THE DEVELOPMENT OF
DAPPAM,
A GLASS FIBRE CABLE BOLT

by

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B.A.Sc. , University of British Columbia, 1992

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

MASTERS OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

Department of
Mining and Mineral Process Engineering

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA
February 1995

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ABSTRACT

An iterative test program was developed between Pacific Pultrusions and the Mining & Mineral Process Engineering Department at the University of British Columbia. The program focused on the research and development of a commercially competitive composite cable bolt for mining applications.

Laboratory testing consisted of tensile, preliminary shear, compression, grout column and Instron testing in addition to observations through the use of the scanning electron microscope at the University of British Columbia. Additional laboratory testing was completed at the United States Bureau of Mines (Spokane) for the purpose of destructive tensile testing and modified shear testing. Trial installations using prototype cable bolts were completed at four mines throughout Canada.

An optimum prototype, known as DAPPAM, was developed, tested and is currently being marketed. The physical properties of the cable bolt are given. A market analysis of current cable bolt usage in Canada is presented.

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ACKNOWLEDGEMENTS

The following thesis is dedicated to my parents, Jackie and James Peterson, who, without their loving support I would not have had the aspiration or confidence to complete a Bachelors or a Masters Degree.

Special thanks to the people who contributed to the thesis from the Mining & Mineral Process Engineering Department (UBC), Metals & Materials Engineering Department (UBC), Myra Falls Mine, Dickenson Mine, Dome Mine, United States Bureau of Mines (USBM - Spokane), Thiessen Team and Pacific Pultrusions.

I am greatly indebt to John Goris (USBM) for the laboratory testing and assistance he provided. The hospitality given while I was at the USBM will always be remembered. The results presented within would not have been possible without the advice and dedication to the project as given by Charlie Gould, thank you.

Special thanks to Marina and Gordie for the help, guidance and smiles given day after day. The long nights in the laboratory went by fast as a result of the assistance given by Tina, Casper, Sandy and the liquid refreshment they provided, thanks again. The time spent constructing DAPPAM for the first trial installation was very enjoyable as a result of Erica's company. Thanks for the help. I am indebt to Pius and Sally for the day to day help and the smiles they provided.

The laboratory test program would not have been possible without the dedication and guidance provided by Frank. The delicate workmanship, hardwork and long hours given by Frank were the backbone of being able to complete such a large laboratory program in such a short time span. Thank you.

Without the opportunity given by Rimas, I would not have been inclined to complete a Masters Degree. Continually amazed by his intelligence, warmness and ability to drink beer, he is a true role model. The resourceful guidance, dedication and the freedom he has given over the past several years is reflected within the thesis. Thank you for taking the time and giving me the opportunity to further my knowledge. It will always be remembered.

Preface

The development of a commercially available composite cable bolt can be divided into three phases. Phase I (1989-1991) was sponsored by Hard Rock Mining Research Ltd. (HDRK), a consortium of mining companies including Inco, Noranda and Falconbridge. The primary goal was to evaluate composites for the purpose of pre-support utilized within a continuous hard rock mining operation. Research was undertaken at the University of British Columbia by G. Peter Mah under the direction of Dr. Rimas Pakalnis.

The results from Phase I presented a glass fibre cable bolt comprised of Polystal, a patented composite rod imported from Germany. The prototype was technically comparable to that of conventional single steel cable bolts, however high cost and low availability hindered its use as a routine method of ground support (Mah 1994).

In observing the results from Phase I, it was conceived that through extended research, an economical competitive composite cable bolt could be developed, manufactured and used as a routine method of ground support in hard rock mining.

Phase II (1991-1992) of the research program was directed at evaluating several composite materials and their modifications, in addition to defining a prototype cable bolt which had similar technical properties to that of steel cable bolts. Research was funded by the Science Council of British Columbia and was conducted at the Department of Mining & Mineral Process Engineering at UBC by Don Peterson under the direction of Dr. Rimas Pakalnis.

Phase III (1992-1993) focused on developing a locally manufactured glass fibre cable bolt which is commercially available and competitive to conventional steel cable bolts. Research was funded by the Science Council of British Columbia and Pacific Pultrusions Inc., while conducted at the Department of Mining & Mineral Process Engineering at UBC by Don Peterson under the direction of Dr. Rimas Pakalnis.

The following thesis details the progress and findings of Phase II and Phase III of the research program. As a result of the research conducted, the following advancements within the field of rock mechanics are presented:

1) A glass fibre cable bolt called DAPPAM was designed, developed and evaluated. DAPPAM is currently manufactured in North Vancouver, British Columbia and commercially available to the mining industry.
2) Critical problems with grout coverage of steel cable bolts were identified with the grout tube method of cable bolt installation. Approximately 50% of the mines in Canada which utilize cable bolt support use the grout tube method of installation.
3) A relationship between the grout strength, bond length and pull out load for conventional single steel cable bolts was identified and expanded upon.
4) Conclusions from a market survey of cable bolt usage in Canadian mines as a result of a comprehensive survey are presented.

Chapter 1

INTRODUCTION

The following chapter introduces conventional steel cable bolts as a form of rock support in addition to their applications and methods of installation. A brief history of their origin is given. The pullout mechanisms of cable bolts are discussed, in addition to the parameters which effect the performance of cable bolt support. The modes of cable bolt failure are introduced.

1.1 Cable Bolts

Reinforcing rock support consists of installing support within the rock mass (internal) or within the excavation (external) (figure 1). Internal support may be installed either after excavation (post support) or prior to excavation from an adjacent opening (pre-support). Cable bolts are a type of internal support and are generally used as pre-support. They are long, grouted, high tensile strength elements used for reinforcing and supporting the rock mass both above and below the surface in mining and civil applications (figure 2).

Cable bolts may be of any length, though for mining purposes, are generally less than 20m. One of the major advantages of cable bolts is that it is flexible and can be coiled to approximately 1.2m in diameter. This allows long support (>20m) to be installed in areas with limited head room (approximately 1.8m). The cables may be tensioned (active support) or untensioned (passive support) as is usually the case in underground mining. The cable bolt is usually made from high tensile steel and is comprised of seven wires (5.3mm diameter) per cable with an overall cable diameter of 16mm. They have an ultimate strength between 245kN to 267kN and a modulus of elasticity of approximately 203 GPa (figure 3).

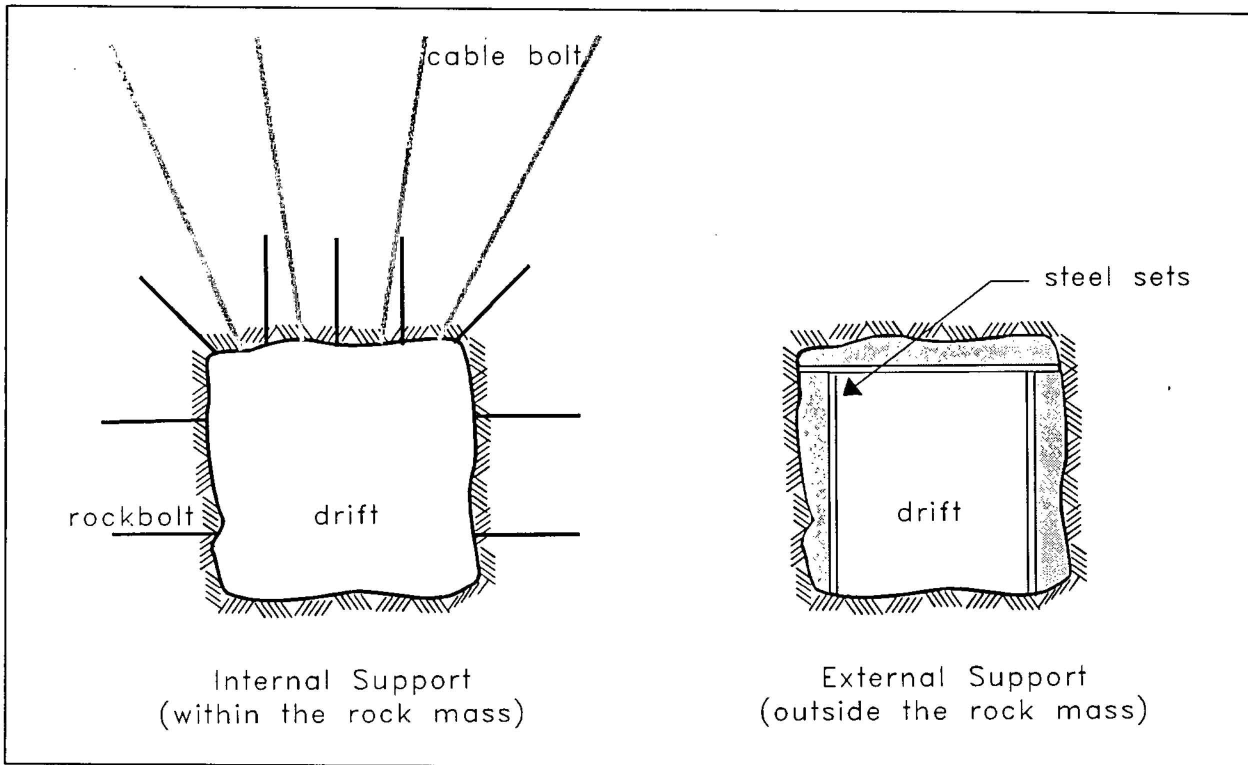


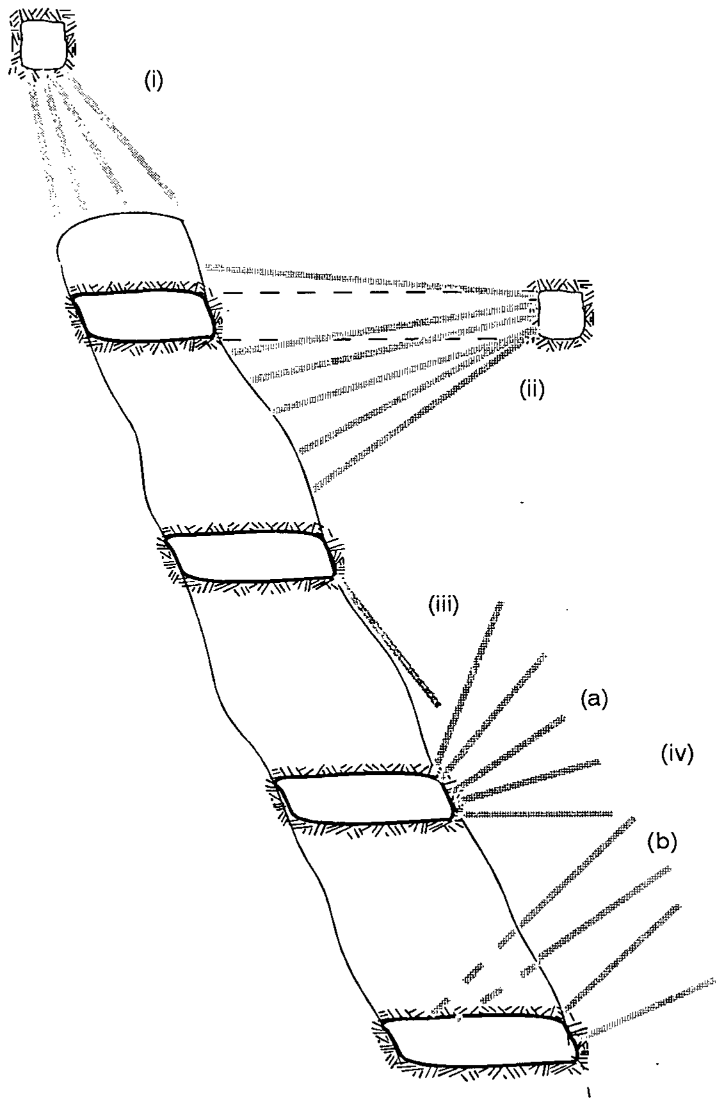
Figure 1. Internal Support vs. External Support

The principle components of a cable bolt system include:

1) Drill Hole: The diameter of the hole can vary between 40.5mm and 63.5mm and is regulated by the type of cable (size) and the size of tubes used. The hole is drilled either by a pneumatic or a hydraulic percussive drill.

