Factors governing the strength and elastic properties of a physical model material used for strata mechanics investigations

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Synopsis

Physical modelling is one of the research tools in the understanding of the failure mechanisms and the deformations likely to be experienced by the strata during mining operations. Success of the physical models to predict the strata behaviour depends on satisfaction of the scaling requirements in modelling material used. This paper gives results from a laboratory work carried out into the factors influencing the strength and elastic properties of a physical model material to satisfy the scaling requirements determined from application of dimensional analysis to the pertinent variables affecting the deformation and failure of the underground structures. It was found that the conditions for preparing the material over its composition had a great influence on the final properties. The effect of different water quantities, sand size and mixing time upon the properties of modelling material was studied and water requirement for different proportions of sand/plaster to prepare the material was optimized. Various sand/plaster ratios of compositions were cured at three different levels of oven temperatures. Curing at low temperature produced material within the average modulus ratios ranging from 290 to 432, which are common to most rock types according to Deere's rock classification, whilst curing at high temperature produced material within the low modulus ratios ranging from 64 to 140 depending on its composition. A combination of low and high temperature curing resulted with an increase in modulus ratio compared to high temperature curing. Curing the material at low temperature compared to other curing temperatures provided a satisfactory range of strength ratio. It has been shown that the relative amount of filler to plaster in the mix controls the frictional properties of the material and results with an increase in strength and modulus ratio of the material provided that suggested preparation and curing conditions were applied. Model material developed by curing at low temperature simulated modulus ranging from 241 to 343 and strength ratios ranging from 11.6 to 14.8 of a coal mine rocks, satisfactorily.

Introduction

Physical modelling of underground structures provides an important function in the understanding of the failure mechanisms in operation and the deformations likely to be experienced. A physical model is a representation of a section of disturbed ground (prototype) reproduced in the laboratory. This requires appropriate scaling of the body in terms of dimensions and strength. Relations between the parameters affecting behaviour of the prototype are established by using dimensional analysis. Dimensionless products obtained from dimensional analysis are related to the model by Buckingham's Pi theorem (Obert and Duvall, 1967). The scaling requirements derived through dimensional analysis and Buckingham's Pi theorem are introduced in this paper to investigate the ability of a model material to simulate coal measure rocks with improved and standardized preparation conditions for the model material.

Numerous materials have been used to satisfy the scaling conditions for models. Plaster has been the commonly used binder for rock mechanics and geomechanics modelling studies since it is easy to cast, easily obtainable, sets relatively fast, unlike cement, the strength of the material does not change for long curing periods (Hobbs 1966, Rosenblad 1968, Barton 1970, Whittaker and Hodgkinson 1971, Bandis 1980, Moon and Hucka 1985). In the past, improvement of the plaster properties to scale the rock properties was achieved to some extent by adding different types of granular material which was commonly sand (Hobbs 1966, Rosenblad, 1968) or sand accompanied by other fillers such as lead (Barton, 1970), barytes and alumina (Bandis, 1980). Hobbs (1966) developed model materials consisting of sand and fine casting plaster mixed in various proportions of sand to plaster ranging from 1.5:1 to 5:1 with a set of 1:3 ratio of water to solid for all mixes and then cured the material at 90°C oven temperature for one week. These conditions produced materials with compressive strengths varied from 0.1 to 1.61 MPa, with modulus ratios (elasticity modulus/compressive strength) varied from

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132 to 184, and with strength ratios (compressive strength/tensile strength) varied from 1.5 to 2.9. Rosenblad (1968) employed a 7.6:1 ratio of sand to hydrocal B-11 gypsum plaster with a water to solid ratio of 1:6 in the preparation of a material and then cured the material at 47°C for more than 14 days. The compressive strength, modulus and strength ratios of the material produced were 4.2 MPa, 442 and 7, respectively. Barton (1970) produced materials having low compressive strength values ranging from 0.071 to 0.220 MPa by adding 1:4.3 ratio of water:filler to the dry (sand+lead): plaster mixes in the range from 14.5:1 to 24:1. Curing these mixes at 105-110°C for about 5 days resulted with modulus ratios ranging from 350 to 450 and with strength ratios ranging from 8 to 10. Whittaker and Hodgkinson (1971) preferred sawdust and granulated coal to improve the plaster properties. Two mixes consisting of sawdust:plaster ratio of 0.2:1 and of (sawdust+coal):plaster ratio of 0.7:1 were prepared by adding 1:1.2 and 1:1 ratios of water:solid to the dry mixes, respectively. Both materials were cured at 90°C oven temperature for one month. Plaster, sawdust and water mix had compressive strength, modulus and strength ratio values of 0.850 MPa, 185 and 4.25 whilst plaster, sawdust, coal and water mix had compressive strength, modulus and strength ratio values of 0.830 MPa, 132 and 4.5, respectively. Bandis (1980) used plaster and sand accompanied by barytes as 50% of sand in weight and alumina as 33% of barytes in weight. Filler:plaster ratios were changed in the range from 7:1 to 15:1 whilst water:filler ratio was kept constant as 1:4 in all mixes. Specimens cured at 80°C for 1–2 days resulted with compressive strength values in the range from 0.24 to 1.15 Mpa, with modulus ratios in the range from 110 to 232, and with strength ratios in the range from 4.2 to 7 whilst specimens cured at 50–55°C for 2–4 days resulted with compressive strengths in the range from 0.7 to 3.4 MPa, with modulus ratios in the range from 352 to 445 and with strength ratios in the range from 5.7 to 6.6. Moon and Hucka (1985) used plaster as cementing agent and glass beads having an average size of 0.32 mm as a granular material. The weight ratios of glass beads to plaster were changed between 0.25:1 and 4:1. An average water:solid ratio of 1:1.4 was employed in the preparation of the mixes. Curing the material at 200°C for 1 day led to production of material with compressive strength values between 1.1 and 1.8 MPa. The modulus ratios were between 485 and 1366 whilst strength ratios were between 4.2 and 5. When the final properties of developed model materials relative to their filler:plaster ratios are compared, it can be seen that not only addition of other fillers together with sand but also the preparation and curing conditions used resulted in the production of various material properties. In this respect, the ability of the production process to control the final material characteristics has been investigated. The average size of sand grains, the amount of water added to the mix, mixing duration relative to the amount of water, curing temperature and curing time were considered to be the major factors influencing the material properties over the type of filler added.

