Evaluation of the influence of grout pre-stressing systems on the performance of timber packs: static and dynamic considerations

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Synopsis

A method is proposed for the evaluation of the influence of grout prestressing systems on the support resistance offered by timber packs. It is shown that, in order not to reduce the load-carrying capacity of timber packs, grout prestressing systems need to be at least as stiff as a single timber rise. The method was used to establish strength specifications for the grout prestressing systems to be used under non-seismic and seismic conditions.

For non-seismic requirements, the 24-hour grout strength needs to be at least 1,7 MPa, and the 7-day grout strength 4,9 MPa. The investigation showed that the proposed strength specification is realistic in the light of current grout-strength capabilities.

For seismic requirements, the grout strength needs to be at least 4 MPa and 8 MPa to prevent extensive damage to the grout during seismic events with a peak velocity of 1 m/s and 3 m/s respectively.

Introduction

Grout-based prestressing systems are widely used as a method for the prestressing of timber packs, thus enabling the packs to provide immediate support resistance and preventing them from being dislodged by blasting. Traditionally, packs are prestressed by blocking and wedging and, up to the recent development of a wedge-driving machine, the popularity of this technique was decreasing owing to the human effort required to drive the wedges into the packs.

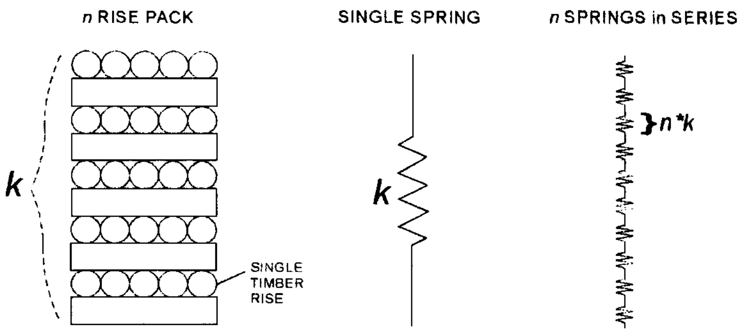

Figure 1—A pack consisting of *n* rises modelled as a single spring or *n*k* springs in series, the total stiffness of the pack being referred to as *k*

This paper examines the extent to which the performance of timber packs is influenced when the packs are installed with grout prestressing systems. The load–deformation characteristics of actual grout systems and timber packs are used to ensure that the study pertains to reality. Most grout manufacturers supply two types of grout: one engineered for normal stope-closure rates, and one for seismic conditions. The influences of both types of grout systems are evaluated, i.e. for non-seismic and for seismic requirements.

The paper begins by describing the methodology used in the comparison of grout strength with the strength of timber packs. This methodology is then applied to an evaluation of the influence of grout systems in non-seismic and seismic conditions and, finally, conclusions are drawn and recommendations made.

Methodology used in the evaluation of strength

To evaluate the influence of grout prestressing systems on the support resistance offered by timber packs, the packs can be modelled as a single non-linear spring or, alternatively, as a system consisting of n individual springs in series, each spring representing a single timber rise from a pack consisting of n rises (Figure 1).

The single-spring and $n*k$ spring systems can be represented mathematically by

$$F = k\left\{x_p\right\} * x_p \text{ (single spring) and} \qquad [1]$$

$$F = \frac{1}{\sum_{i=1}^{n} 1 / k_{sr}^{i}\left\{x_{sr}\right\}} * x_p \text{ (multiple springs),} \qquad [2]$$

where F is the compressive force, $k[x_p]$ is the non-linear stiffness of the single spring depending on the pack displacement (x_p), and

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$k_{ST}[x_{ST}]$ is the stiffness of the single rise depending on the single-rise displacement (x_{ST}). By equating the for (F) expressed by equations [1] and [2], it can be shown that each spring of an n spring system is n times as stiff as the total stiffness of the system. For example, each rise in a ten-rise pack is ten times as stiff as the total pack.

