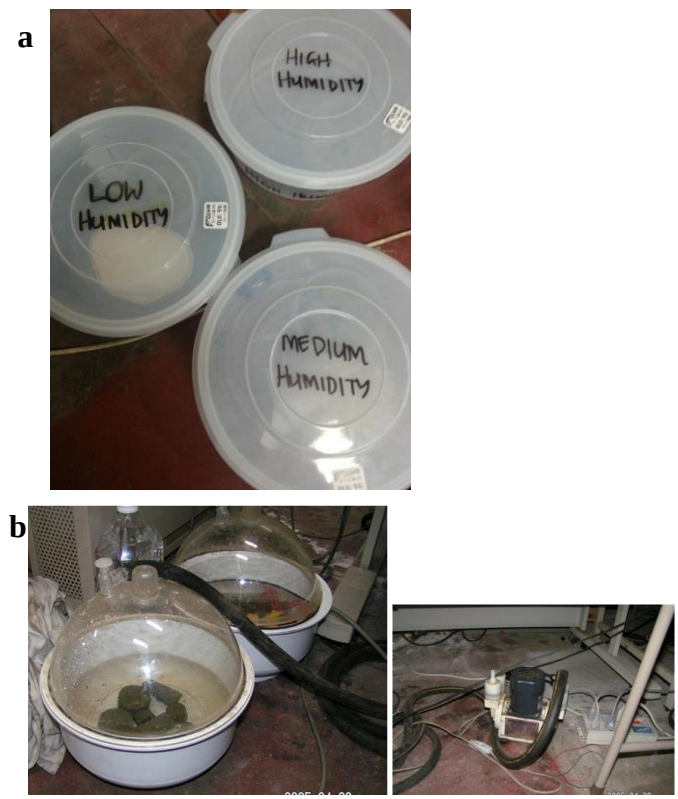


Fig. 9. (a) Air-tight containers with specimens in the laboratory, (b) Vacuum saturation of specimens

4.3. Brazilian disk test

After the treatment period of 30 days, Brazilian test, using an Instron loading frame, was carried out on the specimens (Figure 10) to calculate the indirect tensile strength using the following expression:

$$T_0 = \frac{2F_{max}}{\pi \cdot d \cdot l} \qquad (2)$$

where F_{max} (N) is the maximum compressive load, (d, m) the diameter of specimen and (l, m) length of specimen.

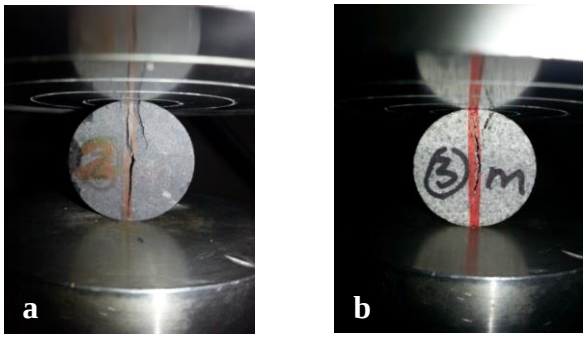


Fig. 10. Rock specimens on the loading frame under Brazilian test (a) Mchenga fine-grained sandstone (b) Mchenga arkose sandstone.

5. RESULTS

5.1. Density change

From the measurement of mass of the rock specimens (Figure 11), it was evident that bulk density of specimens increased with increase in relative humidity except for the moderate humidity of the arkose sandstone. It was noted that arkose sandstone had higher values of density as compared to other sandstones.

5.2. Porosity

The calculated porosity for arkose sandstone was 6.9%, while for fine-grained sandstone it was found to be 8%. The porosity of Kimachi sandstone was found to be ranging from 18.54% to 22% as discussed by Dassanayake, 2015. In this study, 18.54% was used.

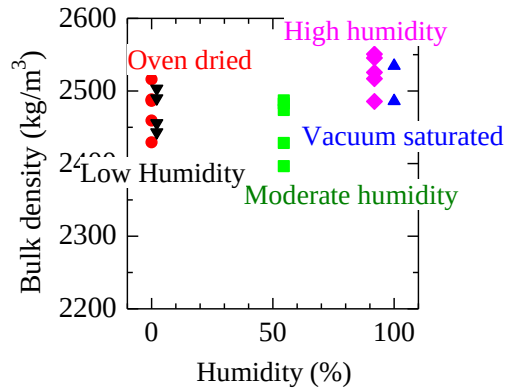
5.3. Indirect tensile strength

The oven dried specimens showed a greater compressive load which resulted in greater values of indirect tensile strength (Figure 12). In the same manner, specimens treated in low humidity (2%) had higher indirect tensile strength than those treated in moderate humidity (58%), high humidity (96%) and vacuum saturated specimens. It is shown that Kimachi sandstone registered higher indirect tensile strength followed by fine-grained sandstone and finally arkose sandstone.