2) Cable: The system utilizes one or two cables per drill hole. The cables can be installed manually by pushing them or by a cable bolt inserter. Though manual insertion is more labour intensive for the workers, it is still the preferred method. The cables can be pre-cut at specified lengths or on a continuous coil. Variations of cables are available (geometry, material, mechanical properties).

3) Grout/Breather Tube: Depending on the method of installation, grout tubes or a combination of grout/breather tubes are used to install the cement based grout paste into the hole via a grout pump. The tubes are made of high density PVC (virgin or recycled) and range in diameter from 9.5mm to 22mm.



(i) Creation of rock beam in the back by installing cable bolts.

(ii) Cable bolt support system for a hanging wall, installed from a parallel bolting drift.

(iii) Support of the hanging wall by mandolin bolting

(iv) Creation of a rock beam in the hanging wall by installing cable bolts.
   (a) Localized high density of cable bolts
   (b) Countersinking of cable bolts.

Figure 2. Underground Mining Applications of Cable Bolts

Figure 3. Conventional Steel Cable Bolt, Plate and Barrel/Wedge Assembly

Figure 4. Langford Grout Pump

4) Grout: A cement based grout is used to solidify the cable into the rock mass. Most commonly used is a normal Portland cement (type 10) mixed with water at a pre-determined water:cement ratio. Additives can be used in order to increase the grout's pumpability, strength and bleeding characteristics (Goris 1990). The mixer/pump units used for grouting cable bolts have generally been designed specifically for cable bolting purposes in order to cope with the harsh underground environment (figure 4).

5) Collar Support: Once the cable bolt has been installed, additional collar support can be utilized. This is in the form of plates, barrel and wedge, mesh and/or screen (figure 3).

1.2 History of Cable Bolts

Applications within the underground mining industry have progressed since the early sixties, when the first application saw Geco Mine in Canada install degreased hoist ropes as support (UBC, 1992). The method of support evolved from a combination of three factors:

1) The practical need to install longer ground support in poor ground conditions to ensure sound anchorage could be developed.
2) The requirement to install support as soon as possible after rock excavation was completed in order to achieve the best results possible.
3) To provide support for the larger spans being used in open stope mining.

Using discarded hoist ropes was relatively inexpensive, however, excessive labour was required to unwind and degrease the rope. In addition, the limited availability of hoist rope for mine-wide cable bolting reduced the attractiveness. Multiwire pre stressed steel tendons were introduced as an alternative, however the load transfer characteristics of the plain wire is poor due to its smooth, straight profile. Subsequently, strand cable bolts were introduced in the early

1970's (figure 5). During the late 1970's and early 1980's, cable bolt technology, which was developed for cut and fill mining, was applied to support and reinforce the large spans commonly encountered in open stoping (Windsor, 1992). Table 1 displays recent cable bolt practices for various mining operations as compiled by Pakalnis *et al*, 1989.

A review of cable bolt applications which experienced ground failures revealed that in most instances the steel cables were still intact, while the grout and rock were stripped from the cable (figure 6). Figure 7 shows the different type of failures associated with cable bolts.

This type of poor performance of strand cable bolts for larger spans was continually observed into the early 1980's, initiating several modified cable designs. These designs focused on trying to increase the cable's pull out resistance (load) by altering its configuration through the addition of buttons, coatings and unwinding the individual strands of the cable (birdcage) (figure 5).

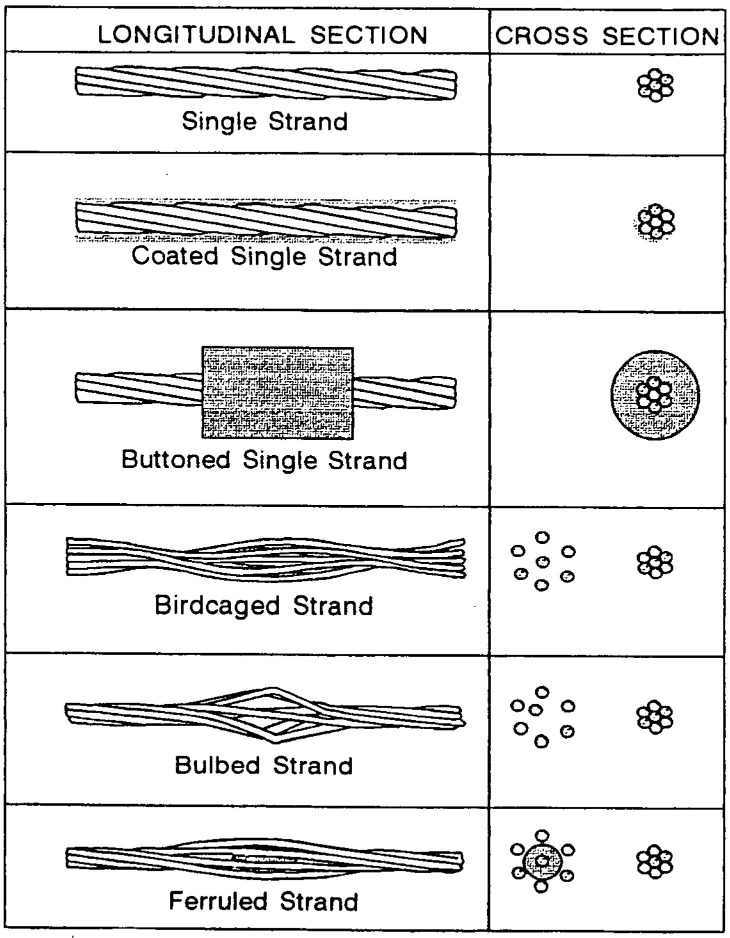


Figure 5. Types of Steel Cable Bolts (after Windsor, 1992)

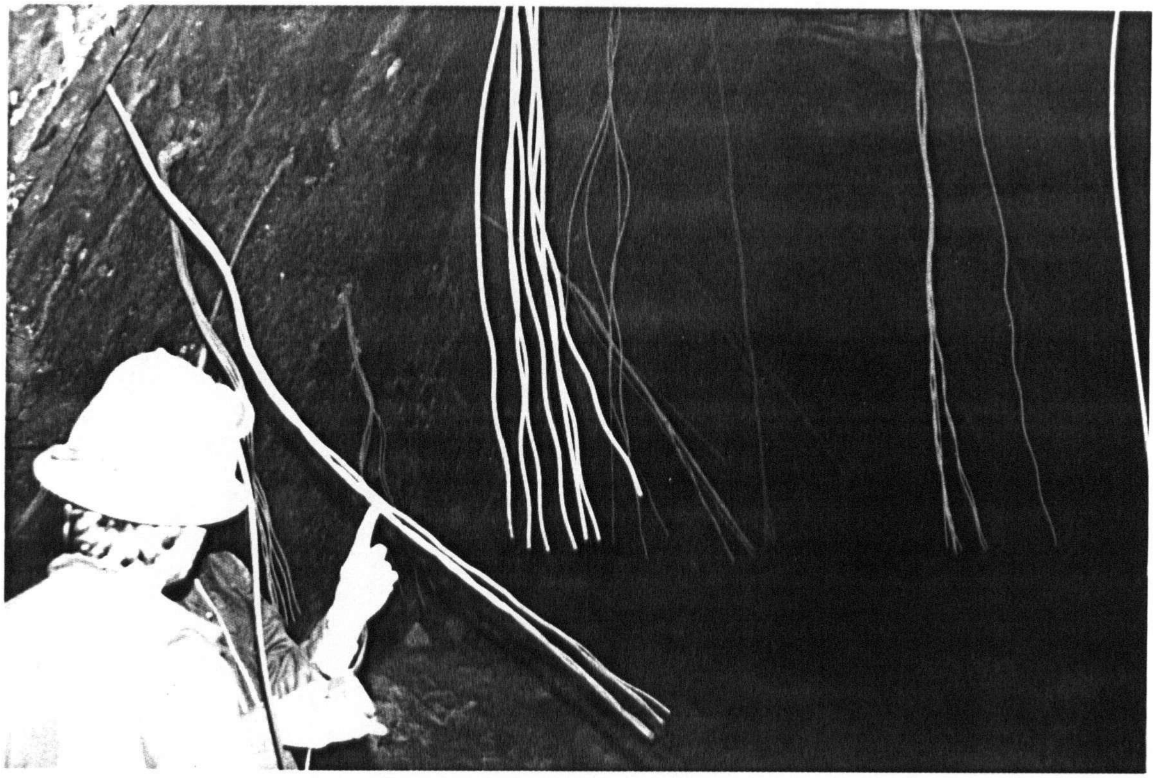


Figure 6. Typical Failure of Cable Bolt Support

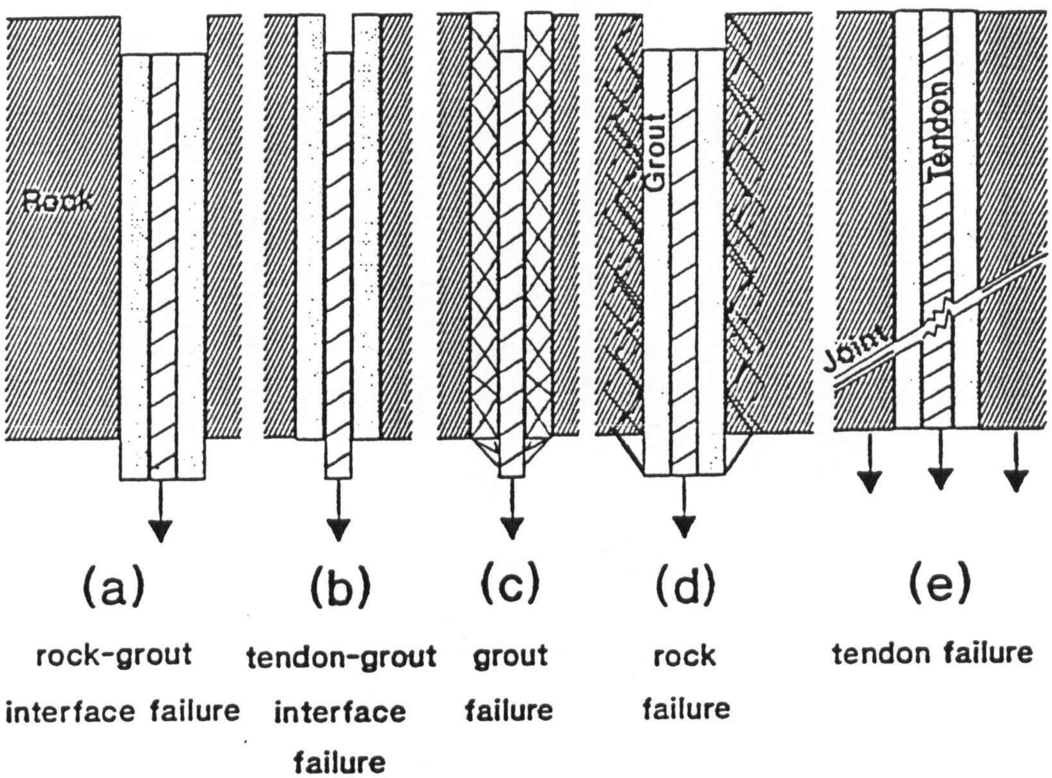


Figure 7. Possible Types of Cable Bolt Support Failure

1.3 Methods of Installation

Four variations of cable bolt installations are used within the mining industry. The method used will vary depending upon the length of hole, type of pump used, type of grout (additives) and the experience of the cable bolt crew. The methods used are (figure 8):

1) Pump grout in hole then insert cable: A medium to thick grout (0.40 - 0.35 w:c) is pumped into the hole allowing the grout to displace the grout tube. Once grouting is completed, the cable is pushed into the grout. The method is very messy for upholes and cannot be used for cable lengths greater than six meters. The method is not commonly used.