To assess the traditional means of pack prestressing by blocking and wedging, it is assumed that an additional timber rise in the form of blocks and wedges is added to the pack. A wedged pack thus consists of $n + 1$ rises (n timber rises + 1 rise of blocks or wedges), whereas a grout prestressed pack of the same height consists of n timber rises and one grout pillow. For a grout prestressed pack to offer at least as much support resistance as a wedged pack, *the grout pillow needs to be at least as stiff as the layer of blocks and wedges*. In this study, the layer of blocks and wedges is assumed to be as stiff as a single timber rise; i.e., for an n rise pack, the layer is at least n times as stiff as the total pack.

In the following sections, it is assumed that a grout prestressing system needs to be at least as stiff as a single timber rise of n times as stiff as the total stiffness of the pack. This methodology is applied to grout systems tested for non-seismic and seismic requirements.

Grout prestressing systems in non-seismic applications

The performance characteristics of eleven different non-weeping grout systems were established in a series of tests conducted in August 1993 at the T & DS Anglo American testing laboratories based at Western Holdings Gold Mine in Welkom. In the evaluation of the eleven grout systems, grout was pumped at a pressure of 400 kPa into grout bags 65 x 65 cm in size. Before the pumping, the bags were placed between the platens of a loading frame that restricted the thickness of the pressurized grout bag to 6,5 cm. Tests were carried out on each make of grout after the following curing intervals: 2 hours, 24 hours, and 7 days. After curing, the systems were compressed in a press at a constant rate of 10 mm per minute, and the force versus displacement characteristics were recorded. These experiments are henceforth referred to as the August 1993 tests.

The 65 x 65 cm grout bags were designed to be used in conjunction with 55 cm x 55 cm timber packs. The most widely used packs in this size are Matpacks and Hercules packs, the force–deformation characteristics of which had previously been established at CSIR Miningtek. The evaluated packs consisted of ten 10 cm rises, thus having a total height of about 1 m.

The load path of the Matpack is compared with the behaviour of the grout systems in Figures 2 and 3. In Figure 2, the weakest sample tested during August 1993 is compared with the load–deformation characteristics of a Matpack, while Figure 3 compares the strongest August 1993 sample.

The behaviour of the grout systems shown in Figures 2 and 3 is dependent upon (i) strain and (ii) curing time, and the grout offers higher load resistance at increasing compression and increasing curing time. After a compression of 6,5 cm, virtually all the grout had been extruded from between the press loading platens and, as the press platens came into contact, the load measured by the press transducers rapidly increased to the maximum press-loading capacity.

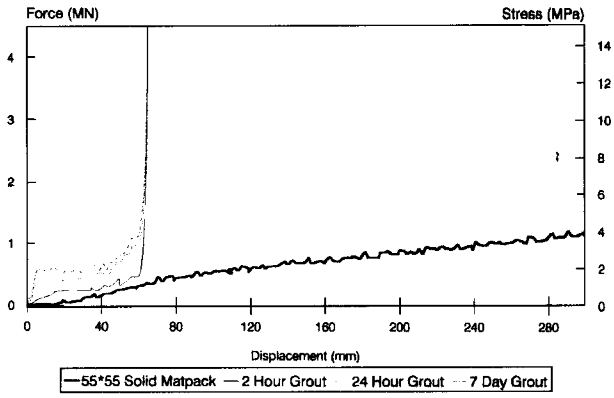

Figure 2—The force–displacement path of the weakest grout sample tested in August 1993 compared with the behaviour of the Matpack

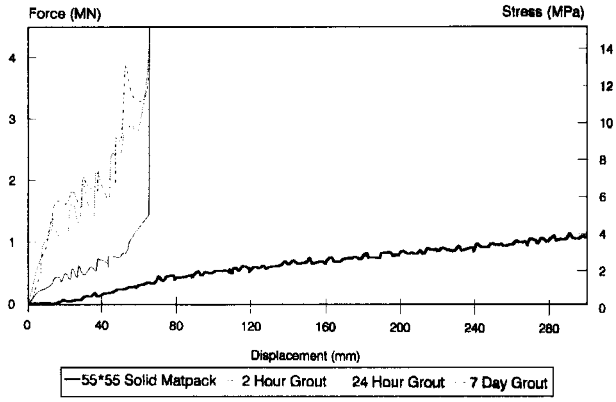

Figure 3—The force–displacement path of the strongest grout sample tested in August 1993 compared with the behaviour of the Matpack

