Chapter 8.0

Conclusions and recommendations

8.1 Conclusions

The ultimate aim of this thesis was to obtain an understanding of the fundamental mechanisms of roof failures and the fundamentals of roof bolting in South African collieries to provide guidelines and a design methodology for their amelioration. This was achieved through underground instrumentation, monitoring, testing and using well established stochastic modelling technique.

The conclusions arrived in this thesis are:

Literature review (Chapter 2.0):
Since the introduction of mechanical bolts in the 1940s, the amount of research into the understanding of the behaviour of roof bolts has been significant. Today, almost all coal mine roofs are supported with roof bolts in South Africa.

In the early years, the design of roof bolt patterns was based on local experience and the judgement of mining personnel. The suspension mechanism was the most easily understood and most widely used roof bolting mechanism. However, significant advances have been made over the last 20 years, in particular, the development of resin anchors, tendon elements, and installation hardware. These advances have resulted in an increase in the use of full column resin bolts.

The design of roof bolt patterns has also been improved, and four main rock reinforcement techniques have been developed: simple skin control, beam building, suspension, and keying. The geology and the stress levels determine the appropriate mechanism for a particular application.

The importance of tensioning roof bolts remains a subject of controversy. Due to the fact that the roof deformations in South African collieries are relatively small, it is recommended that tensioned roof bolts are beneficial in that they allow less roof deformation to take place after the support has been installed. However, if the bolting system is stiff enough, tensioning may not be required.

Although there have been many studies into the support of intersections, a better understanding of rock behaviour in intersections is required.

Numerical models are useful in understanding roof and roof bolt behaviour; however, extensive laboratory studies are required for determining the input parameters for site specific conditions. The Australian technique, subsequently adapted in the UK, has proven that numerical modelling can be used to back analyse underground scenarios. Once the model is calibrated, then the results obtained from the numerical models can be used for design. No attempt has been made to develop a generic numerical model to be used in the design of roof support systems.

The selection of roof bolt type for different geological environments is well documented. However, the changing conditions underground must also be determined and the design and the support system have to be modified accordingly. Widespread instrumentation and vigilant visual observations are important for ensuring safety and stability in coal mines.

While the effect of roof bolt diameter on support performance is well understood, there is still controversy over the length of the roof bolts. It has been shown by Molinda et al. (2000) that the probability of roof failures increases with decreasing bolt length. Since skin failures (< 0.5 m thick) are more common in South Africa than larger roof falls (Canbulat and Jack, 1998, van der Merwe and Madden, 2002), short roof bolts and/or areal coverage for skin control may make up part of an effective support system.

This review also highlighted that different support design methodologies have been developed based on rock mass classification techniques, numerical modelling, instrumentation and monitoring and physical modelling. However, no attempt has been made to develop a probabilistic design methodology, which takes into account the natural variations exist within the rock mass and the mining process.

In conclusion, despite the fact that roof bolting has been the most researched aspect of coal mining, FOG still remain the major cause of fatalities in South Africa. There are no commonly accepted design approaches available for underground coal mines. Roof bolts were found to behave differently under different loading conditions, emphasising the importance of understanding the interaction between the roof bolts and the rock mass. The most important key to the design of a roof support system is a better understanding of roof behaviour and variations that can be encountered during extraction.

Monitoring of roof and support behaviour (Chapter 3.0):

The sonic probe extensometer, which was found to be the most accurate and reliable instrument capable of monitoring roof behaviour up to 7.2 m into roof, was used throughout the underground monitoring programme.

A preliminary study into the height to which the openings migrate in the roof (height of roof softening), i.e. height to which instabilities could occur was conducted. In all monitoring sites all the displacements measured in the roof were confined to within 2.5 m of the roof skin. The height of instability in the intersections was compared to that in the roadways with the elevation differences being converted to percentages. These differences were relatively small, varying between -5.0 and 33 per cent with an overall average of 13 per cent.