Once a standard preparation condition was defined, the compressive strength of the material was controlled by changes to the sand to plaster ratio in order to scale the strength of specific rock types. Comparisons with rock properties were made by modulus ratio and strength ratio of the material. Most of the rocks possessing an interlocking fabric and little or no anisotropy normally fall in average modulus ratio category which is bounded by an upper value of 500 and by a lower value of 200 according to Deere's (1968) classification. The modulus ratio changes from 300 to 400 for most British coal measures rocks. A strength ratio of between 10 and 20 is common for most rock types, although measurements have been observed outside of these ranges. The failure strains in the range of between 0.15 and 0.4% may be considered broadly representative of the required brittle behaviour for unconfined compression tests (Barton, 1970). Throughout this investigation, sand/plaster ratios of between 2.25 and 5.50 to 1 have been employed to investigate the effects of various factors into the strength and elastic properties of the model material and specifically to simulate the properties of rocks for Bilsthorpe Colliery of a British coal mine. The compressive strengths (σ_c), tensile strengths (σ_t) and elasticity modulus (E) of these rocks are given in Table I.

Scaling principles for the modelling material

The distance between two points in the model system (L_m) must bear a constant ratio to the corresponding points in the prototype (L_p). The geometric scale factor (l) is determined independently, and justified according to financial and laboratory constraints as follows:

$$\frac{L_M}{L_p} = l \qquad [1]$$

From the application of the dimensional analysis to the pertinent variables affecting the deformation of the underground structures, the following dimensionless product was obtained:

Table I

Properties of Bilsthorpe Coal Mine rocks and their scaled values

Properties	Sandstone	Model material	Mudstone	Model material	Siltstone	Model material
σ_c (MPa)	83	0.500	58	0.350	63	0.380
E (MPa)	21100	127	14000	84	21600	130
σ_t (MPa)	5.6	0.034	5	0.030	4.9	0.030
E / σ_c	254	254	241	241	343	343
σ_c / σ_t	14.8	14.8	11.6	11.6	12.9	12.9

$$\frac{s_p}{\gamma_p L_p} \qquad [2]$$

Where S_p is the strength of prototype, γ_p is the unit weight of prototype.

If this dimensionless product is referred to as the π_p term for the prototype and π_m for the model, π_p should be equal to π_m according to Buckingham's Pi theorem. The strength scale was found as follows:

$$\left(\frac{s_m}{s_p}\right) = \left(\frac{\gamma_m}{\gamma_p}\right)\left(\frac{L_m}{L_p}\right) \qquad [3]$$

Where subscripts *m* and *p* refer to model and prototype. Equation 3 can be expressed as

$$S = \gamma\, l \qquad [4]$$

Where *S* is the strength scale factor and γ is the unit weight scale factor. Unit weight scale factor changes from simulation of one stratum to another because of the changing density of the strata. Therefore, an average density of the structures modelled could be employed.

The Poisson's ratio and angle of internal friction and ultimate strain by considering maximum yield point are dimensionless parameters and should be equal in model and prototype. The following dimensionless ratios (strength and modulus ratios) should be as close to each other as possible

$$\frac{E_p}{\sigma_{cp}} = \frac{E_m}{\sigma_{cm}} \quad \text{and} \quad \frac{\sigma_{cp}}{\sigma_{tp}} = \frac{\sigma_{cm}}{\sigma_{tm}} \qquad [5]$$

Where σ_{cp} and σ_{cm} are compressive strengths of the prototype and model material, σ_{tp} and σ_{tm} are the tensile strengths of the prototype and model material and E_p and E_m are elasticity modulii of the prototype and model material.

To simulate the properties of rocks given in Table I, a geometric scale factor (l) of 1/100 was assigned depending on dimensions and boundary conditions of the physical models arranged (Yavuz, 1999). The average unit weight of these rocks and modelling material developed are 0.025 MN/m^3 and 0.015 MN/m^3, respectively. When these values are put into Equation 4, a strength scale factor of 1/166 is found. According to this scale factor, the required compressive strength, tensile strength and elasticity modulus values to be satisfied in model material are given in Table I. The modulus and strength ratios of each rock satisfy the condition in Equation 5 are also given in Table I.