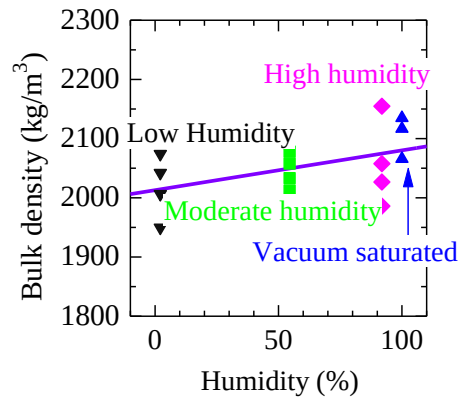
The following equation is proposed to represent the relationship between humidity, H (–) and indirect tensile strength, T_0 (MPa).

$$T_0 = A(1-B)H \tag{3}$$

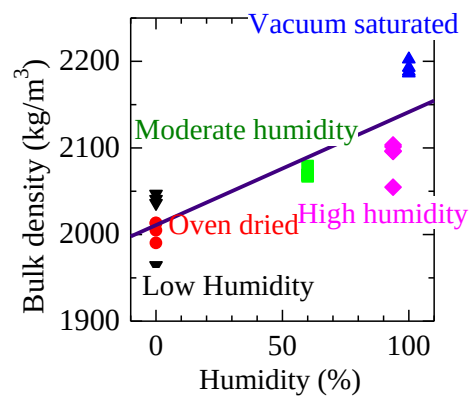
where A (MPa) is indirect tensile strength at zero humidity and B (–) is the sensitivity of indirect tensile strength to humidity from zero (no strength decrease) to unity (strength becomes zero at H is one, namely, 100%).



(a) Mchenga arkose sandstone

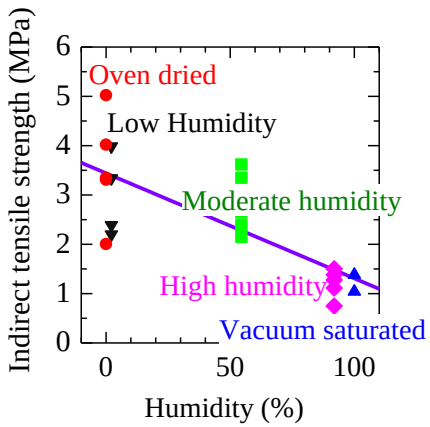


(b) Mchenga fine-grained sandstone

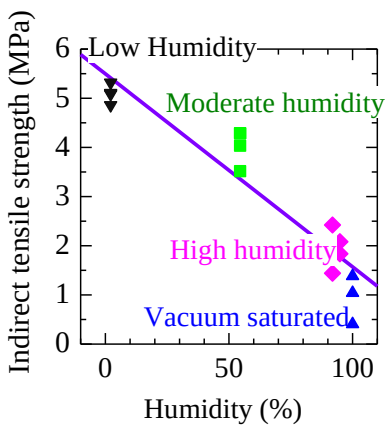


(c) Kimachi sandstone

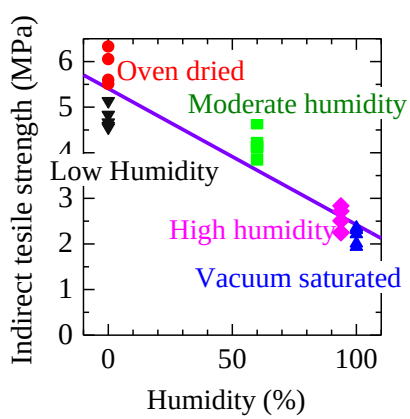
Fig. 11. Bulk density variation against humidity for Mchenga mine rocks (arkose sandstone and fine-grained sandstone) and Kimachi sandstone.



(a) Mchenga arkose sandstone



(b) Mchenga fine-grained sandstone



(c) Kimachi sandstone

Fig. 12. Indirect tensile strength variation against humidity for Mchenga mine rocks (arkose sandstone and fine-grained sandstone) and Kimachi sandstone.

It was found that the sensitivity of indirect tensile strength to humidity for Mchenga arkose sandstone was 0.62, for Mchenga fine-grained sandstone was 0.71 and that for Kimachi sandstone was 0.55 (Table 1).

Table 1. Constants in Eq. (3) for three types of rocks.

Rock	Constants	
	A (MPa)	*B* (–)
Mchenga arkose sandstone	3.44	0.62
Mchenga fine-grained sandstone	5.50	0.71
Kimachi sandstone	5.42	0.55

6. DISCUSSION

In the introduction, it was hypothesized that roof falls are frequent during the rainy season because there is a build-up of high humidity in the northern region of the Malawi - where underground coal mines are located. Pellet et al., 2013 discussed that the stability of rock masses is largely affected by the humidity conditions which are, for example, responsible for landslides that occur after heavy rains. This is particularly true for stratified rock masses with clay-infilled discontinuities, because most of clay minerals are highly sensitive to water. The results got from the experiment are in tandem with the published data in other studies which show a decrease in mechanical properties of rocks with an increase in relative humidity, moisture content and clay mineral content (e.g. Chugh and Missavage, 1981; Nara et al., 2011; Li et al., 2012).