In the vast majority of cases the stable elevation in the roof was fully developed a short distance behind the face. In the drill and blast sections, the stable elevation was reached after a single blast, where the face advance increased the unsupported span to 3.0 m on average.

In the continuous miner sections, it was difficult to accurately determine at what point the stable elevation had fully developed. The only two monitoring sites that indicated obvious increases in the height at which displacement occurred in the roof as further mining occurred, were both in the partial column resin supported roof.

An investigation into the time effects of a static face indicated that close to a static face (within 0.5 m), the roof does not deform significantly. If a face remains static, the roof within its zone of influence (approximately 5.0 m away) experiences some degree of creep with time. An area of roof outside the zone of influence of the face (11 m away) is not affected by the face irrespective of whether it is stationary or be advanced.

The monitoring results also showed that there was no evidence of a dramatic increase in the stable elevations as is the case in the high horizontal stress driven beam buckling mechanism experienced in overseas collieries. It is thus concluded that in the sites monitored relatively high horizontal stress played little, if any role in increasing the deformations measured.

A roadway widening experiment was carried out to establish the critical roof displacements. The maximum width attained was 12 m at which stage $\pm$ 5 mm displacement was measured. No roof falls had occurred. However, in the same panel falls had occurred at 5 m widths. Also, falls took place in some of the areas where evidence of high horizontal stress had been noted. This indicates the significant variations that occur in a single mining area.

During the monitoring period no roof falls occurred at any of the 29 sites and road widening experiment site, even where 12 mm displacements were measured. As a result it was not possible to try and establish critical roof displacement values for any of the geological regions.

In conclusion, these results showed that the roof conditions in South African collieries can be classified as gravity loaded beams.

Effect of cut-out distance on roof performance (Chapter 4.0)

The literature survey yielded little in the form of directly applicable research. It appeared that little work on determining roof failure per se as a function of cut-out distances has been done elsewhere. The limitations on cut-out distances were mainly due to other issues, like preventing underground workers being under unsupported roof and methane and dust control. Recent work done by researchers in the USA seems to indicate that extending the cut-out distance in the USA had little effect on roof stability, mainly because operators tended to reduce the cut-out distance under adverse roof conditions and only extend it if roof conditions were good.

During underground tests it was not possible to advance unsupported faces until failure occurred without exposing people to considerable risk. The next best was to monitor the universally accepted precursor to roof failure, which is roof deflection, under a range of different situations. This was done under the widest possible range within the constraints of time and funds, but it was still found that there were too many combinations of the variables that determine the roof deflection to derive complete answers.

The measurements were then complemented by numerical modelling, which affords the possibility to vary only certain parameters and keep the rest constant. It was then found that the underground observations fitted the patterns derived from the models and consequently there is a high level of confidence in the final conclusions.

The most important conclusion from this investigation was that once the face had advanced to a distance equal to twice the bord width, there was insignificant additional roof deflection with further face advance. This conclusion was confirmed by numerical modelling and is in line with the analytical beam solutions. For typical South African conditions, with bord widths in the range of 5.5 m to 7.2 m, the implication is that roof stability would not be adversely affected by advancing further than 11 m to 14 m. Majority of all of the total roof deflection that would take place, would occur during the first 11 m to 14 m of development. Therefore, if it is intended to limit roof deflection by restricting the cut-out distance, the cut-out distance would have to be limited to less than the bord width. During the investigation, it was observed that where adverse roof conditions existed, this was in fact done by underground personnel.

With regard to the effects of time on roof deflection, it could only be studied for the initial period of 48-hours following roof exposure. The reason for this was operational, as leaving faces for longer periods would have had an adverse effect on production and the sequence of mining. The instrumentation was usually done on Friday afternoons, preceding weekends during which faces would not be mined. It was found that the roof continued to deflect during that period, but that the amounts of deflection were not significant. However, it is still deemed necessary to support a roof as soon as possible, as even minute fractures resulting from the additional deflection may change the roof behaviour and eventually result in failure.