2) Grout/Breather tube method: A breather tube is installed into the drill hole along the full length of the cable. A grout tube is installed along the cable for the first half metre only. A plug is installed at the collar of the hole to prevent cement from escaping. When the grout is pumped, it is forced from the grout tube (collar) to the toe of the hole. The grout displaces air which is allowed to escape down the breather tube. When the drill hole is filled, the grout is forced down the breather tube. The operator knows the hole has been filled when grout is extruded from the breather tube. The method is not suitable for thick grout mixtures, but works well for long holes. The method is commonly used.

3) Grout tube method: A grout tube is installed into the drill hole along the full length of the cable. Grout is then pumped up the tube, filling the drill hole from the toe towards the collar. The grout tube is left within the hole. The hole is considered filled when grout is extruded at the collar of the hole. No plug or breather tube is required for this method, making it a fast and low cost method of installation. The method requires the use of a thick grout and an adequate pump which can achieve sufficient pumping pressures. Cement additives are required to

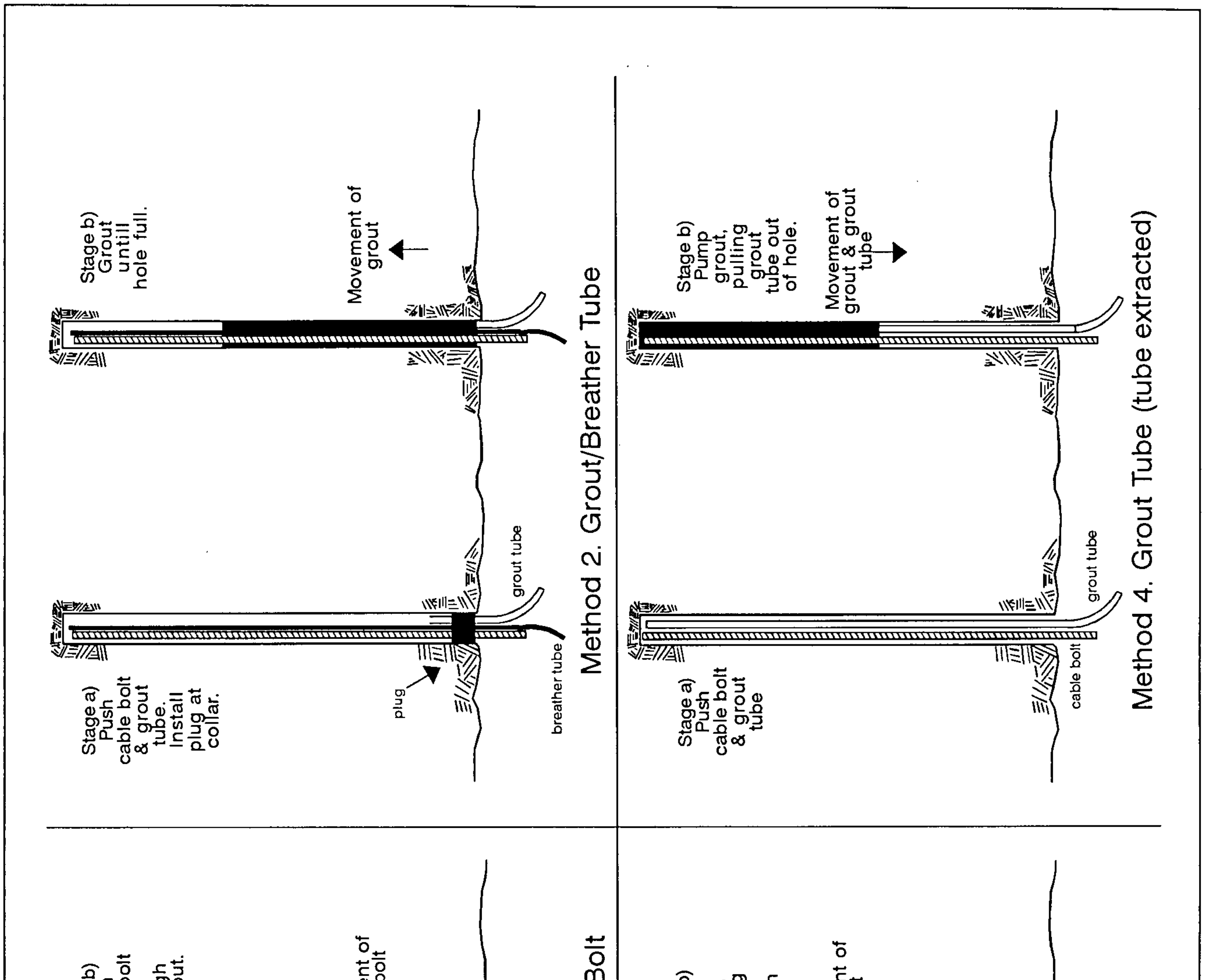


Figure 8. Methods of Grouting Cable Bolt Support

insure high grout quality after pumping. The method has become very popular with the recent introduction of high quality pumps to the industry.

4) Grout tube method (tube extracted): The method is similar to method 3, grout tube method, with the exception that the grout tube is extracted from the drill hole as the grout is pumped into the hole. The grout displaces the tube to a large extent, however operator experience is necessary to retract the grout tube at the correct speed to insure air voids are not introduced into the grout column. This method is utilized by the Tamrock Cable Bolter, a machine which mixes the grout, pushes the cable and pumps the grout, while the operator is housed in a climate controlled cab. Due to the high capital cost of the cable bolt machine, very few are currently used.

1.4 Pullout Mechanisms of Cable Bolts

The working principle of a cable bolt is that the load generated from the rock mass must be transferred through the grout to the cable bolt. Depending on local conditions, this load will be in the form of an external tensile force, a shear force, torque, or a combination thereof (figure 9). These external forces are transmitted to the cable creating internal radial and hoop forces within the grout. This is known as the load transferring *mechanism,* from external (outside the drill hole) to internal (inside the drill hole). Figure 10 shows a pull test sample after being loaded having fractures within the grout as a result of radial and hoop forces. The load transferring mechanisms for different configurations of cable bolts are the same.

Once the external load is applied to the cable bolt, the support system exhibits load carrying capacity by utilizing several *methods of resistance* to the loading force. These are called the load resistance *methods* and when combined, create the total resistance force developed by the support system. The degree in which each method of resistance contributes to the total resisting force varies depending on the configuration of the cable bolt.

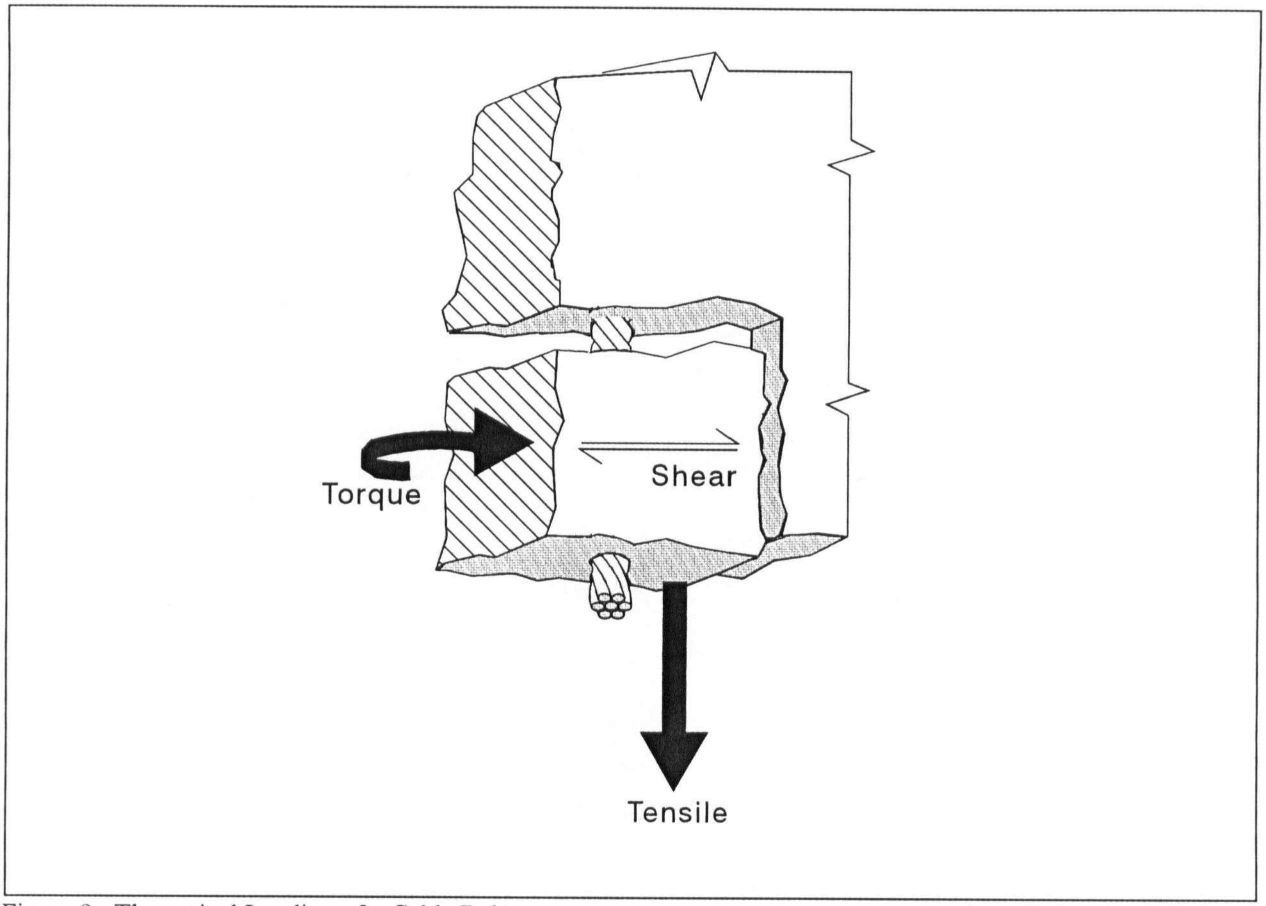


Figure 9. Theoretical Loading of a Cable Bolt

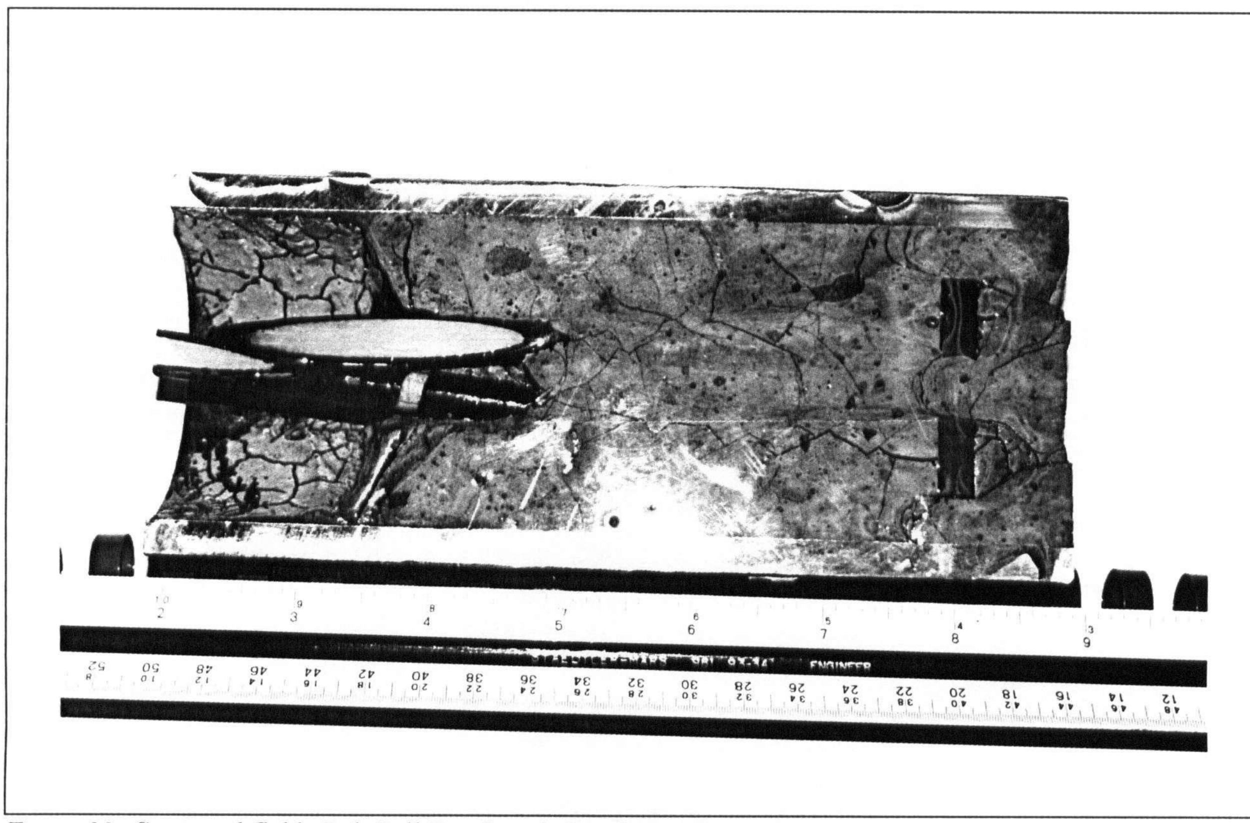


Figure 10. Sectioned Cable Bolt Pull Test Sample Displaying Grout Fractures

The methods of load resistance are:

1) Cohesion between the cable and grout
2) Friction due to the micro-interlock between the steel/composite and grout
3) Friction due to the macro-interlock between the cable configuration and grout (mechanical interlock)
4) Dilation caused by grout movement along the cable results in a normal force acting on the grout and cable (Goris, Pakalnis 1992)

Most of the cable bolts installed in underground mining applications are installed untensioned (passive system) and require movement of the rock mass to initiate a load onto the cable. When the applied load and cable/rock displacement are constantly monitored, a characteristic graph is created. This graph can be broken down into four distinct stages, as shown in figure 11.

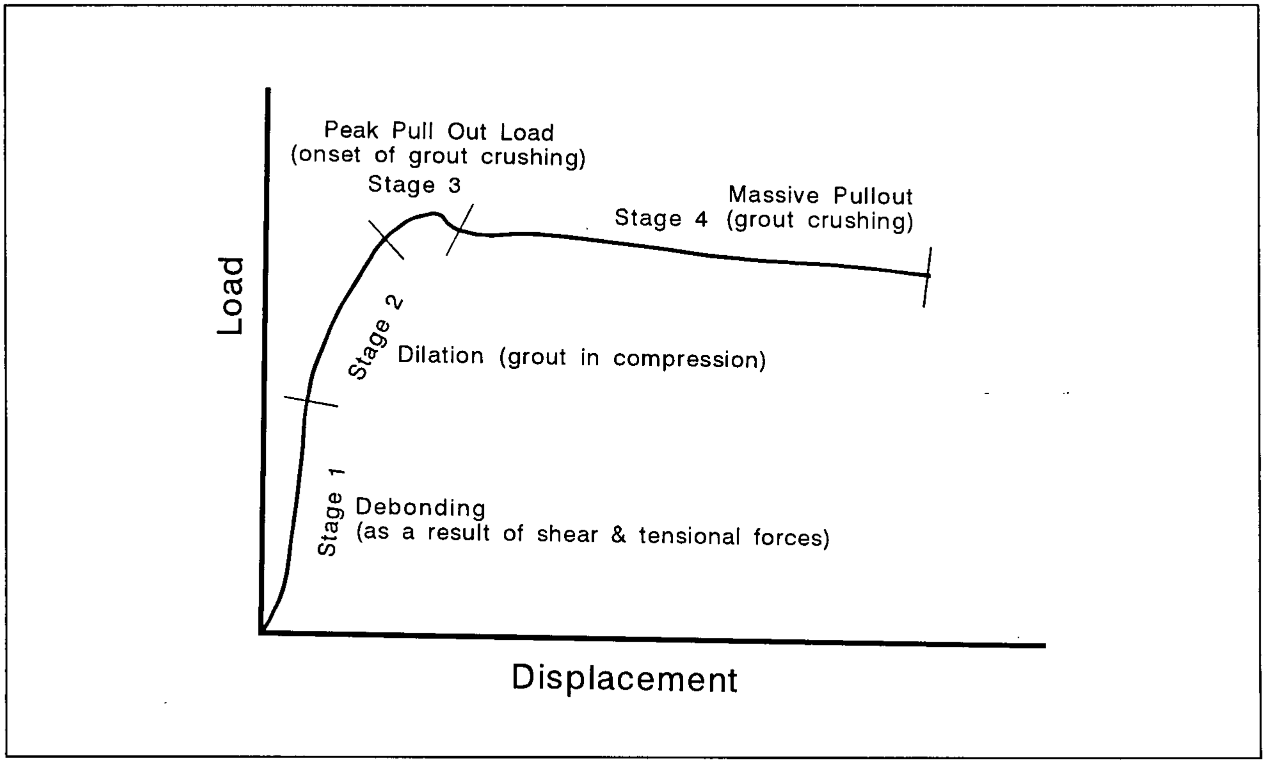


Figure 11. Tenisle Loading of a Cable Bolt in Laboratory Conditions

The four stages of theoretical cable bolt loading (pure tensile) can be best described when a joint in the rock mass opens, initiating a load onto a cable bolt which passes through the joint plane. The resisting force developed by the cable bolt is a function of displacement (among other factors) between the rock mass and cable.

Stage 1: When initial loading of the cable occurs, a tensile and shear stress occurs at the grout-cable interface. The tensile stress is a result of the cable decreasing in diameter due to elongation caused by the pull out load, and lasts until progressive breaking of the cohesive bond at the cable-grout interface occurs (debonding). This will first occur on the segment of cable closest to the rock joint where joint separation is taking place, and will propagate along the cable away from the joint in both directions (figure 12)(Milne, 1993). Debonding is a result of the applied shear and tensile stress at the grout-cable interface.

Stage 2: Once debonding has occurred, pull out resistance of the cable bolt is dependent on friction (micro and macro) and dilation. Mass cable bolt displacement does not occur at this stage, nor does the peak pull out load of the cable bolt.

Stage 3: As displacement between the cable and rock mass continues, the cable bolt will begin to shear some of the grout particles known as flutes. Flutes are formed when the grout solidifies around the perimeter of the individual wires which make up a cable (figure 13). The grout flutes are compressed and crushed, utilizing the compressive strength of the grout. This increases the lateral pressure on the wall of the hole and an equal but opposite force is directed towards the cable (dilation) increasing the cable's frictional resistance (figure 14). These forces reach a peak when the optimum area of the grout around the cable is crushed and the peak pull out load of the cable bolt is achieved.

Stage 4: Immediately following the peak pull out load, massive displacement between the cable bolt and grout occur. From visual observations, the grout within the flutes remain undisplaced with respect to the cable bolt, while completely separating and displacing from the remaining grout. A general decrease in pull out load is experienced in this stage.

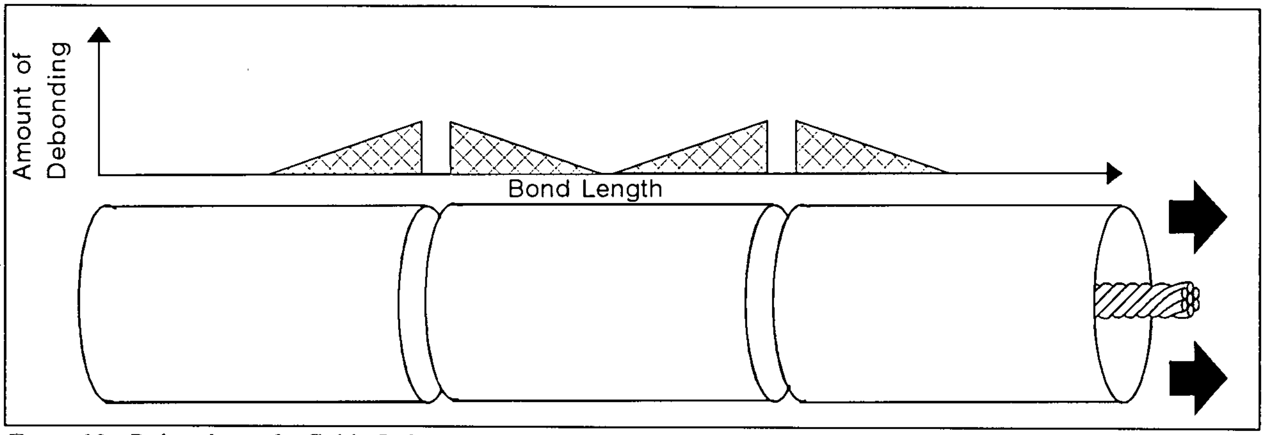


Figure12. Debonding of a Cable Bolt

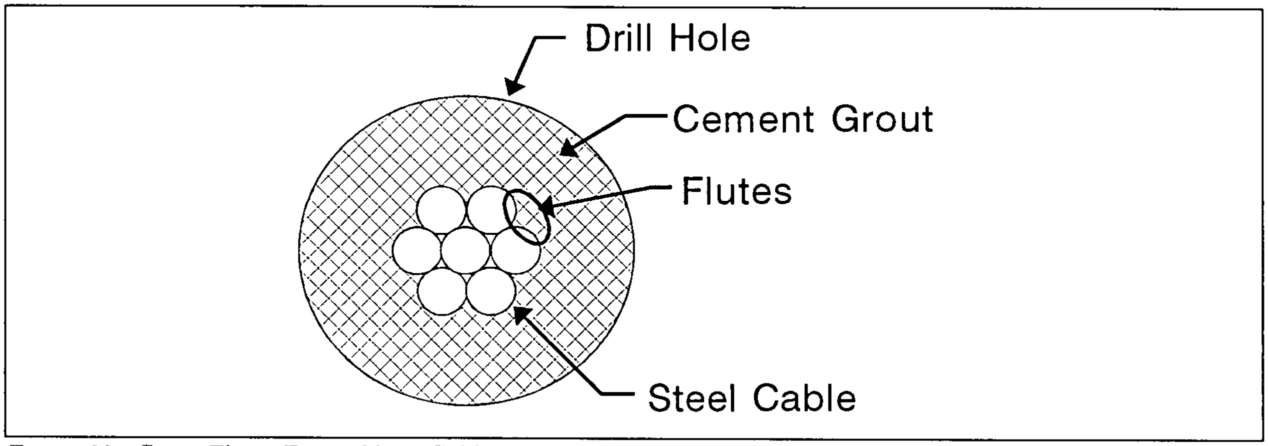


Figure 13. Grout Flutes Formed by a Cable Bolt

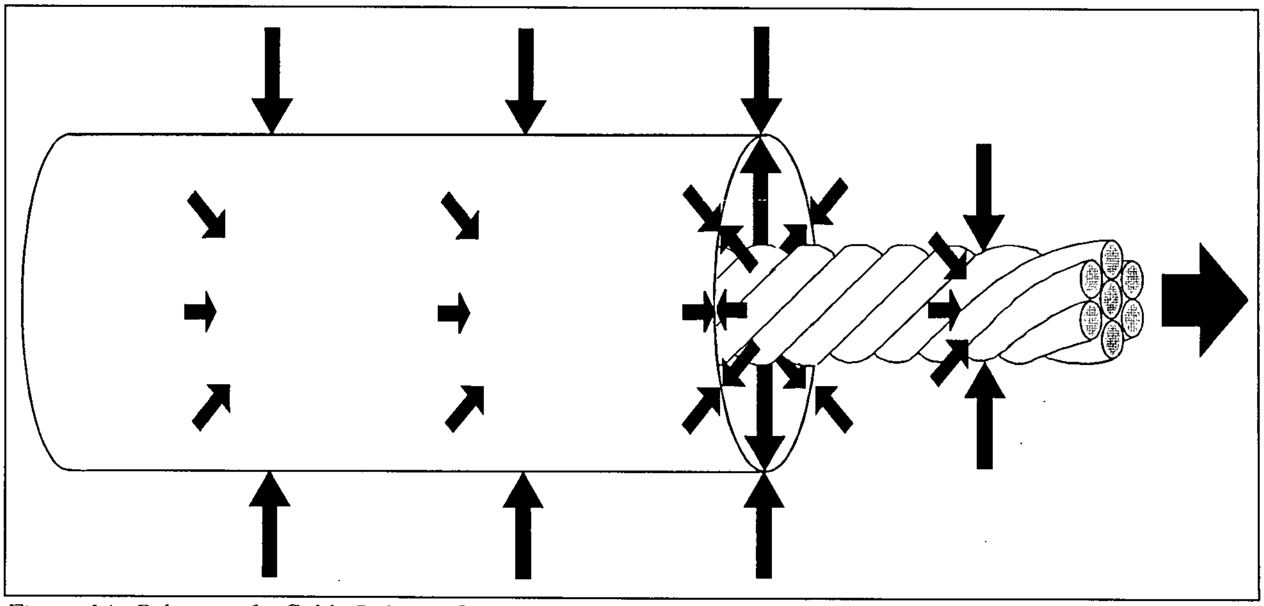


Figure 14. Dilation of a Cable Bolt (UBC, 1992)