Components of the modelling material and testing method

Fine casting plaster, which is the hemihydrate of calcium sulphate and has the composition $CaSO_41/2H_2O$, was selected as a cementing agent because of its suitability for modelling purposes. It is commercially produced by calcination of gypsum ($CaSO_42H_2O$) at temperatures of 190°C–200°C. Addition of water results in reversal of the above process and needle-like crystals of dihydrate ($CaSO_42H_2O$) are formed (Coquard and Boistelle, 1994). The amount of water to cast plaster affects the compressive strength of the material. The dry compressive strength of plaster reduces from 19 MPa for a water content of 37% of to 7.5 MPa for a water content of 49%. Sand was considered an essential filler since it was needed to reduce the strength of plaster and to provide an angle of friction. Silver sand is the most appropriate filler to produce the characteristics of rocks and consists of a high percentage of quartz, the remainder is feldspar and mica, and has a density of 2.62 g/cm^3. Two size distributions were sieved to examine the effect of grain size and are shown in Figure 1. The sizes of the sieves for which 50% of the sand passes were 160 μm and 255 μm which enables classification as fine and medium-coarse sands, respectively.

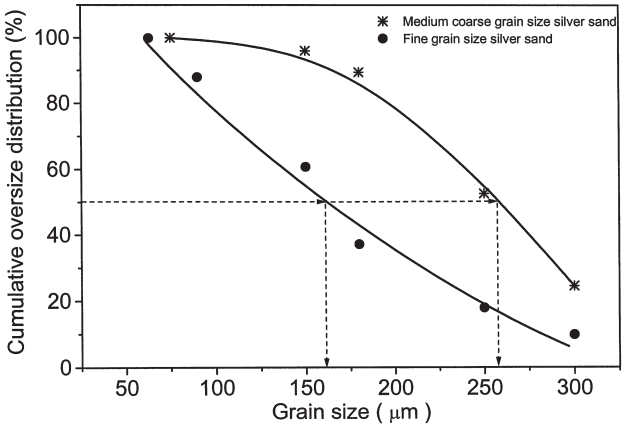

Figure 1—Cumulative oversize distribution for medium coarse and fine grain size sands

Two plastic cylindrical moulds 50 mm and 30 mm diameter with the lengths twice the diameters were used for the preparation of specimens. Adhesion between the surface of the material and plastic mould led to broken specimen ends. A small amount of lubrication removed this problem when thinly spread on the surface of the moulds.

The stress rate during testing ranged from 0.7 to 3.5 kPa/s depending on the proportion of sand in the sample. An LVDT (linear variable differential transformer) was used to measure axial deformation of the samples during loading. Attempts have also been made to measure radial strains in unconfined compression tests by sticking strain gauges on the surface of specimens but the results obtained were not reliable because of dusty surface of specimen and soft structure of material relative to adhesive. The Brazilian test was selected for the determining tensile strength of the material. Tensile strength was calculated by the following relation:

$$\sigma_t = \frac{2P(1000)}{\pi . d . t} \quad (\text{MPa}) \qquad [6]$$

Where *P* is the load at failure (kN), *t* is the thickness of the specimen (mm) and *d* is the diameter of the specimen (mm). The diameter of the samples tested was 50 mm, as for the compression tests, whilst the thickness was 25 mm.

Investigation into the factors effecting the properties of the model material

Effect of sand size and mixing

An investigation was carried out on two different graded

Table II

Sand size effect on the strength properties of the model material

Average sand size (μm)	Sand/plaster ratio	Compressive strength (MPa)	Tensile strength (MPa)	Compressive strength to tensile strength ratio
255	1.75:1 – 5.5:1	1.567 – 0.273	0.277 – 0.043	6.15 – 7.13
160	1.75:1 – 5.5:1	1.338 – 0.300	0.215 – 0.046	5.81 – 6.96

sands, fine and medium-coarse, in order to examine the influence of sand size on the strength of the material. The sand/plaster ratios were varied from 1.75:1 to 5.5:1. The water content used for the 255 μm sand was the same as that for the 160 μm sand. The grain size of sand decreased the viscosity of the mix for the same ratios of water to sand. Specimens were cured for one day at room temperature and then 4 days at an oven temperature of 105–110°C. The upper and lower ranges of compressive strength, tensile strength properties and strength ratio are shown in Table II. Medium-coarse sand comparative to the fine sand provided increase in strength and relatively in strength ratio of the material.

Homogeneity of the material was directly related to the dispersion of plaster amongst the sand particles. This was controlled by the mixing process which was performed using a mixer for the different groups of mixtures. The mixing time was 1, 3 and 5 minutes dependent upon the water quantity relative to sand/plaster ratio. Specimens were cured at room temperature (approximately 20°C) for one day and then oven cured at 105–110°C for 4 days. Maximum strength was obtained with 3 minutes of mixing (Figure 2). The strength of material was lower for both shorter and longer mixing periods, but this was more evident in the case of excessive mixing or low ratios of sand/plaster as illustrated in Figure 2. Mixing time had no significant effect on the strength of the material containing high percentage of sand (5.5:1 in Figure 2). This is an advantage for small-scale model studies.

Effect of water content

The most crucial constituent is the water quantity added to the filler-plaster dry mixture, with the quantity of water governing the strength and elastic properties of the mix. Minimal or excessive water quantities will increase the volume of pores in the mix. While it is not possible to pour the mix into the moulds in the case of low water contents, excessive water will cause the production of a heterogeneous, inconsistent material. The water requirement of a mix is related to the grain size of the sand and the amount and type of plaster used. The effects of different water quantities upon the properties of the mix were studied in order to draw up some guidelines for the optimization of proportions. A constant sand/plaster ratio of 2.75:1 has been employed for these tests. The water quantity was adjusted between a maximum of 35% and a minimum of 23%. All specimens were left at room temperature for 24 hours and in the oven for four days at a temperature of 105–110°C. Mechanical testing was not begun until three hours after removal of the specimens from the oven.