Results from one sonic probe monitoring hole showed that roof bolting had no remedial effect on roof deformations. Although the effect of roof bolting was specifically monitored by only one sonic probe monitoring extensometer, in general, the results showed that in none of the monitoring holes where roof displacements were recorded, was there any evidence of the roof being lifted due to installation of pre-tensioned roof bolts. This indicates that the roof bolt tensioning was not sufficient to close the pre-existing openings within the roof strata, where roof displacements were recorded. However, as indicated by the differences in the maximum displacements between the No 1 and No 2 holes, it may be concluded that roof bolting prevented further deterioration from taking place. In all the cases the displacements recorded by the No 1 holes (drilled next to the previously installed bolts) were less than those recorded by the No 2 holes (drilled in the centres of the unsupported areas) during the same monitoring period.

It was found that the lithological composition of the roof strata played a major role in the amounts of deflection that were recorded. Bedding separation was seen to occur at the positions where different strata types joined. This implies that the roof behaved like a set of composite beams of different characteristics. It was then also found that the amounts of deflection corresponded with the deflection that would be expected from gravity loaded beams.

Within the limits of horizontal stress that were present in the study areas (three of the sites exhibited obvious signs of elevated horizontal stress), the stress appeared not to have had a noticeable effect on roof deflection. This was confirmed by the numerical modelling. It was concluded that as long as the magnitude of the stress is insufficient to result in failure of the roof, it does not contribute meaningfully to deflection.

The implication of this is that the dilation in the roof is determined by bord width and roof lithology rather than cut-out distance, once the cut-out distance exceeds twice the bord width.

This last conclusion is significant, as it offers the first possibility to predict roof deflection and consequently roof failure. The recommended process is as follows:

- Determine the thicknesses of the roof plates (or beams) by careful scrutiny of borehole logs.
- Calculate the maximum deflection for the desired road width using standard beam solutions.
- Calculate the induced beam stresses using the standard beam solutions.
- If failure is not predicted, the road width is confirmed.
- The cut-out distance should be determined by other considerations (ventilation requirements, etc), but at least it is known that there is little to be gained in terms of roof stability by restricting it to any distance that is greater than twice the bord width.

Roof deflection should then be monitored underground and the first warning sign should be where the amount of deflection exceeds the calculated amount, as that would indicate a change in conditions. Where that occurs, it would be prudent to reduce the cut-out distance, but even more so to reduce the road width.

Exemption from the 12 m restriction on cut-out distance may be obtained from the Principal Inspector provided that the mine can show that the risk to underground workers will not be adversely affected. This implies that a comprehensive risk assessment is required to obtain the exemption. The results of this investigation show that in general, the increased risk to roof instability due to extended cut-out distances is not a major factor and that the emphasis in the risk assessment should be on the other factors, namely the control of dust and methane and the probability of workers being under unsupported roof.

As with any matter relating to roof stability, it is recommended to base this type of exemption on a comprehensive hazard analysis. It is important to obtain a broad view, based on a general roof hazard plan that is required for other purposes as well.

The following steps are recommended for determining the effective cut-out distances for a given site:

1. General roof hazard plans should be drawn up for each section based on the borehole logs,
2. A detailed geotechnical analysis should be conducted. This analysis should include mapping of geological discontinuities, stress regime and roof lithology,

3. The characteristic behaviour of the roof should be determined for the range of conditions, such as change in the thickness of the immediate roof layer, stress regime and bord widths,
4. Once the bord width and support method are established from the above, the cut-out distance can be determined as well. The most important control parameter is the bord width. If the bord width is chosen such as to result in deflection that is less than that resulting in failure using beam theory, there is little to be gained by restricting the cut-out distance.
5. With the previous steps in place, it remains to also stipulate a procedure that will prevent any person being under unsupported roof.
6. The support system that will be used in the section should also be monitored by continuing the monitoring after the installation of support. The critical factors in determining the support performance are the height of the instability into the roof, which determines the length of support, and the separations within the bolt horizon, which determine the stiffness of the support.
7. Once the cut-out distance is determined with regard to ground control, it should be checked against the ventilation and risk assessment plans.