1.4.1 BOND LENGTH

The length at which a block of rock is grouted to the cable bolt may be defined as the bond length for that specific piece of rock (figure 15). A relationship exists between the pull out load (failure load) and the bond length. For a conventional steel cable bolt, this relationship is linear as defined by Goris, 1990 (figure 16). The cable bolt support system will experience one of four modes (figure 17). The modes are:

Mode 1) Failure of the cable. When a load is applied to a cable bolt from a piece of rock which has sufficient bond length, a continued increase in pull out resistance from the cable bolt is experienced until the applied load exceeds the tensile strength of the cable, resulting in a tensile failure of the cable bolt. When the cable fails, the system will have reached its ultimate pull out load (equal to the cable's ultimate tensile strength). The minimum bond length which is sufficient for the cable bolt to achieve its ultimate tensile strength is called the critical bond length (as defined in figure 17).

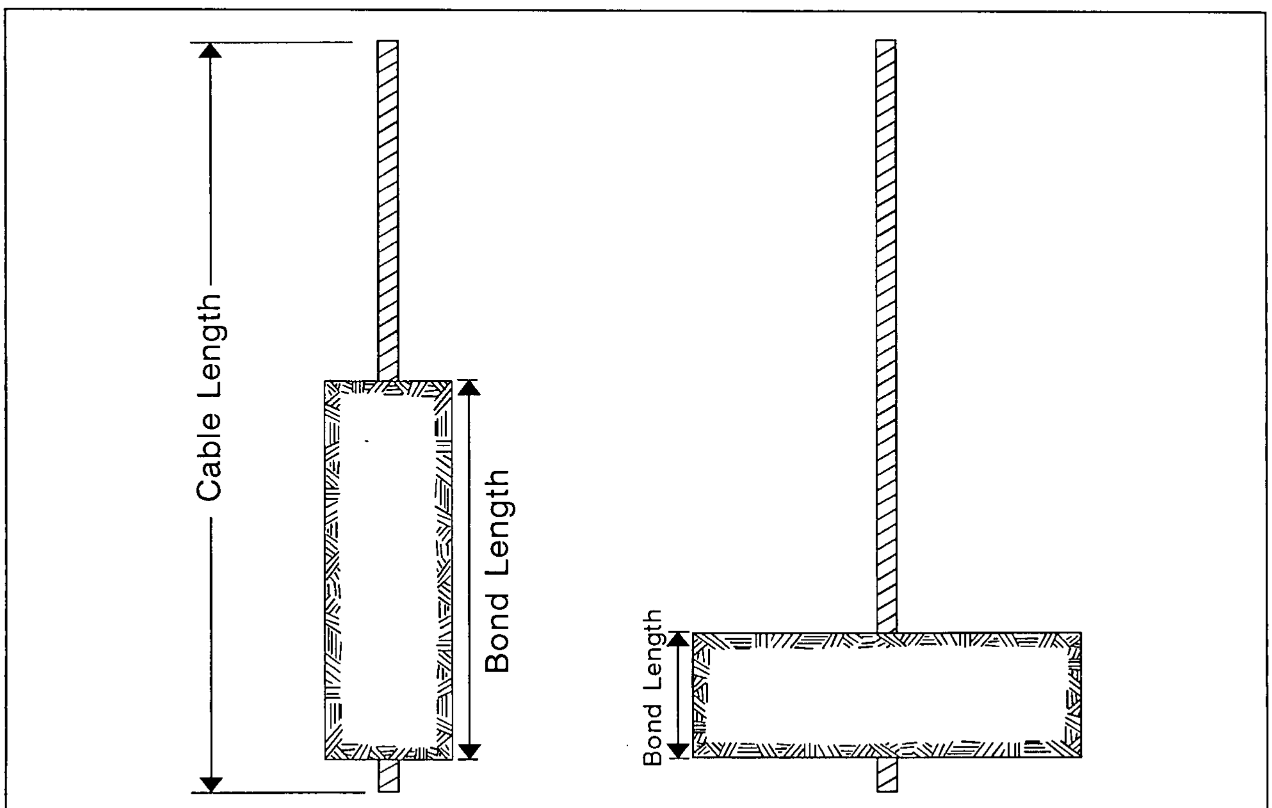


Figure 15. Bond Length

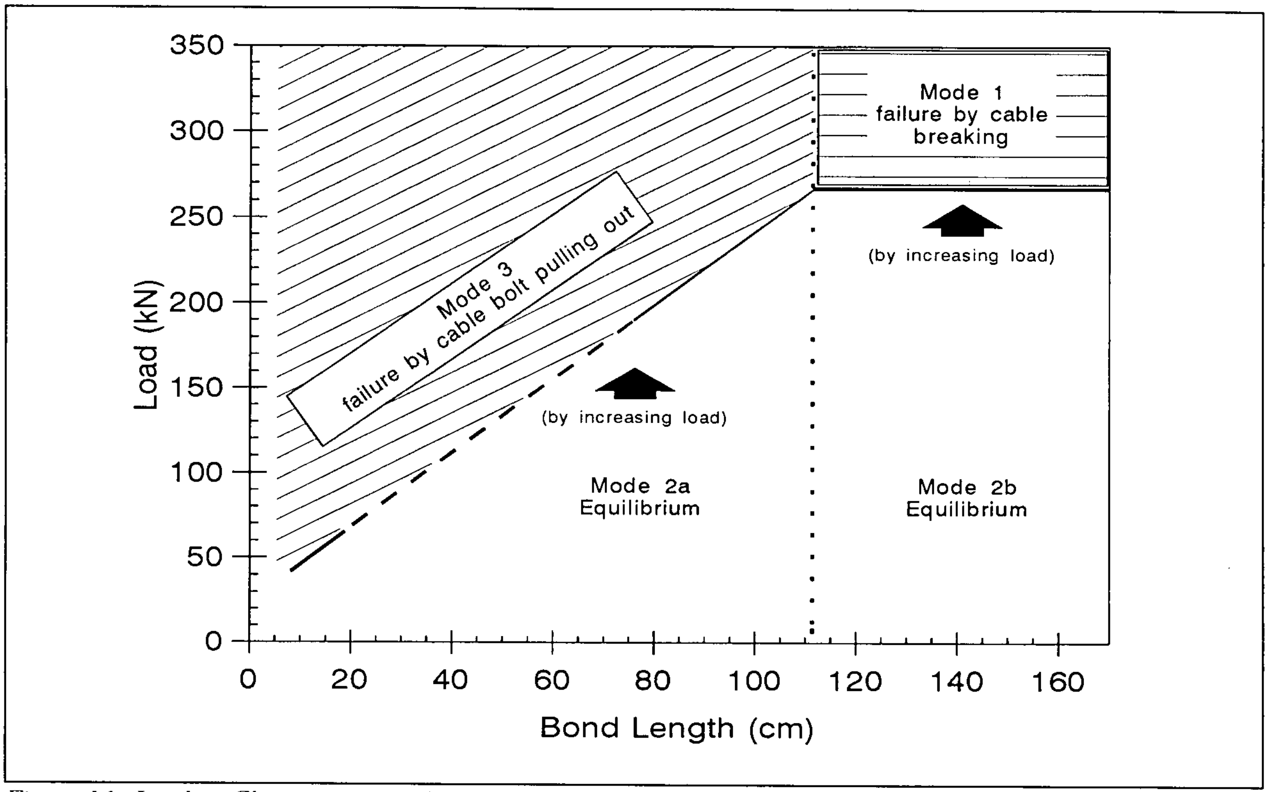


Figure 16. Loading Characteristics of a Steel Cable Bolt (modified after Goris, 1990)

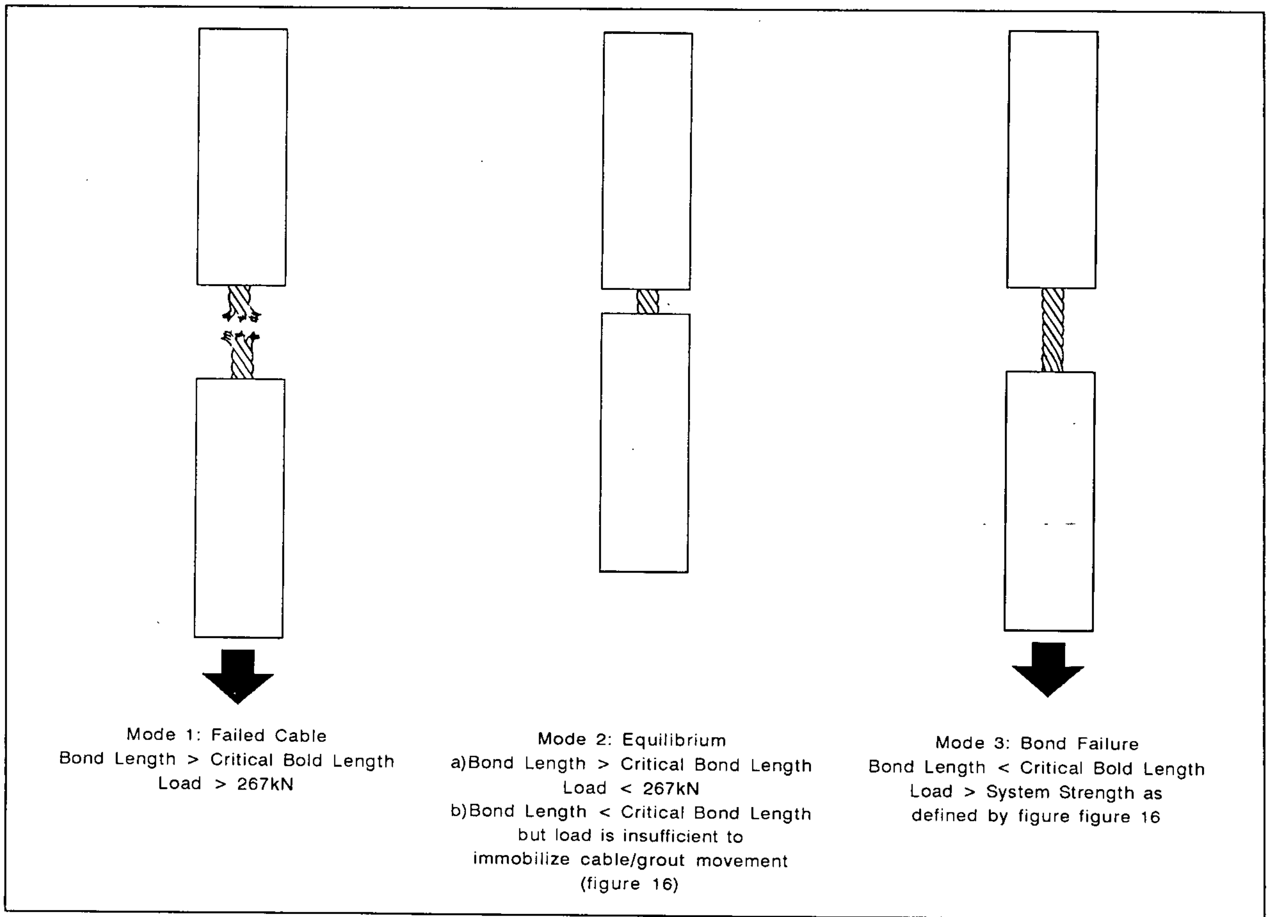


Figure 17. Four Stability Modes of Cable Bolt Support

Mode 2a) Equilibrium. When the bond length is less than the critical bond length and the applied load is insufficient to immobilize the cable bolt (phase IV), the support system is in equilibrium. The amount of applied load needed to immobilize the cable bolt is a linear relationship as defined in figure 17. If the applied load increases so it is higher than what the bond length can support, mode 3 will be experienced and the cable bolt system will fail by having the rock stripped from the cable bolt.