The grout strength required so that the prestressing system does not degrade the pack performance needs to be standardized according to the type of pack and the stope-closure rate. The two most common 55 cm x 55 cm packs (Matpack and Hercules pack) are considered. Typical load–deformation curves of a 1 m high Matpack and a Hercules pack of the design commonly used are shown in Figure 4. The load–deformation characteristics of both types of pack are idealized by a linear and bi-linear approximation for the Matpack and the Hercules pack respectively.

In the first section of the paper, it was shown that, for the grout prestressing system not to degrade the support resistance of the pack, the grout has to be at least as stiff as a single timber rise. Taking into account that the single-rise elements will be ten times as stiff as the idealized ten-rise packs shown in Figure 4, Figure 5 gives load–deformation paths of idealized single-rise Matpack and Hercules elements, and the minimum grout strength for a given curing period such that the pack behaviour is not degraded. The required performance of the grout systems is given for two rates of stope closure, namely 25 mm and 50 mm per day.

Figure 6 displays the required minimum grout strength versus grout age for stope-closure rates of 25 mm and

50 mm per day. This graph is of value for experiments in which the grout stress is measured continuously as the grout system is compressed at 25 mm or 50 mm per day. During the slow compression, the stress transmitted by the grout system should not be less than depicted by the curves shown

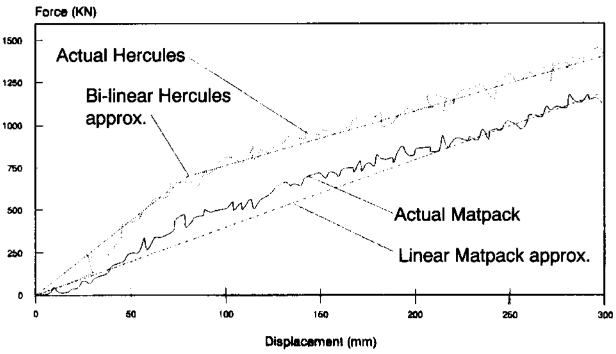

Figure 4—Linear and bi-linear approximation of force–deformation characteristics of a Matpack and a Hercules pack respectively

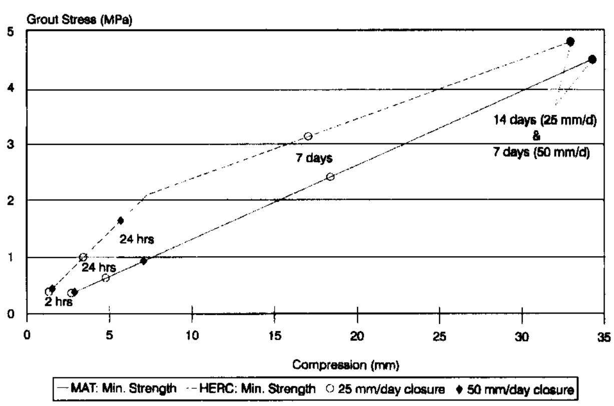

Figure 5—Load–deformation curves showing minimum grout strength for non-seismic requirements. The solid and broken lines represent the load–deformation behaviour of single-rise Matpack and Hercules pack elements respectively. The markers indicate the minimum required grout strength such that the load-carrying capacity of the pack is not reduced when the pack is pre-stressed by a grout bag, i.e. the grout stress at a given compression equals the stress transmitted by a single-rise pack element. The grout strength is calculated for grout ages of 2 hours, 24 hours, 7 days, and 14 days (only for a closure rate of 25 mm per day) and for stope-closure rates of 25 mm and 50 mm per day