The study area included one site where there was a high incidence of jointing, but in that area the effects of the jointing did not materialise in the measurements, most probably due to "experimental gremlins." The irony is that the roadways next to the one where the instrumentation was done suffered severe damage and the cut-out distances in those were reduced substantially by the operational crews. However, in the instrumented roadway, no damage occurred and the roof deflection was minimal.

Finally, logic dictates that the longer the cut-out distance, the higher the probability of encountering unexpected jointing with its accompanying negative effects on roof stability. This may be countered by instituting measures that will prevent personnel being under unsupported roof.

Geotechnical classification techniques (Chapter 5.0)

The purpose of this task was to evaluate and compare existing roof rating system that are used in South Africa and others that have been developed in other countries, and proposing the way forward for the development of a system that could be used universally on South African collieries to determine the roof conditions and quantitatively required support. The results showed that although many collieries have hazard plans, these plans do not readily quantify the mechanistic behaviour of the roof strata, they are mostly descriptive and are subject to different opinions. Therefore, they cannot be used for roof support design purposes. Furthermore, there is no uniform methodology behind the development of these plans, which makes it difficult for another person to apply them.

The CMRR could overcome most problems associated with the application of rock mass classification systems to coal mining. Also, in principal, the borehole core CMRR is a very similar system to impact splitter. However, due to its origin from case histories from the United States, certain modifications need to be applied to the system for the different conditions in South African coal mines. In the context of the South African coal mining industry, the following summary can be drawn regarding future improvements in the system:

- Requires exposure into the roof (underground CMRR only)
- Only the bolted height is rated. In South Africa, 2.0 m into the roof is the height that is usually rated.
- Although sets of joints have been considered in CMRR, single joints can have an influence and should thus also be included.
- Joint orientation is not included (underground CMRR only).
- Stress adjustment is required in the rating system to account for the influence of high horizontal stress (underground CMRR only)
- Blasting adjustment is not considered (underground CMRR only)
- Does not consider the position of soft or hard layers into the roof (both underground and borehole core CMRR)
- Requires skilled personnel to carry out ratings (both underground and borehole core CMRR)

Rating systems will continue to play an important role in coal mining practice. These systems should relate to the expected mode of failure of the strata for design and planning purposes. Underground rating and performance systems need to be incorporated with the roof rating systems into the overall ground control management to ensure adherence to design and overall mine standards. However, these systems cannot quantitatively determine the required support system in a given condition.

Although most collieries studied had some form of hazard identification systems in place, these systems are mostly descriptive in nature and therefore tend to be subjective. Moreover, these rating systems are used mainly for planning purposes, and not to determine the changing conditions underground. The systems have worked in some cases where one person had extensive experience at one mine. However, due to movement of personnel, there has been a loss of knowledge, insufficient documentation and a lack of updates of the local systems.

Impact splitting test has been found to be an appropriate system to eliminate human error in core rating. The advantage of impact splitting over the individual colliery's geology based rating systems is its ability to readily quantify the roof instead of a mere description that can change from one person to another. Geology based systems have been developed from experience by mine personnel that certain soft or hard layers in the roof were a major cause of instability. During this study, impact splitting has shown a very good correlation with the geology based rating systems. The system can therefore be used during planning for good prediction of conditions ahead of mining. Furthermore, the system requires minimal training time and therefore does not require skilled personnel.

In conclusion, impact splitting tests, section performance rating and physical risk ratings systems developed in South Africa can be described as the most effective and appropriate for South African conditions. Impact splitting can readily quantify the roof conditions during planning with minimum subjectivity. Section performance and physical risk rating can be used for identifying changing conditions while mining and determining the best response to the different conditions.