Mode 2b) Equilibrium. When the bond length is greater than the critical bond length, but the applied load is less than the cable's ultimate tensile strength (single steel ≈ 267kN) the support system will be in equilibrium and will not fail. The length of cable subjected to loading (strain) is a linear function dependent on load (among other factors). If the applied load increases higher than the cable's ultimate tensile strength, mode 1 will be experienced and the cable bolt will fail.

Mode 3) Pull out failure. When the bond length is less than the critical bond length and the applied load is higher than the resistance strength determined by the bond length, the support system will fail by having the rock/grout stripped from the cable. The load at which failure occurs is dependent on the same linear relationship as defined in mode 2a (figure 17). The same type of failure will be experienced regardless if the applied load is larger than the cable bolt's tensile strength, since the bond length is less than the critical bond length.

In addition to bond length, the load carrying capacity of the cable bolt system is dependent on:

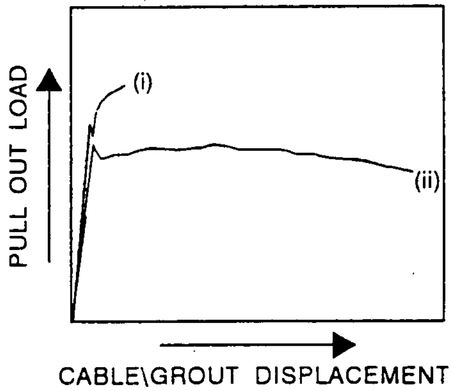
1) modulus of the rock
2) strength of the grout

3) strength of the cable

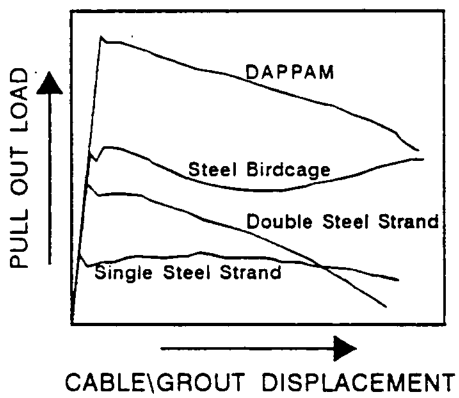
4) mechanical bond between the grout and cable

5) mechanical bond between the grout and rock

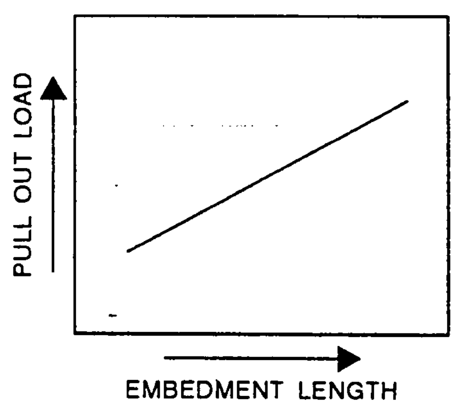
Figure 18, 19 and 20 shows the relationship of cable bolt pull out to selected criteria.



a) *Critical Bond Length (CBL):* If the bond length is > than the CBL, failure of the system will generally occur through cable failure, depicted by small displacements as shown by (i). If the bond length is < than the CBL, failure of the system will generally occur through cable/grout interface failure, depicted by large displacements as shown by (ii).

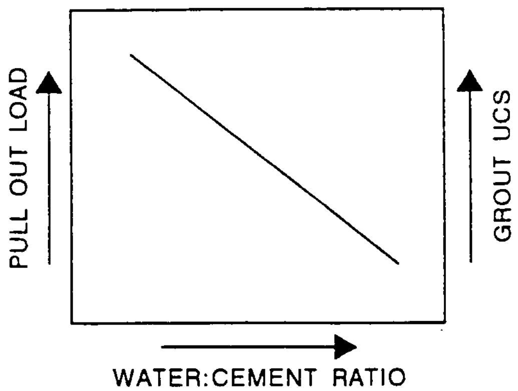


b) *Cable Configuration:* Cable configuration and surface roughness effect the system's pull out load significantly. Residual loads after the cables' peak pull out load are characteristic of that particular type of cable. (Goris, 1990)

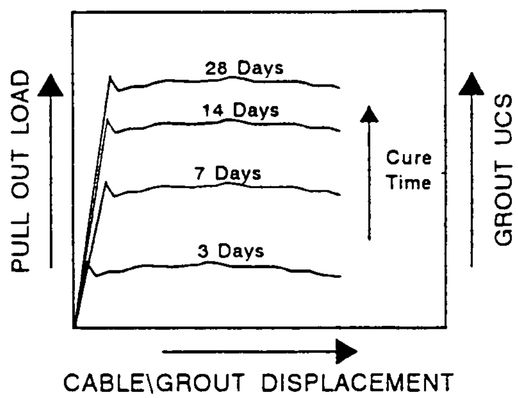


c) *Bond Length:* As bond length increases the cable's pull out load increases. The function which relates bond length and pull out load varies with respect to the type of cable used. (Goris, 1990)

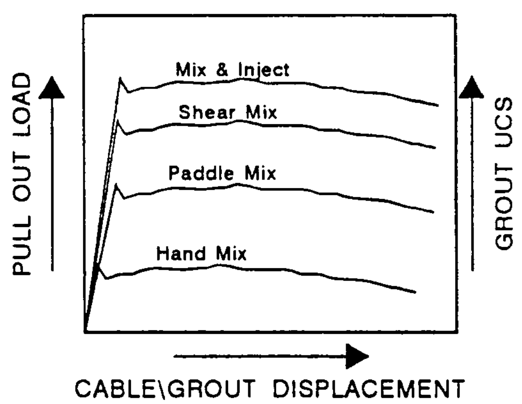
Figure 18. Cable Bolt Pull Out Relationships



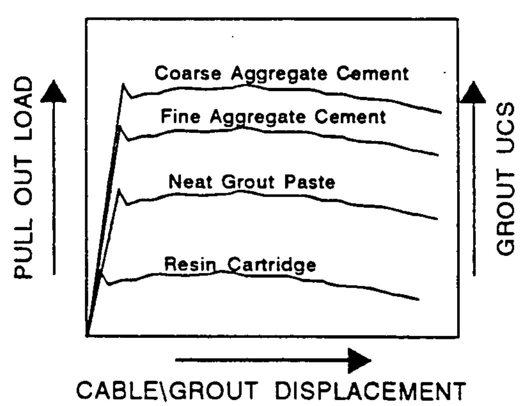
d) *Water:Cement Ratio:* As the water content increases (water:cement ratio) the compressive strength of the grout decreases. As a result, the cable bolt's pull out load decreases. (Goris, 1990)



e) *Cure Time:* The compressive strength of the grout is dependent on its cure time. In turn, the cable bolt's pull out load is also effected. (Reichart, 1992)

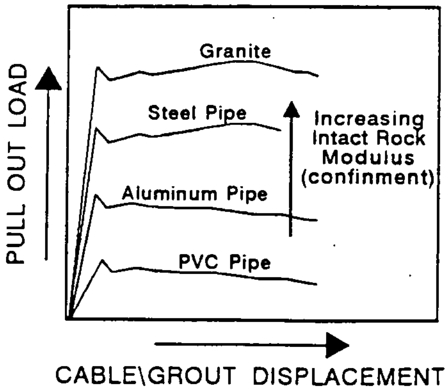


f) *Method of Mixing:* The grout's compressive strength is dependent on the method of mixing, duration of mixing, etc. As a result of the varying grout strengths, the cable's pull out load is effected. (Reichart, 1992)

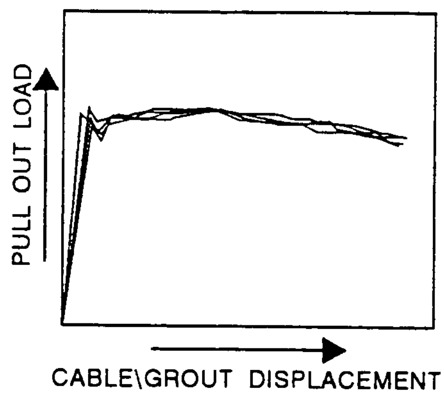


g) *Grout/Cement Type:* The compressive strength of the cementatious material depends on its composition. The cable's pull out load will in turn be effected. (Hassani, *et al*, 1992)

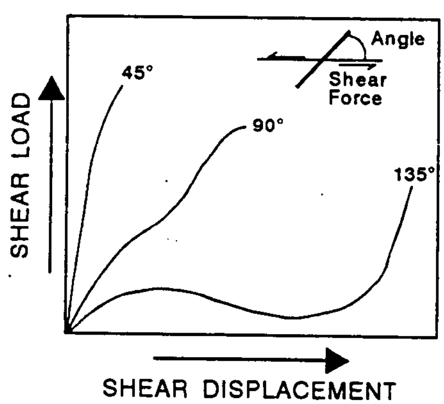
Figure 19. Cable Bolt Pull Out Relationships



h) *Confinement:* The confinement offered by the surrounding rock mass effects the support system's pull out load. Increasing the confinement of the rock mass increases the cable's pull out load. (UBC, 1992)



i) *Rate of Loading:* As the rate of loading changes, the cable's pull out load is unaltered. (Hassani *et al*, 1992)



j) *Shear Strength:* The cable bolt's performance varies depending on the orientation of the load with respect to the cable, i.e. pure tensile 0°. The cable's pull out load and displacement are effected. (Fuller, 1983)

Figure 20. Cable Bolt Pull Out Relationships

Chapter 2

COMPOSITE MATERIALS

The following chapter introduces basic concepts and definitions which pertain to the composite materials used within the test program for the development of a glass fibre cable bolt.

2.0 Composite Materials

The definition of composites may be restricted to those materials which contain a reinforcement (such as fibers) supported by a binder (or matrix) material (Reinhart *et al*, 1988). Load applied to the composite is transferred by the matrix material to the reinforcement fibers through interfacial shear. For mining applications which involve the composite being grouted into the rock mass, a third component, the surface coating, is added to the composite structure to provide a preferred surface which allows sufficient bond strength between the chemical/cement based grout and to provide protection from the immediate environment (figure 21).