The densities were calculated from the ratio of specimen weight, after curing, to the specimen's total volume. The water volume settled in the pores of the specimen was found by the weight difference of specimen at the time when no water leakage was noticed after casting and after the curing process. The porosity of the specimen was calculated from the ratio of removed water volume to the specimen's total

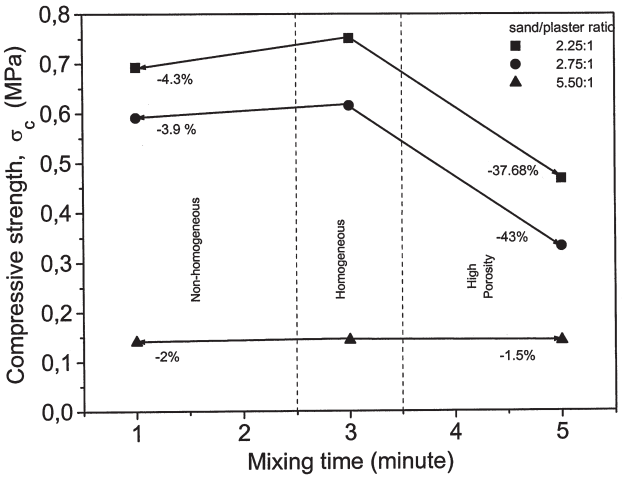

Figure 2—Mixing time versus compressive strength for sand/plaster ratios of 2.25:1, 2.75:1, 5.50:1

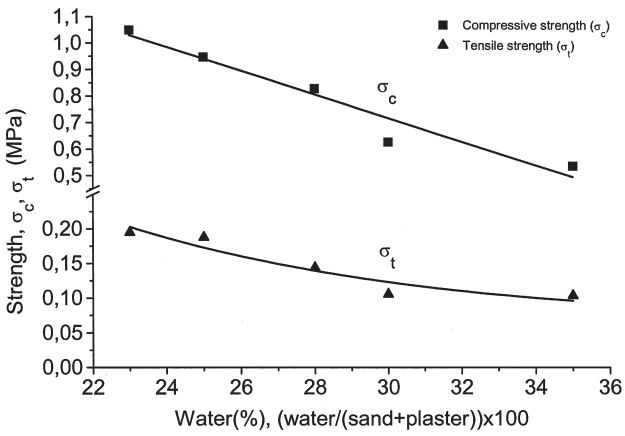

Figure 3—Effect of water content on the strength properties of the material

Table III

Effect of water content on the properties of model material

Component s/p	W (%)	Density gr/cm³	Porosity (%)	Strength properties Dia (mm)	σ_c (MPa)	σ_t (MPa)	Elasticity Modulus, E (MPa)	Modulus ratio (E/σ_c)	Str. ratio (σ_c/σ_t)	% Strain at failure
2.75:1	23	1.55	62.41	50 30	0.980 1.117	0.194 -	146	149	5.05	0.76
2.75:1	25	1.53	63.18	50 30	0.895 0.995	0.188 -	115	129	4.76	0.85
2.75:1	28	1.45	68.14	50 30	0.820 0.838	0.144 -	93	113	5.69	1.16
2.75:1	30	1.43	68.75	50 30	0.603 0.655	0.106 -	61	101	5.68	1.10
2.75:1	35	1.42	74.56	50 30	0.551 0.570	0.104 -	-	-	5.29	-

volume. The properties of the material determined for 30 mm and 50 mm diameter specimens are shown in Table III. Increasing the water content led to a decrease in strength and density and an increase in the porosity of the material. Compressive and tensile strengths of the material showed an average of 45% decrease when the water added to the mix was increased from 23% to 35% as illustrated in Figure 3. However, the strength ratio is a maximum value of 5.69 for 28% water content. On either side of this range, a slight decrease was observed. Decrease in porosity and relative increase in density of material will contribute to estimation of *in situ* gravity related strata failure phenomenon in physical models. The water content mix appears to be a main influencing factor on the modulus ratio. Decreasing the amount of water yielded a higher modulus ratio (Table III). The modulus ratio may be considered to be adjusted by changing the water content during preparation of the mix as illustrated in Figure 4, but a better solution for adjusting the modulus ratio is to change the sand/plaster ratio of the mix for a fixed amount of water (Figure 9). This is because the strain at failure will increase for a higher percentage of water. Low water quantities yielded a brittle material, whereas excessive quantities led to irrecoverable deformation of material under uniaxial compression. For increasing sand/plaster ratios the water requirement for preparation decreases. From the experiences gained from a series of trials, the best combination for a brittle behaviour, acceptable strength, smooth surface characteristics and minimum number of bubble holes was found for fine casting plaster with a water/plaster ratio of 0.46 and a water/sand ratio of $(33.42\text{-}0.05D_{50})/100$ (by weight) where D_{50} is average sand grain size (μm). This relationship was derived with respect to the changes in the apparent surface area of the sand particles.