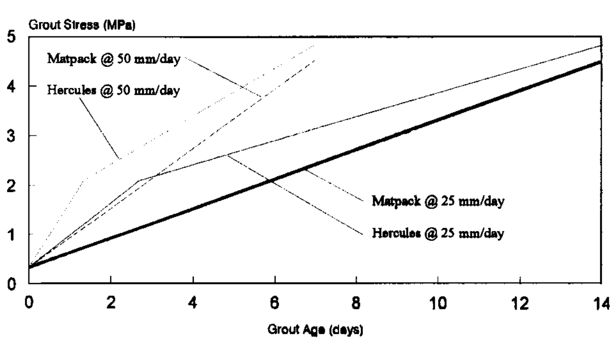

Figure 6—Minimum non-seismic grout stress versus grout age for Matpacks and Hercules packs at compression rates of 25 mm and 50 mm per day

in Figure 6, which represent the load–deformation behaviour of single-rise Matpack and Hercules pack elements compressed by either 25 mm or 50 mm per day.

As indicated by Figures 5 and 6, grout systems used in conjunction with the comparatively stiffer Hercules pack require a higher strength than grout systems used in conjunction with the softer Matpack if the pack support resistance is not to be degraded. In addition, the minimum required grout strength to maintain the support resistance offered by the pack increases with increasing rates of stope closure.

One of the functions of grout systems is to pre-load the pack so that the pack is not dislodged by blasting in the immediate vicinity of the pack. The pre-load is obtained by the pumping of the grout bags with liquid grout to a maximum pressure of 400 kPa, which then exerts an axial pre-load of 121 kN on a 55 cm x 55 cm pack. Laboratory tests conducted at CSIR Miningtek have shown that, as the grout cures in the first hour after pressurizing, the axial pre-load decays to a residual load, which for various makes of grout varies from 40 to 100 kN. In the present investigation, the average pre-load is assumed to be 100 kN. The pre-load is taken into account when the minimum grout strength is calculated, and is the reason that, at the same grout age and stope-closure rate, the Hercules and Matpack single-rise elements are not compressed equally. The initial pre-load of 100 kN compresses the Matpack more than the comparatively stiffer Hercules pack, and thus the minimum grout strength for the Hercules pack needs to be attained at smaller strains than with the Matpack.

To show how realistic these specifications are in the light of current grout strengths, Figure 7 indicates the strength of the grout types tested in August 1993 relative to the minimum required grout strength. The minimum required grout strength is given by the solid line for grout systems used in conjunction with Matpacks, while the broken line specifies the minimum strength in the case of Hercules packs. The actual strengths of the grouts tested in August 1993 are indicated by markers; the strengths are given for grout that had cured for 2 hours, 24 hours, and 7 days. The reactive forces generated by the grouts were determined at a strain equal to the amount that the grout would be compressed at stope-closure rates of 25 mm and 50 mm per day.

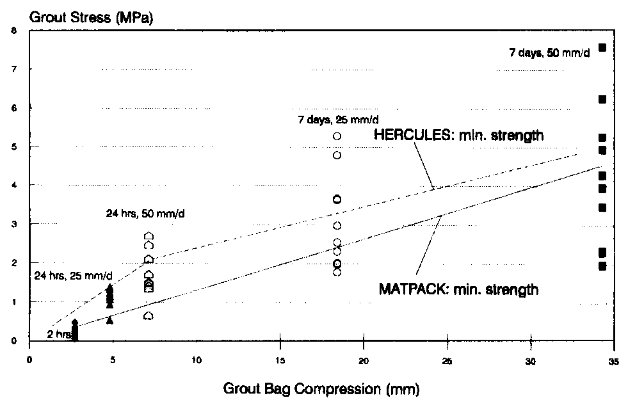

Figure 7—Tested grout strengths relative to the minimum required grout strength. The strengths were calculated for stope-closure rates of 25 and 50 mm per day

The specification for grout strength depends on the type of pack and the stope-closure rate; the most stringent specification analysed in this study entailed a minimum strength at least equal to that of a Hercules rise subjected to a compression of 50 mm per day, whilst the least stringent specification was for a Matpack at a compression of 25 mm per day.