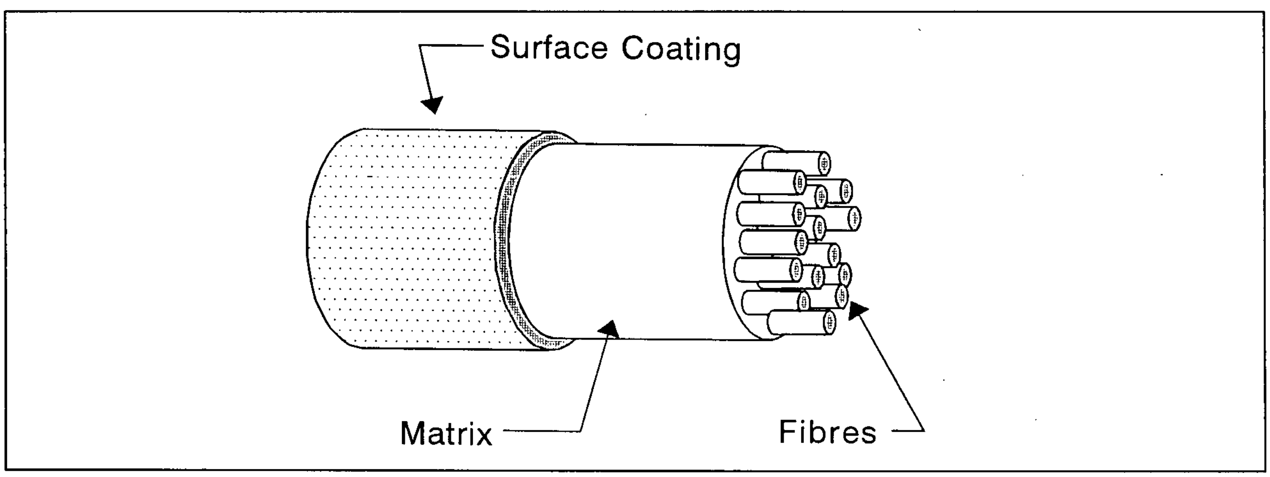


Figure 21. Composite Structure

2.1 Fibers

There are two classes of fibre reinforced polymers, continuous and discontinuous. Work conducted in Phase I of the project by Mah (1994) concluded that continuous fibres are better suited than discontinuous fibres when used in the construction of ground support. This is a direct result of the composite's physical properties.

Continuous fibre composites utilize fibers with lengths comparable to the overall composite length. Unlike discontinuous fibers, any further increase in fibre length does not change the composite mechanical properties. In a continuous fibre reinforced composite, the fibers provide virtually all of the load carrying characteristics (stress-strain analysis) of the composite, the most important of which are strength and stiffness. The multiple fibers in a composite make it a very redundant material because the failure of even several fibers results in the redistribution of load onto other fibers rather than a catastrophic failure of the part.

2.1.1 FIBRE TYPE

Glass fibers are unique materials that exhibit the familiar bulk glass properties of hardness, transparency, resistance to chemical attack, stability and inertness, as well as fibre properties of strength, flexibility, lightness of weight, and process ability (Reinhart 1988). There are several glass fibre types with differing compositions that reflect the chemistry needed to provide specific chemical and/or physical properties.

1) E-glass is used as a general-purpose fibre when strength and high electrical resistivity are required.
2) S-glass demonstrates high strength and is therefore used in applications where very high tensile strength is required.
3) C-glass (or ECR) is often used in composites that contact or contain acidic materials

Composite products used in Phases II and III used either E-glass or ECR glass within their composite structure.

2.2 Matrix

Numerous materials used as a matrix exist, but not all are suitable for mining applications. The matrix must be low cost, easily cut, versatile, low to medium temperature resistant and low density. For mining applications, the low cost of the matrix material is important in order to remain commercially competitive. The matrix resin provides five essential functions. These include (Reinhart 1988):

1) bind the fibers together
2) maintain the pultruded profile
3) transfer the load to the fibers through interfacial shear
4) protect the fibers from the surrounding environment, including corrosion
5) protect the fibers when the composite is in compression (support)

In addition, the matrix keeps the reinforcing fibers in the properly oriented position so they can carry the intended loads, distribute the loads more or less evenly among the fibers, provide resistance to crack propagation and damage, and provide all of the interlaminar shear strength of the composite.

Since material cost of pultrusion accounts for the largest percentage of the overall fabrication cost, resin cost becomes particularly important to price sensitive applications, such as ground support. Previous work completed in Phase I (Mah 1994) has concluded that for either physical reasons or cost, the best suited polymer for ground support applications are thermosets. Three types of thermoset resins were used within products tested in Phase II.

2.3 Composite Surface Coatings

Surface coatings can be added to the composite for various reasons. For cable bolting, it is important that the surface coating provides a preferred bonding surface for the cement based grout. In addition, it provides protection against mechanical damage (impact) and corrosion. For mining applications, the surface coating can be tailorable, yielding a desired surface roughness (altering the bond strength). This can be completed at a cost considerably lower than what surface modifications to steel cable bolts can be completed at. Three types of resins have been used for surface coatings on products for mining applications:

1. polyethylene
2. nylon (polyamide)
3. epoxy

2.4 Manufacturing Composites By Pultrusion

Pultrusion is a continuous fabrication technique which combines the fibres and resin into a composite material (figure 22). The raw materials are pulled through a profile forming dye yielding a product with constant cross sectional area. Multi-profile dyes are available to increase production rates while decreasing operating costs (figure 23). Product sizes available may range from a thickness of 2mm to 76mm, a width of 2mm to 1000mm and may vary in length.

Surface coatings are applied on the production line, but generally after the initial pultrusion process. The advantages of pultrusion are low capital outlay, low cycle times and simplicity of operation. It is the most suitable fabrication technique for commercially produced cable bolts. Figures 24 and 25 show the pultrusion of rods used for laboratory testing in the development of a glass fibre cable bolt.