It must however be noted that as shown in the previous chapters of this thesis that the roof lithology, stress regime and roof characteristics can change within meters in a production section. Therefore, in order to predict these changing conditions many boreholes required for a section, which would be very expensive and time consuming. In addition, borehole core based systems like the impact splitting are dependent on the quality of the core. Layers that are very weak or have very low cohesion can easily break during the drilling process. Geophysical techniques may therefore be more accurate in such cases for identification of these layers.

Evaluation of roof bolting systems (Chapter 6.0)

As part of this task all support components that are currently being used in South African collieries were evaluated.

Although a considerable amount of time was spent on the effect of the roofbolters on the performance of support systems, few trends could be observed in the parameters influencing the support performance. The study showed that there are no standards in South Africa for the parameters investigated (speeds, torque, and thrust). Underground testing showed that the variations in the parameters are greater than was previously believed. No correlation between the hole profiles and the parameters investigated could be discerned.

Nevertheless, this indicates that in South Africa, the installation quality of bolts varies significantly. Irrespective of design, the bolts are installed in completely different manners.

Unfortunately, there is no data available on the relationship between roof collapses and the quality of bolt installation. It is therefore impossible to determine empirically which support installation performs the best. This highlights a need for the best equipment performance for the best support installation to be investigated in detail. Such a study would assist in reducing the falls of ground and, therefore, the rock-related casualties in South African collieries. However, experience gained during the underground experiments showed that such work can only be done in a more controlled environment, such as with the laboratory.

Investigation into the effect of wet-dry drilling showed that both the bond strength and system stiffness were relatively greater for wet drilling than for dry drilling. The reason for this was not determined but is probably related to the surface condition of the holes and its influence on the adherence of the resin to the rock.

Five important elements of a bolting system have been identified. The impacts of those elements were qualified through short encapsulated pull tests.

The performance of roof bolts that are currently supplied to South African mines was also investigated. A series of short encapsulated pull tests in shale indicated that, on average, bond strengths obtained from the roof bolts supplied by Manufacturer “C” (referred to in the report) were approximately 18 per cent and 28 per cent greater than those obtained from the roof bolts supplied by Manufacturers “A” and “B”, respectively.

To determine whether variations in the profile of bolts supplied by the different manufacturers could account for the differences in performance, the bolt-core diameters and rib diameters from different bolt manufacturers in South Africa were measured.

The parameters that determine the contact strength between bolt and resin are rib-height, spacing between the ribs, and the rib angle. An investigation was conducted into the dimensions of roof bolts that are used currently. The results showed insignificant differences between the parameters that determine the bolt profile of South African roof bolts. Owing to the physical similarity between the bolts studied, it was not possible to determine the influence of these parameters.

The effect of rib angle was investigated and the results of a literature search showed that, as the rib angle increases away from normal to the bolt axis, so the pull-out load of the bolt decreases. It is therefore suggested that, in order to achieve relatively high pull-out loads, low rib angles on the bolts are required. This was confirmed by laboratory tests on different bolts with different rib angles in Australia (O'Brien, 2003). However, it is noted that lowering the rib angle may result in poor resin mixing performances.

Using a conceptual model to determine the effect of bolt profiles, it is shown that maximum pull-out loads can be achieved between the resin and roof bolt when:

- The ribs are relatively high;
- The distance between the ribs is relatively low; and
- The ribs are relatively thick.

The performance of resins that are currently being used in South African collieries was also investigated by means of short encapsulated pull tests. The results indicated that in sandstone the resin types from the two different manufacturers performed similarly. However, the strength of slow (5/10-minute) resins from both manufacturers was much lower than that of fast resins. It is concluded that in the majority of pull tests, failure took place at the rock-resin interface, indicating that the rock failed before the resin shear strength had been reached. It is therefore suggested that the strength of resin currently being used in South Africa is adequate. However, the stiffness of the system of which resin is a part should be determined by short encapsulated pull tests.