The decrease in indirect tensile strength with increase in humidity in Mchenga arkose sandstone and fine-grained sandstone indicates a high sensitivity of the rocks with humidity increase. The sensitivity of indirect tensile strength to humidity for Mchenga fine-grained sandstone (0.714) was 29% greater than that for Kimachi sandstone (0.552). On the same note, the sensitivity for Mchenga arkose sandstone (0.620) was 12% greater than that for Kimachi sandstone, shown in Figure 13.

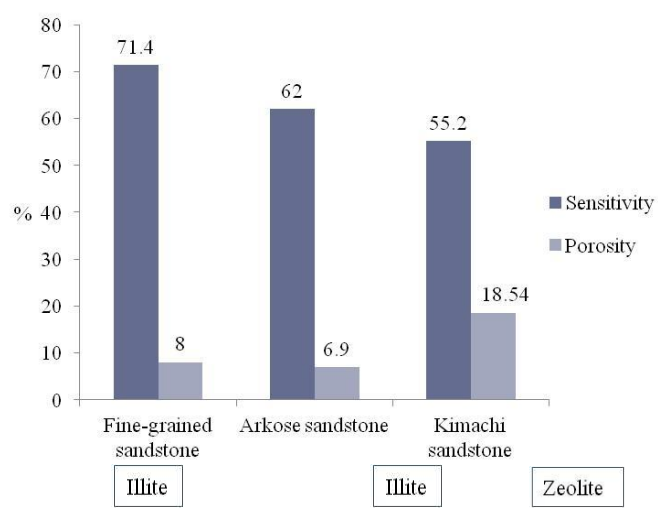


Fig. 13. Sensitivity of three types of rocks to humidity levels

The greater sensitivity to humidity can be attributed to the content of illite, which is more sensitive to humidity (moisture), as the clay mineral in Mchenga rocks while Kimachi sandstone contains zeolite which is less sensitive to humidity. Nara et al., 2011 reported that the influence of the relative humidity on the crack velocity in rock was more significant when the rock included larger amount of clay minerals such as smectite and illite. Additionally, Nepper Christensen, 1965 suggested that many rock types containing illite are sensitive to variations in the relative humidity of the surrounding atmosphere since they shrink or swell as they give off or absorb moisture, especially in shales, which make part of the roof rocks in the coal mine.

A number of researchers have revealed through experimental studies that the reduction of rock strength depends not only on moisture content but also other internal and external factors. The internal factors include porosity, matrix mineral (fabric) and density. Among others, subcritical crack growth (SCG) is a cause of time-dependent fracturing in rocks. Since indirect tensile strength of rocks is related to fracture toughness, the water vapour pressure is also known to exert an influence. More recently, Nara et al., 2011 reported that the crack velocity increased with increasing the relative humidity in Shirahama sandstone, Kushiro sandstone and Berea sandstone, at constant temperature.

This effect can be the cause of the roof falls as big as 5 m recorded in the mine as progressive failure of roof layers may cause slab type failures or plate type failures due to swelling perpendicular to bedding planes.

At the current stage, the following methods can be suggested for implementation to prevent the hanging roof fall accidents.

(i) Control of humidity changes

As stated earlier, humidity variations with change in seasons in intake airways in the vicinity of a mine adit or shaft are quite large and most roof rock instability conditions due to moisture effects are initiated in these areas. Controlling the humidity changes would involve conditioning the air being circulated in the mine to reflect temperature and humidity equilibrium conditions in the mine. For Mchenga and Kaziwiziwi coal mines, there is need to install smaller fan units without ducting to improve circulation and mixing of still air and incoming humid air in the mine. This is being applied in South African underground coal mines as reported by Meyer, 1993. To this effect, relative equal distribution of humidity in the mine adits can be achieved consequently reducing weakening effects of roof rocks.

(ii) Monitoring and alert systems

With the technological advances at hand, installing humidity recording devices and connecting to alarm systems could be a way to avert impacts of roof falls.

In deeper adits and shafts, mechanical hygrometers with visible markings could be installed. These instruments could be located in critical areas where coal extraction is in progress. Where humidity readings reach critical levels, miners would be alerted by ringing bells to take precautionary measures. Given the sensitivity of the Mchenga fine-grained sandstones, high humid conditions should be avoided at all times as they would be a cause of hanging roof falls.

Above all, affordability and effectiveness of these methods should be considered based on the production scale of the coal mines in Malawi.

Going forward with the research, the installed data loggers will be retrieved in March 2017 as well as roof fall data from accident reports. An attempt is underway to simulate on roof weakening due to vapour diffusion from intake air by 2D FEM.

7. CONCLUSION

The sensitivity of indirect tensile strength with humidity for Mchenga coal mine rocks, arkose and fine-grained sandstone, and Kimachi sandstone were determined. It was found that rocks from Mchenga mine are more sensitive (12% or 29%) than Kimachi sandstone. This was explained by the higher sensitivity of illite than zeolite as a clay mineral. This research suggests that roof falls can be a result of possible weakening of the sedimentary planes and/or joints due to humid conditions during rainy season.

ACKNOWLEDGEMENTS

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