The most important specifications for non-seismic strength are for curing periods of 24 hours and 7 days. After 2 hours, the performance of the grout system is heavily dependent on the load decay immediately after the grout bag has been pressurized and, at that stage, a minimum load decay is more critical than the grout strength at approximately 3 per cent strain.

The percentages of the August 1993 samples that passed the 24-hour and 7-day specifications are 77 per cent for the least stringent specification, i.e. a grout system used with a Matpack compressed at 25 mm per day, and 46 per cent for the most stringent specification, i.e. a Hercules pack at a closure rate of 50 mm per day.

This analysis serves to illustrate that nearly 50 per cent of the tested products passed the most stringent 24-hour and 7-day specifications, and thus it is concluded that current grout technology is sufficiently advanced to enforce this specification (a Hercules pack at 50 mm per day). Ideally, this should be applied across the industry to ensure that the resistance of pack supports is not degraded by the addition of grout-based prestressing systems.

The required 24-hour and 7-day grout strengths are as follows:

Grout age: 24 hours	Grout strength: 1.7 MPa at 9 per cent strain
Grout age: 7 days	Grout strength: 4.9 MPa at 50 per cent strain.

In addition, it is necessary to apply a specification governing the minimum residual load immediately after the bag has been pressurized. This specification should ensure that packs cannot be dislodged by blasting, and that packs provide adequate support resistance immediately after installation. Further research is necessary to determine the required minimum residual load.

Grout prestressing systems under dynamic loading

Since timber stiffness depends on velocity, the load–deformation characteristics of timber packs will alter when subjected to increasing compression rates. Preliminary evaluations of rapid compression tests conducted on 55 cm x 55 cm (1 m high) Matpacks and Hercules packs indicate that, for every order of magnitude, the compression rate increases and the pack stiffens by about 16 per cent (Taggart[1]). This rate dependence can be quantified by the equation

$$F_1 = F_2\left(1 + {}^{\%_{stiffen}}\!\Big/_{100}\right)^{\log\frac{V_1}{V_2}}.$$

where V_1 and V_2 represent two compression rates, F_1 and F_2 are the support resistance offered by the pack at velocities V_1 and V_2, and $\%_{stiffen}$ is the percentage increase in support load for an order of compression-rate increase (16 per cent in this analysis).

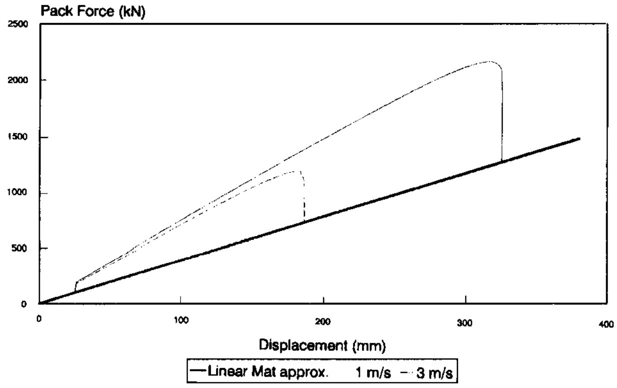

Figure 8—Load–deformation characteristics of a 55 cm x 55 cm Matpack due to a rockburst of 1 m/s and 3 m/s. The stope closure was 25 mm per day, and the events occurred 24 hours after the installation of the pack

In South African deep-level gold mines, 55 cm x 55 cm packs are typically spaced 2 m apart skin to skin. Thus, each pack supports 2,5 m x 2,5 m of hangingwall, which can be up to 3 m thick. In the worst case, the total weight of hangingwall above the pack is 500 kN, i.e.

(2,5 m x 2,5 m x 3 m) x 2700 kg/m^3).