Again, the conceptual model developed to determine the effect of resin in the support system concluded that the failure characteristics of a roof bolting system will be determined by the shear strength of bolt, resin, and rock.

- The failure will take place at the resin-rock interface when the shear strength of the rock is lower than the resin (rock will fail).
- The failure will take place at either the resin-rock or resin-bolt interface when the resin shear strength is the lowest in the system.
- When the resin shear strength is the lowest in the system, the failure will be determined by the roughness of the hole and the bolt profile.

The test results showed that the reinforcing system using bolts from all four manufacturers performed almost identically in sandstone, but performed in different ways in the other rock types. The bolts from Manufacturer "A" performed slightly better in coal and shale rock types than the bolts from other manufacturers.

In order to investigate the effect of bit types, a series of short encapsulated pull tests were conducted. The results showed that the 2-prong bit outperformed the spade bit in sandstone and shale rock types. However, the average hole annuli obtained from the 2-prong bit were always greater than the spade bit. It is thought that this is because 2-prong bits drilled a rougher hole profile. Both the stiffness and the maximum load obtained from the 2-prong bits were greater than for the spade bits. These findings suggest that 2-prong bits are more effective in collieries than spade bits are.

The effect of hole annulus was also investigated. The results show that an annulus between 2.5 mm 3.8 mm resulted in the most effective bond strengths. Another interesting point is that as the annulus drops below 2 mm, it appears to have a negative effect on the bond strengths.

The effect of wet and dry drilling was also investigated by means of short encapsulated pull tests. The results showed that bond strengths and overall support stiffnesses are greater with the use of the wet drilling in all three resin types.

Tensioned versus non-tensioned bolts is one of the most discussed topics in roof bolting. A number of papers have been published on this topic in Australia and the US. An additional 25 short encapsulated pull tests were conducted to determine the effect of tensioning on bond strength. The results showed that non-tensioned roof bolts achieved significantly higher bond strengths than the tensioned bolts in sandstone and shale roofs. Similarly, the overall support stiffness of non-tensioned roof bolts was significantly greater than that of the tensioned roof bolts. This finding may be significant and therefore the effect of tensioning and non-tensioning on overall support system performance should be investigated in a control environment.

The effect of rock type on support performance was also investigated by means of a series of short encapsulated pull tests. The results from these tests highlight the very distinct differences between bolt system performances in different rock types. Sandstone was shown in the tests to produce significantly better results than shale and coal. From these results it can be concluded that rock type is one of the primary factors influencing the support system performance.

An investigation into the quality control procedures of support systems was also conducted. Quality control procedures for compliance with the design, support elements and quality of installation are presented in the thesis. Recommendations for improving quality control measures and for developing testing procedures for bolt system components, installation quality and resin performance are provided.

Most importantly, similar to stress regime, geology and roof characteristics presented in the previous Chapters, there is a significant variation in the performance of support systems using different support components in different geotechnical environments. Therefore, it is concluded that a deterministic approach is not adequate for a roof bolting system design in such a complex system. A probabilistic approach is required in order to take all these variations into account.

Roof support design methodology (Chapter 7.0)

The ultimate aim of this Chapter was to develop a roof support design methodology that takes into account all natural variations exist within the rock mass and the mining process. This was achieved by adapting a probabilistic design approach using the well established stochastic modelling technique, which is widely used in civil and other engineering disciplines.

In the literature, it has been highlighted that one of the disadvantage of the probabilistic approach is the assumptions regarding the distribution functions. Using the data obtained throughout this thesis, the probability distributions of various input parameters have been established using the Anderson-Darling goodness of fit tests.

It is shown in this Chapter that the traditional deterministic roof bolt design methodologies provide some insight into the underlying mechanisms, but they are not well-suited to making predictions to roof support decision-making, as they cannot quantitatively address the risks and uncertainties that are inherently present.