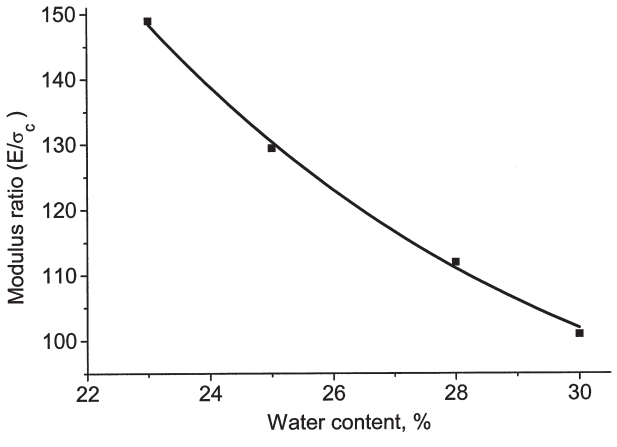

Figure 4—Effect of water content on the modulus ratio of the material

Effect of curing process

An important stage following the preparation of the material is the determination of curing conditions to obtain a final rock-like material. Natural water needed for the hydration process is 18.6 units per 100 units of plaster, but the optimum water quantity is 46% for plaster and $(33.42\text{-}0.05D_{50})$% for sand for a convenient preparation and casting process. Once the mix had set, removal of excess water was achieved through evaporation by exposing the specimens initially to room temperature and then by oven curing. Investigations were conducted to analyse evaporation of free water depending on temperature, oven conditions, bulk of material and time relationships. Drying time is dependent on the degree of ventilation as well as temperature, therefore, the rate of dehydration could be increased by keeping the vapour pressure low with a forced ventilation drying oven (Barton 1970, Bloor 1980). A forced ventilation drying oven was used to reduce the drying time with no detectable effect on the final strength values.

The mix was usually considered to be dry (dehydrated) when the mass of the sample remained constant between weighings. Specimens of 50 mm and 30 mm diameters were prepared with different ratios of sand/plaster from 2.25:1 to 5.50:1. Specimens were weighed at 24-hour intervals. One series of 50 mm diameter specimens was left at a temperature of 55–60°C. The other series consisting of 50 mm and 30 mm diameter specimens were left at an oven temperature of 105–110°C. Changes in the specimen weight are illustrated in Figure 5. Removal of free water from specimens was possible at 105–110°C for a short period of time. After one day of curing, specimens reached approximately the optimum water content. But, at 55–60°C, free water from the material was removed in about 12 days. After

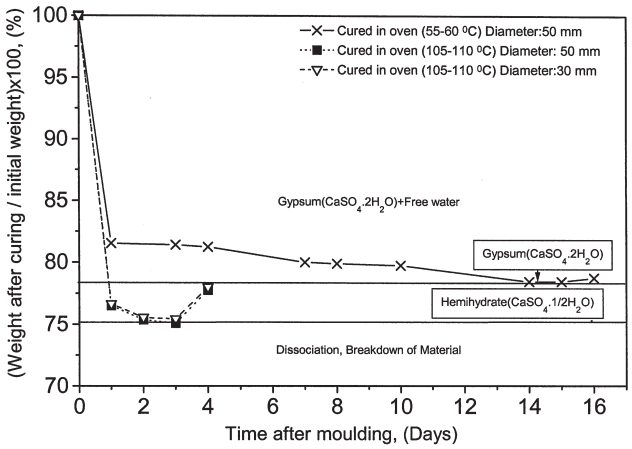

Figure 5—Water loss with time at different temperatures

further curing, no significant weight variation was measured. After the water removal process, specimens cured at 105–110°C started to gain water at room temperature. The reverse chemical reaction through the dihydrate is probably initiated and no weight changes were measured after cooling the specimens. 30 mm and 50 mm diameter specimens lost the same percentage of water after one day of oven curing. The water loss rate for the 30 mm diameter specimens was higher than that of the 50 mm diameter specimens at room temperature. This highlights the necessity of oven curing rather than curing at room temperature for different volumes of material.

The compressive strength of the material decreases with time with respect to the curing temperature. The final strength of the material can be obtained at high temperature after 24 hours due to the rapid evaporation of water. In the case of curing at 55–60°C, considerable time is required to obtain the strength and elastic values required. The 3.25:1 ratio of sand/plaster mix was prepared and cured at 55–60°C. During the first 7 days, the strength of the material reduced rapidly (Figure 6), but no significant variation was measured after 12 days.

To produce a rock-like material, three series of specimens with sand/plaster ratios in the range from 2.25 to 5.5 were

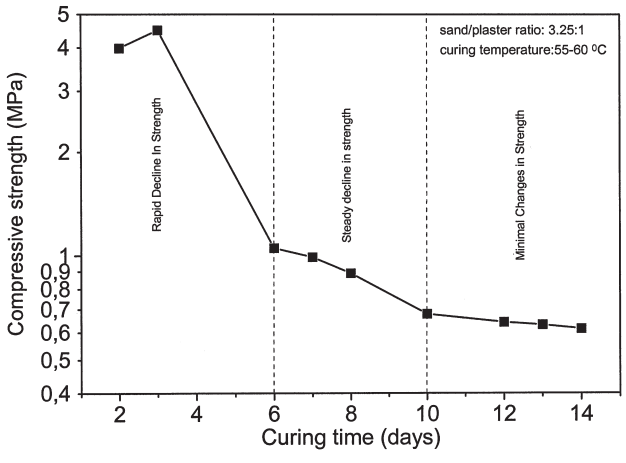

Figure 6—Strength changes versus time at 55–60°C curing temperature

prepared using medium coarse sand and fine casting plaster with optimum water quantities added for different ratios of sand/plaster mixes as 46% for plaster and $(33.42\text{-}0.05D_{50})$% for sand by taking ongoing investigations into consideration. After all series of specimens had been moulded they were left at room temperature of around 20°C for one day to prevent sudden vapourization and later transferred to the oven. Each series have been subjected to three levels of oven temperature as follows:

Series I: Low Temperature curing (specimens cured at 55–60°C for 14–15 days)

Series II: High Temperature curing (specimens cured at 105–110°C for 4 days)

Series III: Combined temperature curing (specimens cured at 40–45°C for 5 days + 105–110°C for 1 day + 40–45°C for 2 days).

Following the defined periods of the curing process, specimens were left outside to cool and stabilize the distribution of moisture. This was to obtain a constant moisture level in the specimen structure up to the relative humidity of the environment. Tests were started after 2–3 hours resting at room temperature. At least two specimens have been tested for the same ratio of sand/plaster and average values of the strength and elastic properties have been calculated.

The average strength and elastic properties of the material produced at low temperature curing conditions have been given in Table IV. Low temperature curing produced low strength values compared to the other curing conditions. A

Table IV

Strength and elastic properties of the model material at the low temperature curing

Sand/plaster ratio (weight/weight)	Strength properties (MPa)		Elasticity modulus (E) (MPa)	σ_c/σ_t ratio	E/σ_c ratio
	σ_c	σ_t			
2.25:1	0.555	0.088	161	6.31	290
2.75:1	0.467	0.070	140	6.67	299
3.25:1	0.440	0.043	109	10.23	247
3.75:1	0.370	0.030	127	12.33	343
4.25:1	0.342	0.028	148	12.2	432
4.75:1	0.244	0.027	-	9.03	-
5.5:1	0.229	0.020	-	11.45	-

Table V

Strength and elastic properties of the model material at the high temperature curing

Sand/plaster ratio (weight/weight)	Strength properties (MPa)		Elasticity modulus (E) (MPa)	σ_c/σ_t ratio	E/σ_c ratio
	σ_c	σ_t			
2.25:1	1.293	0.434	181	2.98	140
2.75:1	1.161	0.336	159	3.46	137
3.25:1	0.798	0.200	68	4.00	86
3.75:1	0.642	0.151	57	4.25	89
4.25:1	0.482	0.110	48	4.38	100
4.75:1	0.382	0.078	26	4.90	68
5.5:1	0.313	0.046	20	6.80	64

Table VI

Strength and elastic properties of the model material at the combined temperature curing

Sand/plaster ratio (weight/weight)	Strength properties (MPa)		Elasticity modulus (E) (MPa)	σ_c/σ_t ratio	E/σ_c ratio
	σ_c	σ_t			
2.25:1	1.316	0.202	205	6.52	156
2.75:1	1.128	0.159	166	7.09	147
3.25:1	0.817	0.117	160	6.98	195
3.75:1	0.647	0.083	109	8.00	169
4.25:1	0.575	0.074	101	7.77	177
4.75:1	0.465	0.064	49	7.27	105
5.5:1	0.292	0.042	26	6.95	92

long duration of curing at these temperatures had a weakening effect on the strength properties of the material. The ultimate strain for the specimens changed between 0.3% and 0.55% which was determined by considering the maximum yield point.

For the high temperature curing condition, the average strength and elastic properties are given in Table V. The strength of the material increased considerably when compared to low temperature curing. The significance of the high temperature curing was that low values of strength ratio were obtained. The ultimate strain of specimens ranged between 0.7% and 1.1%.

At combined temperature curing condition, gradual increase has been obtained in the strength and modulus ratios although the compressive strength was the same as high temperature curing (Table VI). Ultimate strain of the specimens ranged between 0.53% and 0.85%.

Material produced under high and combined temperature curing conditions showed considerable strength differences unless they were cooled until a steady situation existed. This drawback was reduced relatively by low temperature curing. Some investigators appear to have ignored the sensitivity of plaster to moisture in the environment and Moon and Hucka (1985) and Rosenblad (1968) claim that once the water is removed from the structure of the material, the strength of the material will be constant. The decrease in the strength properties was examined by leaving samples at room conditions for 24 hours. The effect of atmospheric moisture on the strength of the material is shown in Figure 7. After the samples were for one day at room conditions, it was noticed that the hardness of the material reduced and the material exhibited a softer structure. This may be caused by reduced interlocking between the crystals and the sand grains. The material gained its strength again if the same quantity of water was removed from the specimen. The disadvantage of plaster cured at high temperatures is that strength, elasticity modulus and so modulus and strength ratios reduce with moisture content. It seems that there is no way to eliminate this disadvantage for this material. If slabs cured at high temperatures, after removal from the oven, are tested in a few hours, strength reductions may be ignored.