During a rockburst, the pack will rapidly become compressed as it dissipates the energy of the moving hangingwall. Two case studies are illustrated in Figure 8: a hangingwall moving with an initial velocity of 1 m/s and 3 m/s.

Figure 8 gives the theoretical load–deformation curves as a pack is compressed rapidly by a 500 kN weight. The curves are calculated by equating the kinetic and potential energy of the 500 kN weight with the strain energy of the pack. As the load–deformation behaviour of the pack, and thus the strain energy, is dependent on the compression rate, an iterative procedure was required to equate the forces.

The rockburst was assumed to have occurred after the pack was compressed by 25 mm. The initial 1 m/s or 3 m/s velocity of the hangingwall results in a sudden increase in the support resistance offered by the pack. The hangingwall continues to accelerate under gravity until the reactive forces generated by the pack match the weight of the hangingwall. The hangingwall is then retarded until movement ceases after a total compression of 175 mm for the 1 m/s rockburst and 330 mm for the 3 m/s event.

A rationale similar to that applied to the evaluation of grout prestressing systems under quasi-static loading is used for dynamic loading. Thus, if the load-carrying capacity of the pack is not to be degraded, the grout needs to be at least as stiff as a single-pack rise. Laboratory tests were conducted using Miningtek's rapid-compression TerraTek machine to compress 65 mm high filled grout bags at rates of 3 m/s. Figure 9 compares the stiffness of grout compressed at 3 m/s with the hypothetical force–displacement curves of single-pack elements during rockbursts of 1 m/s and 3 m/s velocity.

The grout system was initially pre-loaded at a slow rate until a load of about 400 kN was reached (point A); thereafter, the grout was rapidly compressed with a maximum rate of 3 m/s. The load peaks at 1400 kN and further compression initiates large-scale grout failure; the grout is then violently ejected from between the loading platens, and the support resistance falls to around 500 kN.

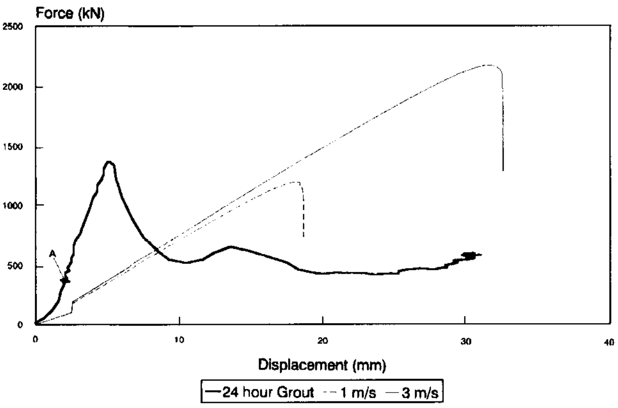

Figure 9—Grout-system performance versus pack performance during rockbursts of 1 m/s and 3 m/s. The grout system was initially pre-loaded to point A, upon which the rapid loading commenced. The hairline and the broken line indicate respectively the hypothetical force–displacement curves of single-rise Matpack elements during rockbursts of 1 m/s and 3 m/s

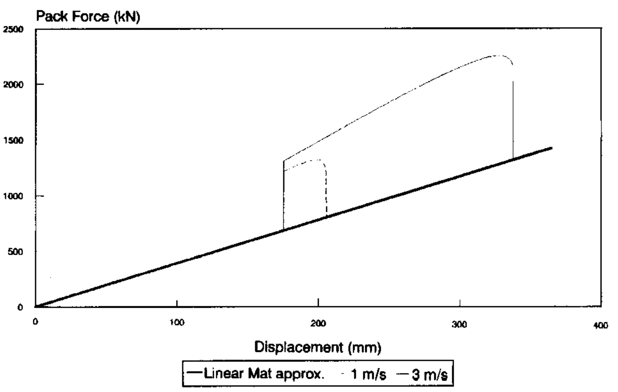

Figure 10—Load–deformation characteristics of a 55 cm x 55 cm Matpack during rockbursts of 1 m/s and 3 m/s. The stope closure is 25 mm per day, and the events occurred 7 days after the installation of the pack