An analysis of the data presented in Chapters 3 and 4 highlighted that for a 40 per cent increase in the span, taken across the diagonal of an intersection, relative to the roadway span, the magnitude of the displacement in the roof increased by a factor of four. The results also showed no evidence of a substantial increase in the height of the bed separated, potentially unstable roof strata, as is the case in the high horizontal stress driven beam buckling mechanism experienced in overseas coal mines. Analysis of the underground monitoring data also revealed that there is a good correlation between the underground measurements and simple beam theory, which has been used in the design of roof support systems for many years in South Africa. Therefore, in the development of the probabilistic approach, the deterministic approaches used in South Africa have been evaluated and improvements have been made, especially in the beam building mechanism.

Underground measurement data also showed that the maximum height of roof-softening measured in 54 sites in South African collieries is 2.5 m, which correlates well with the fall of ground data collected over 30 years in South Africa. The average height of roof-softening measured in these sites was 1.07 m.

The design approach established in this Chapter was applied to a well-defined case study in a colliery in the Witbank Coalfield, where the variations of all parameters that impact the roof and support behaviours were evident. Suspension mechanism has been used in this mine, which resulted in numerous roof falls. It has been shown using the input parameters collected from this mine that the suspension mechanism is not suitable for the conditions present. Therefore, the beam building mechanism was recommended for different risk category areas using four or five roof bolts with different lengths and row spacings.

8.2 Recommendations for future research

The following recommendations are made for future research as part of this study:

- Although there have been many studies into the support of intersections, a better understanding of rock behaviour in intersections is required.

- The effect of time is also important for stable and safer workings. Therefore, the effect of time on support performance needs to be evaluated.

- The different roof strata encountered in the coalfields are likely to have a significant influence on the deformation rates, and thus monitoring should be carried out in all the important geotechnical areas. The quantitative influence of slips, joints and other geological discontinuities is not well understood and should be evaluated.

- The Chapter on geotechnical classification techniques highlighted that borehole core based systems like the impact splitting are dependent on the quality of the core. Layers that are very weak or have very low cohesion can easily break during the drilling process. Geophysical techniques may therefore be more accurate in such cases for prediction of these layers and their accuracy and reliability need to be established. Innovations need to be made to reduce the costs of applying those techniques.

- It is recommended that further work on the effect of bolt profile on roof bolt performance be carried out, with the aim of achieving failure on the roof bolt-resin interface. It is also recommended that the quality of resin mixing should be investigated for different rib angles in order that the most effective rib angles for roof bolts can be determined. Unfortunately, because rib configurations in South African bolt types are very similar and because testing in this thesis took place in an underground environment (uncontrolled conditions), the effect of rib angle, rib height and thickness and spacing between the ribs could not be quantified. It is, therefore, suggested that these tests should be conducted in a controlled laboratory environment.

- The effect of tensioning, non-tensioning on support performance could not be established. It is suggested that a new testing procedure should be developed for testing the performance of tensioned bolts.

- The investigation into the support system design recommended that a study into the shear strength of full column resin bolt is required.

- One other important factor that affects the performance of a support system is the quality of support installation. This was not investigated as part of this thesis. New support installation techniques, such as the “spin-to-stall system”, helped collieries to improve the support installation practice. While the spin-to-stall system provides a simpler underground procedure, it is significantly more demanding on the roof bolting system components. The resin must provide sufficient time for adequate mixing and roof bolt insertion, then transform very rapidly from a liquid to a set state and develop high bond strength. The properties of the resin, the properties of the roof bolt, the breakout torque of the nut and other parameters are important in developing and optimising this new system. Development of an improved installation technique, which will minimise the human error in the installation of support and ensure all components of the bolting system are compatible, is therefore required to ensure the correct installation of support to improve the safety of the underground workforce.