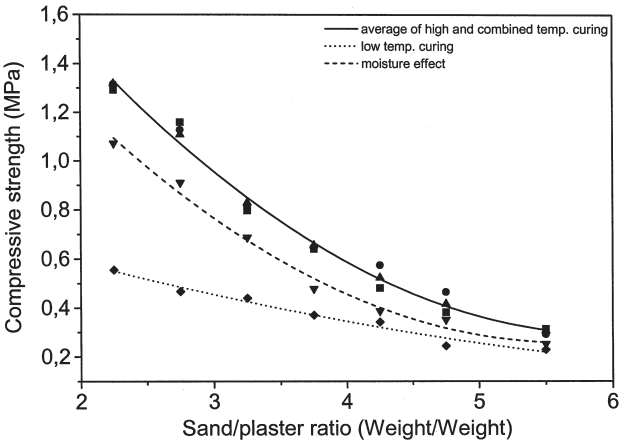

Figure 7—Strength variation of model material at low, high and combined temperature curing for varying sand/plaster ratios

Evaluation of test results

Assuming constant preparation and curing conditions given earlier, the following equations may be used to estimate the sand/plaster ratio for the required compressive strength of the material.

At high and combined temperature curing conditions:

$$\frac{s}{p} = 2.32\sigma_c^{\,2} - 6.72\sigma_c + 7.20 \qquad R^2 = 0.98 \qquad [9]$$

At low temperature curing conditions:

$$\frac{s}{p} = 5.13\sigma_c^{\,2} - 13.36\sigma_c + 8.05 \qquad R^2 = 0.97 \qquad [10]$$

If the model material is cured at a high/combined curing temperature and is left at room temperature more than 24 hours:

$$\frac{s}{p} = 3.99\sigma_c^{\,2} - 8.85\sigma_c + 7.30 \qquad R^2 = 0.97 \qquad [11]$$

Where *s/p* is the weight ratios of sand and plaster added to the mixture and σ_c is the compressive strength of material in MPa. These equations are applicable to the sand/plaster ratios of between 2.25:1 and 5.5:1.

Although the compressive strength of the specimens for the combined temperature curing was the same as the high temperature curing, gradual increase in the modulus and strength ratios and decrease in strain at failure occurred. The compressive strength of the material decreased remarkably when cured at low temperature. Slow removal of water probably led to a strength reduction between the crystal bonds. Comparatively, the modulus ratio, strength ratio and ultimate strain of the final material produced at low temperature curing gives the most valuable results for the modelling of the rocks. Combined curing showed an improvement in the strength and elastic properties of the material when compared to high temperature curing conditions.

Compressive strength and Young's modulus relationships for the material are given in Figure 8. At high and combined curing temperatures, Young's modulus and compressive strengths of the material exhibit an almost linear relationship for ratios of sand/plaster between 2.25:1 and 5.50:1. However, the targeted Young's modulus values for a range of compressive strengths could be achieved at low temperature curing conditions.

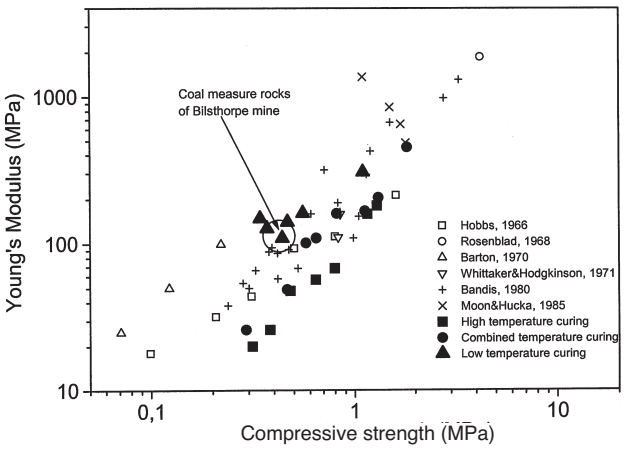

Figure 8—Comparison of compressive strength versus Young's modulus with previous work

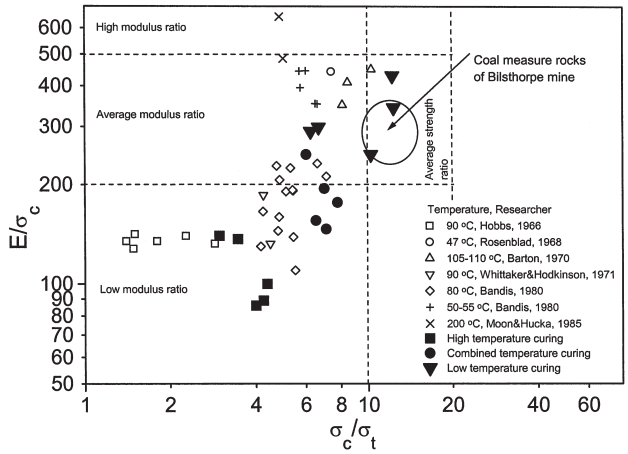

Figure 9—Comparison of strength ratio (σ_c/σ_t) versus modulus ratio (E/σ_c) with previous work

Average modulus ratios common to most rock types have been reached at low temperature, although high temperature curing or combined temperature curing resulted in a range of low modulus ratios. By examination of the results from previous research, curing at low temperatures as illustrated in Figure 9 has provided most of the satisfactory results. Interestingly, low curing temperatures have also shown an increase in the strength ratio of the material. This was actually more significant when the sand/plaster ratio was increased.

The stress-strain curves of specimens cured at combined temperatures are illustrated in Figure 10. It is difficult to establish a relationship between sand/plaster ratio and ultimate strain. Per cent of ultimate strain for the material increased with curing temperatures. The post-failure behaviour of sand/plaster ratios, 2.25:1, 3.25:1 and 4.25:1 are illustrated in Figure 10. The post-failure slope increases with plaster content relative to sand.