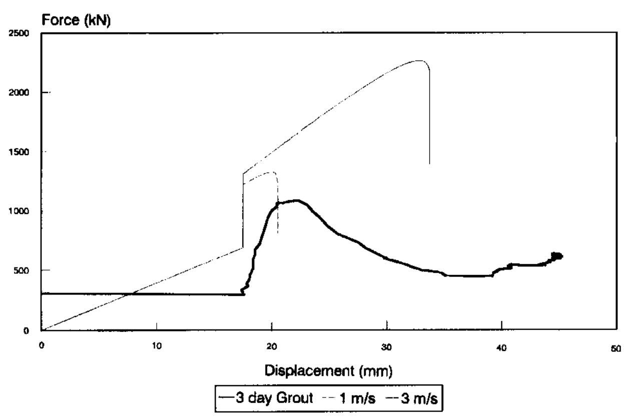

Figure 11—Grout-system performance versus pack performance during rockbursts of 1 m/s and 3 m/s. Rapid loading commenced after the grout system was compressed by 18 mm. The hairline and the broken line indicate respectively the hypothetical force–displacement curves of single-rise Matpack elements during rockbursts of 1 m/s and 3 m/s

The peak pack forces generated by the 1 m/s event are lower than the maximum strength of the grout system (1400 kN), and thus the grout would not fail on a large scale. The theoretical pack forces generated by a rockburst of 3 m/s exceeded the maximum grout strength, and it is expected that the grout would fail on a large scale and be ejected from the grout bag.

A second example is given for a pack subjected to events of 1 m/s and 3 m/s after it has been compressed at 25 mm per day for 7 days. The hypothetical characteristics of the modified pack are given in Figure 10 and, as before, it is evident that the pack is compressed to a much greater extent during a 3 m/s rockburst than during one of 1 m/s.

Figure 11 shows the theoretical load path of a single Matpack rise versus the performance of a grout system tested in the TerraTek press. The filled grout bag was preloaded to 350 kN and then rapidly compressed at a maximum rate of 3 m/s. The peak grout strength was lower than the maximum pack force during the 1 m/s and 3 m/s events, and thus large-scale grout failure was expected and the dynamic pack performance was adversely affected by the addition of the grout prestressing system.

The residual load-carrying capacity after large-scale grout failure for the two systems investigated in this study was approximately 500 kN. This is substantially less than the dynamic forces transmitted through the pack and, once large-scale failure had been initiated, all the grout would be ejected before the pack could regenerate enough support resistance to retard the hangingwall. Consequently, the hangingwall would collapse an additional 6,5 cm (the thickness of the grout pillow) compared with a blocked and wedged system. This would compromise the integrity of the hangingwall and increase the danger to personnel and mining equipment.

Figure 12 displays the minimum seismic grout strength versus grout age for events of 1 m/s and 3 m/s for a grout system installed with a Matpack subjected to a stope-closure rate of 25 mm and 50 mm per day. The required minimum grout strength was calculated from the peak pack forces during events of 1 m/s and 3 m/s, with an initial preload compressing the pack between 0 and 300 mm. The age of the grout can be determined from the stope-closure rate, and the extent to which the pack was compressed from the preload.

At a grout age of less than 3 days (for a closure rate of 25 mm per day), or 1,5 days (at a closure of 50 mm per day), the pack preload is less than the weight of the overlying

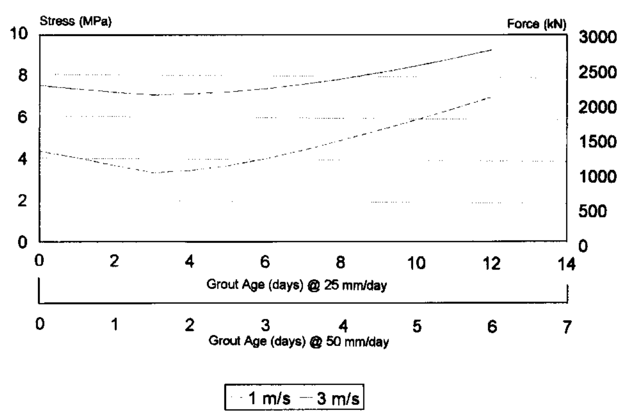

Figure 12—Required minimum grout strength during seismic events of 1 m/s and 3 m/s

hangingwall block, and the rockmass accelerates until sufficient pack forces are generated to retard the movement of the hangingwall. Peak velocities exceed the initial rock-ejection velocity (1 m/s or 3 m/s), and thus the minimum grout strength increases for grout less than 3 days or 1,5 days old for stope-closure rates of 25 mm and 50 mm per day respectively.

Conclusions

This investigation resulted in a method for the evaluation of the influence of grout prestressing systems on timber packs in non-seismic and rockburst-prone conditions. For grout systems not to degrade the support resistance of a pack, they need to be at least as stiff as the single-rise elements constituting the pack. A comparison of the actual strengths of grout systems with the stiffness of single-rise elements led to the following conclusions.

Grout systems for non-seismic conditions

Nearly 50 per cent of the currently available grout passed the most stringent specifications for 24-hour and 7-day strength. To simplify testing procedures, it is recommended that one strength specification should be applied across the industry. For the stiffest packs and highest rates of stope closure, the most stringent specification recommended is a 24-hour strength of 1,7 MPa at a grout-bag compression of 9 per cent, and a 7-day strength of 4,9 MPa at a grout-bag compression of 50 per cent.

A 2-hour test is required for the determination of the residual pre-load of a grout system. This is essential to give the initial support resistance and to prevent blast damage to the pack. Further work is necessary on the minimum residual pre-load that is required.

Grout systems for seismic conditions

Additional rapid compression tests on grout systems are required to provide further understanding of their dynamic characteristics.

Initial evaluations of dynamic tests indicate that, once the peak strength of a grout system has been exceeded, the grout is ejected violently from the grout bag and the support resistance decreases abruptly. This implies that, during a severe rockburst, the hanging would be displaced an additional distance equal to the thickness of the grout system.

To prevent the violent ejection of grout, it is recommended that a grout with a minimum dynamic strength of 4 MPa should be developed for events of 1 m/s, and 8 MPa for events of 3 m/s.

Acknowledgements

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Reference

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More aid for small mines*

A Mintek-developed pilot-scale winnower has been delivered to a small-mine developer in the Steinkopf area of the North-Western Cape. The self-standing winnower is fully portable, and has its own electric motor.

According to Rob Guest, an Assistant Director in Mintek's Extractive Metallurgy Division, the idea is to lend the winnower to developers to test material, and if tests prove successful, to provide technical drawings and plans to individual developers to enable them to manufacture their own prototypes. 'The winnower is a relatively simple piece of equipment to put together, and manufacture will provide more work for other small operators in the area', he said.

'The aid scheme operates through local mining associations, and in this instance, the winnower was lent to the owner of the Witkop Pegmatite Mine. He is currently recovering feldspar from this deposit, and the winnower will enable him to also recover a fine-flake mica from the pegmatite.'

The loan has been facilitated through the Namaqualand Small Mining Association, and after the machine has been sufficiently tested, it will be lent to another small miner in the North-Western Cape.

One of Mintek's principal engineers, Jou Loo, and operator Nicholas Mdlalane, travelled down to the Steinkopf area to deliver the winnower, and to demonstrate its operation to the local miners.

The winnower is seen as an ideal means of adding value on-site, and in this particular instance, Mintek is looking to the fine grind of mica to produce a filler for the manufacture of paint. A further possibility exists that a small paint-manufacturing facility could eventually be developed locally, as a further downstream venture.

For further information contact Mrs Pat Speedie at:
Tel: (011) 709-4111 or Fax: (011) 709-4326. ◆

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