Shear strength properties of the model material

Shear tests were undertaken to compare the cohesion and

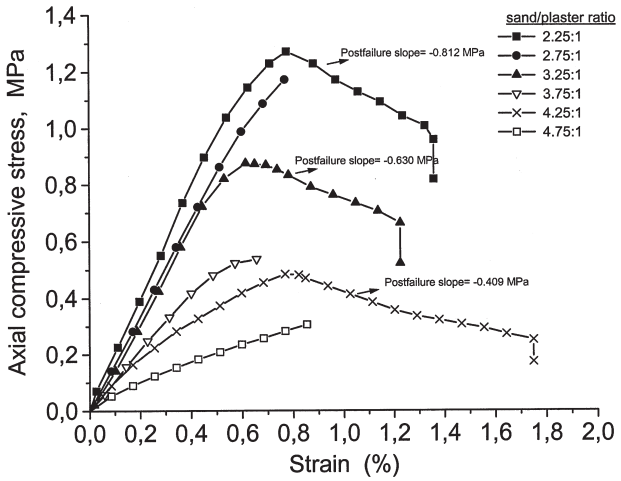

Figure 10—Stress-strain curves of the model material cured at the combined temperature curing

angle of internal friction of the model material with rocks. Sand-plaster mixes with ratios of 2.75:1, 3:1 and 3.5:1 were prepared. The specimens tested were 50 mm in diameter and 100 mm in height. Combined curing conditions were applied to the material. Figure 11 shows that the angle of internal friction of the sand/plaster ratio of 2.75:1 is 15° and is not representative for rocks. The cohesion of the modelling material is 0.24 MPa. The cohesion for the model material with ratio of 3:1 is 0.157 MPa. The friction angle of 25° is not high enough to represent rocks, it is relatively improved with increased amounts of sand in the mix. A sand/plaster ratio of 3.5:1 gives more appropriate shear properties to represent rocks by increasing the friction angle of material to 30°.

The effective factor for the frictional properties of the material is the amount of filler in the mix. The internal frictional angle of the material could be increased by increasing the filler amount relative to plaster amount in the mix. This requires selection of a small strength scale factor when scaling the compressive strength of rocks.

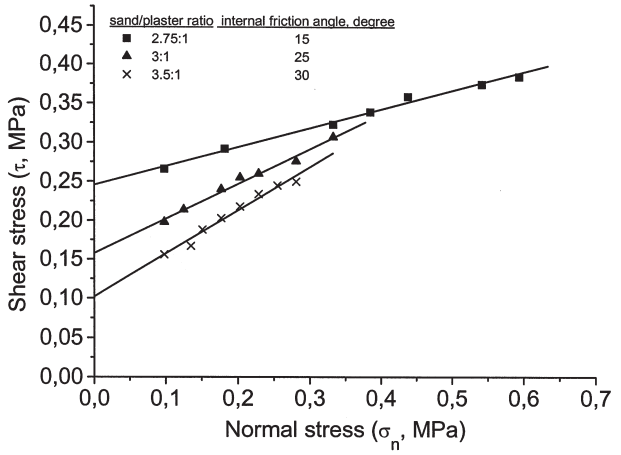

Figure 11—Shear strength properties of model material for ratios of sand/plaster, 2.75:1, 3:1 and 3.5:1

Conclusions

The most important factors influencing the properties of a model material are the amount of water added to the mix and the curing conditions over the sand/plaster ratio. The effect of different water quantities upon the properties of the material was investigated and water content in the mixture for an acceptable strength and elastic properties was optimized as 46% of plaster in weight and $(33.42\text{-}0.05D_{50})\%$ of sand in weight for a convenient preparation and casting process. Excessive water quantities added to the mix resulted with the production of heterogeneous and inconsistent material and so this led to increase in the porosity and strain at failure and decrease in the compressive strength, tensile strength and most importantly modulus ratio of the material. However, the effect of water content on the strength ratio of the material was not remarkable. It has been shown that strength and elastic properties of material could be controlled by curing process. Low temperature curing provided higher modulus ratios, strength ratios and lower strain at failure than those for high or combined temperature curing. Curing at low temperature produced material within the average modulus ratios ranging from 290 to 432, which are common to most rock types, whilst curing at high temperature produced material within the low modulus ratios ranging from 64 to 140 depending on its composition. A combination of low and high temperature curing resulted with an increase in modulus ratio compared to high temperature curing. Increase in curing temperature led to a decrease in the strength ratio of the material. Curing the material at low temperature compared to other curing temperatures provided a satisfactory range of strength ratios. Increase in sand/plaster ratio results with an increase in strength and modulus ratios of the material when suggested preparation and low temperature curing condition were applied. The shear tests for model material showed that increasing the amount of sand relative to plaster increases the friction angle of the material whilst the cohesion was found to decrease. The disadvantage of plaster when cured at high temperatures is that strength, elasticity modulus and so modulus and strength ratios reduces with time between curing and testing process. The drawback was negligible for the material cured at low temperature for about 14–15 days. Model material developed by curing at low temperature satisfactorily simulated properties of Bilsthorpe Colliery rocks where their modulus ratios ranging from 241 to 343 and strength ratios ranging from 11.6 to 14.8.

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