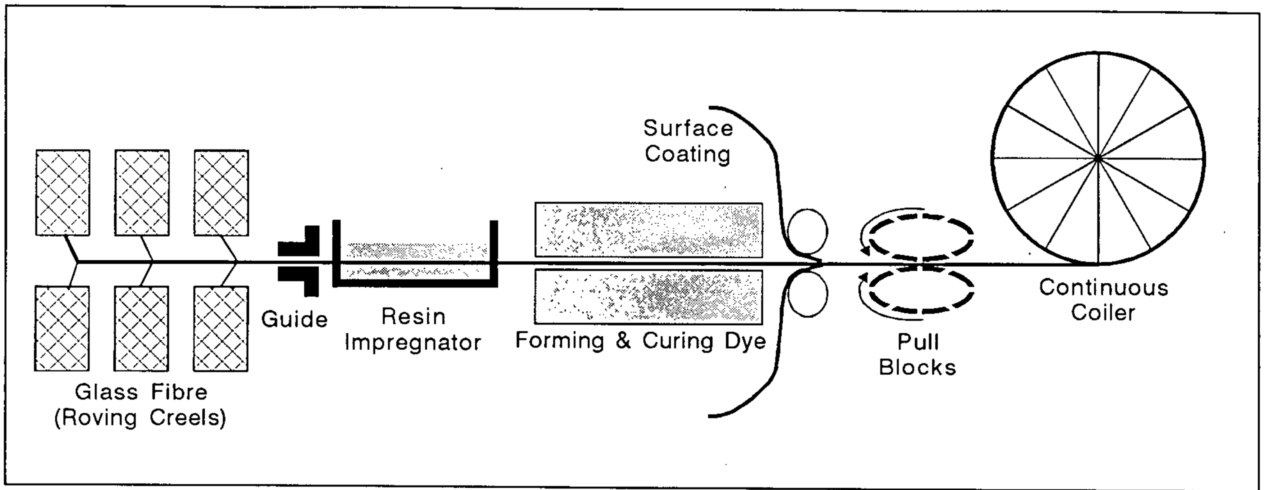


Figure 22. Pultrusion Process

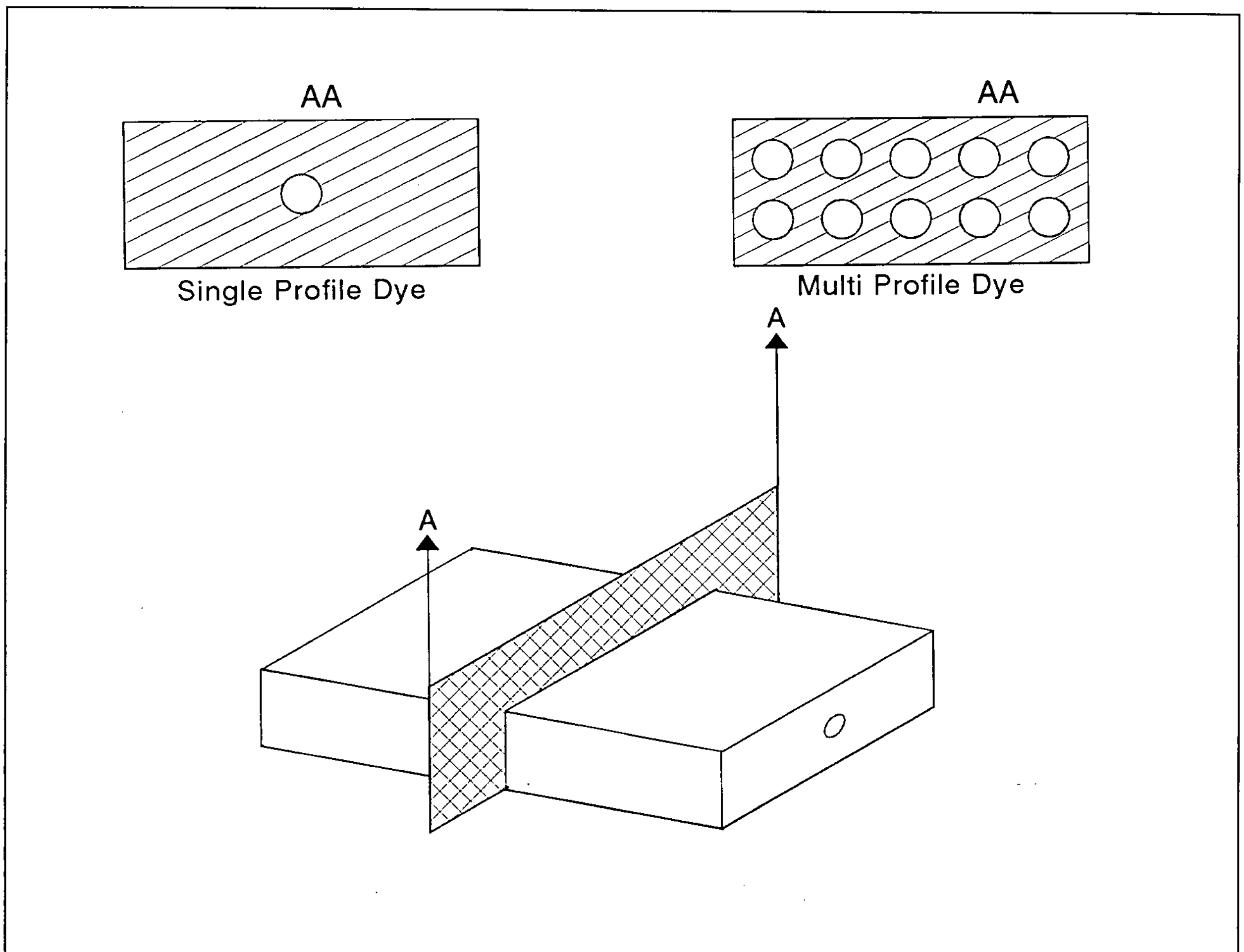


Figure 23. Single & Multiple Dyes

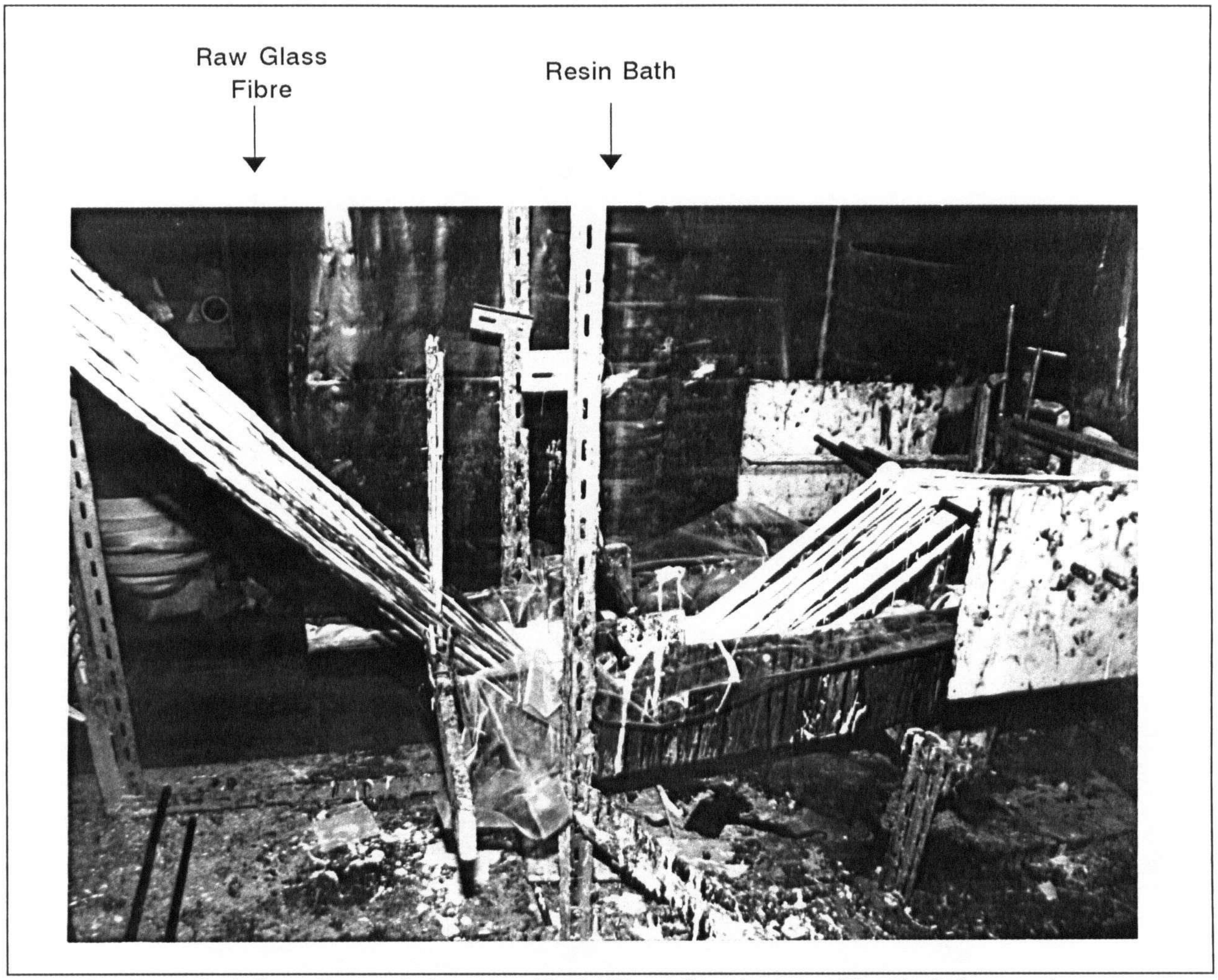


Figure 24. Resin Bath Stage During Pultrusion of Rods (Photo Compliments of Pacific Pultrusions)

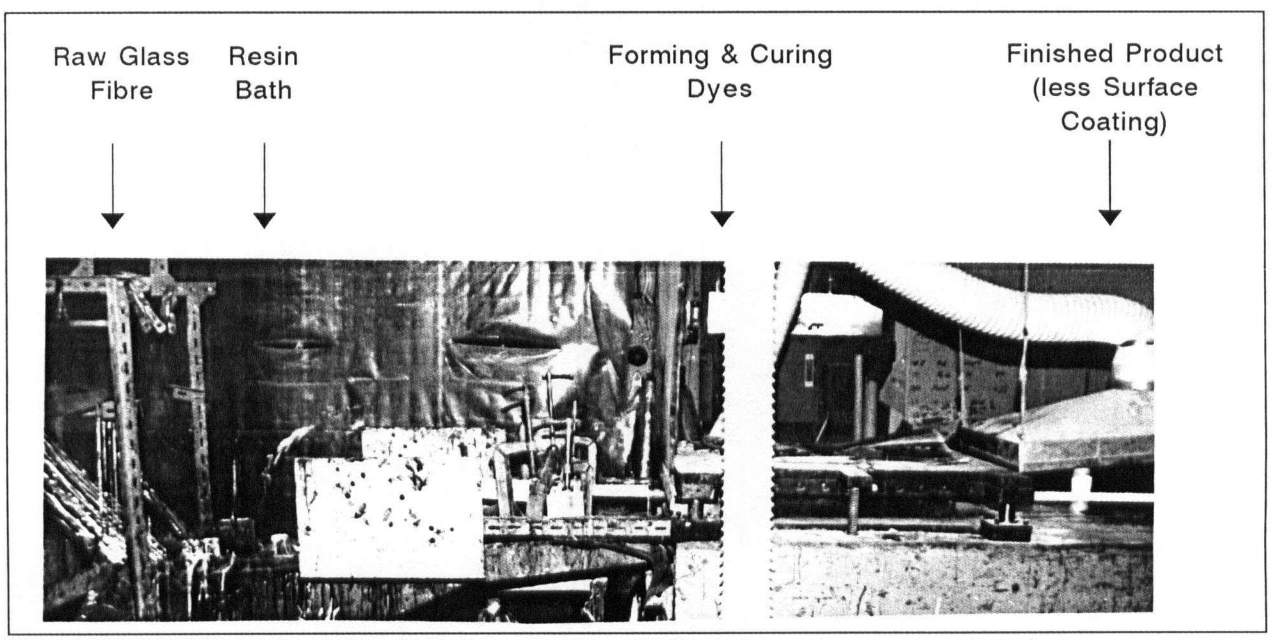


Figure 25. Pultrusion of Rods Used in Laboratory Testing (Photo Compliments of Pacific Pultrusions)

Chapter 3

UBC LABORATORY TEST PROGRAM

The following chapter discusses the test apparatus; sample preparation and test procedures for the pull test and preliminary shear tests conducted at UBC Mining & Mineral Process Engineering Department.

3.1 Laboratory Testing

Laboratory testing to evaluate composite materials and cable bolts were conducted primarily at the University of British Columbia within the Mining and Mineral Process Engineering Department. The tests included pull tests (tensile testing), preliminary shear testing, grout compression testing and grout column testing. Additional testing was completed within the Metals and Materials Department at UBC. These tests include Instron (tensile) testing and Scanning Electron Microscope (SEM) observations. In addition, testing was completed at the United States Bureau of Mines (Spokane) under the direction of John Goris. These tests include destructive pull tests and modified shear testing. Approximately 95% (in excess of 200 tests) of all laboratory testing was conducted within the Mining and Mineral Process Engineering Department at UBC.

During the onset of the test program, several questions were raised concerning the evaluation of the results. Due to the excessive time and expense of the pull tests, the sample populations were kept to a minimum (discussed in 3.1.2.1). Test results were scrutinized through the application of two methods of analysis.

1) Samples were visually observed during and after testing for any irregularities. These included inadequate grout coverage of the cable, improper anchorage within the pull test machine and cable defects. Samples were periodically sectioned for internal observations.
2) A statistical evaluation of the results was completed to determine if the results are within a predetermined variance and if the samples were from the same sample population.

To ensure consistency, the coefficient of variation was computed for each of the data sets. If the coefficient of variation (standard deviation divided by the mean) was below or equal to 15 percent, then the results were considered to be comparable. If the coefficient of variation was higher than 15 percent, the results and samples were re-examined for possible test/preparation errors. If necessary, the test series would be duplicated and tested again, however, this was not necessary throughout the duration of the test program. The cut off value of 15 percent was recommended by Goris from the USBM, (Goris 1990). Once sufficient test results were accumulated from the test program, the value of 15 percent was evaluated and found to be adequate for the pull tests.

Additional statistical evaluation consisted of applying the Students T-test in order to determine if two data sets came from the same population. All analysis used a significance level of 5 percent in comparing the average maximum pull out loads. The guidelines for statistical evaluation were adopted from methods utilized at the USBM by Goris (Goris 1990).

3.1.1 TEST APPARATUS

3.1.1.1 UBC Pull Test

The basis of pull testing is that a tensile force is applied to a cable which is grouted within a pipe/pipes. This represents a grouted cable within the rock mass (figure 26). This constitutes a "sample", in which various parameters, such as bond length, the grout's water:cement ratio, etc. can be tested. The cable/pipe displacement and the tensile force are continuously recorded throughout the test.

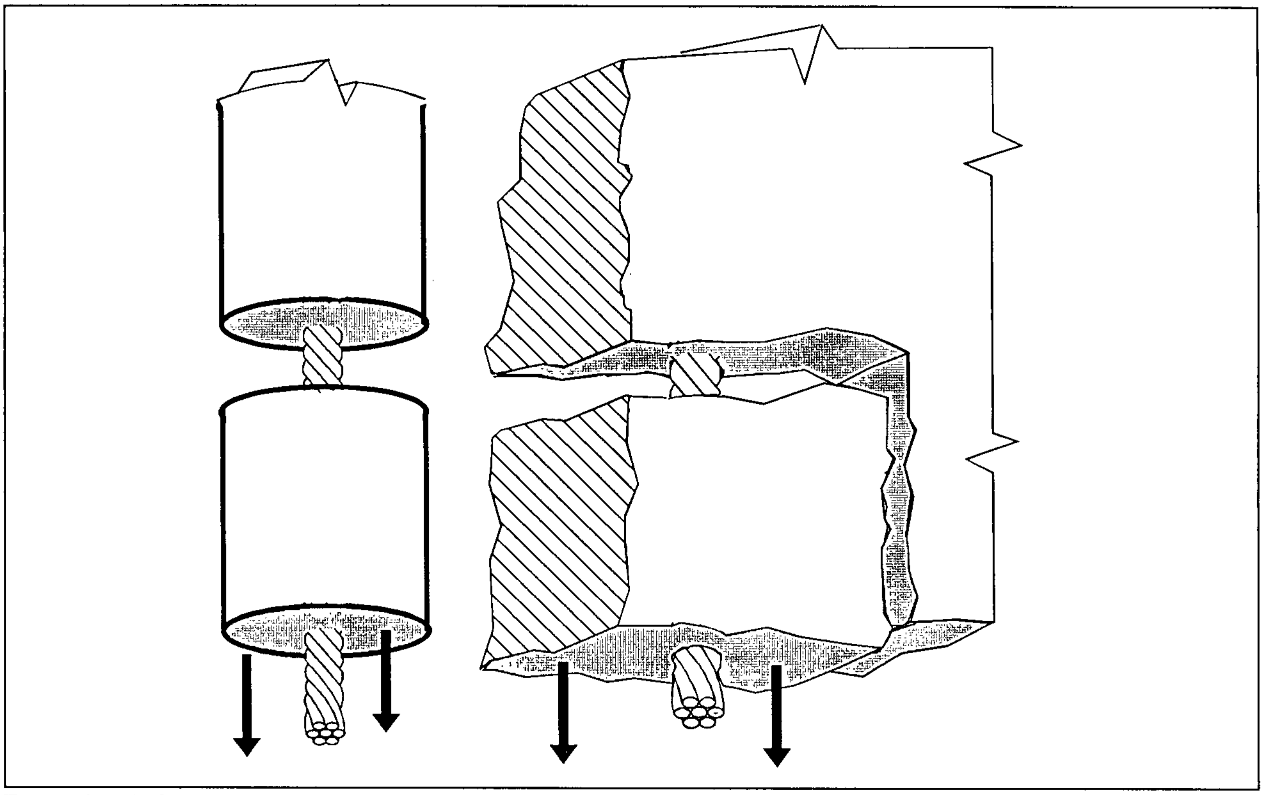


Figure 26. Laboratory Testing vs. Insitu Movement

Two methods of pull testing are used throughout the mining industry, i) single pipe method and ii) double pipe method. Each method is comprised of a test section (which is common between the methods) and an anchor section (which differs between methods).

1) Single Pipe Method (figure 27): A sample is comprised of a cable being grouted into a single pipe. The free length of the cable bolt (229mm) is anchored by the addition of a resin chuck for composite cables or a barrel and wedge assembly for steel cables. A tensile force is applied, attempting to pull the cable from the grouted pipe assembly. The steel resin chuck used for anchoring is 89mm in length, 51mm in diameter and contains four holes into which the individual cable strands are resined (Mah 1994). The

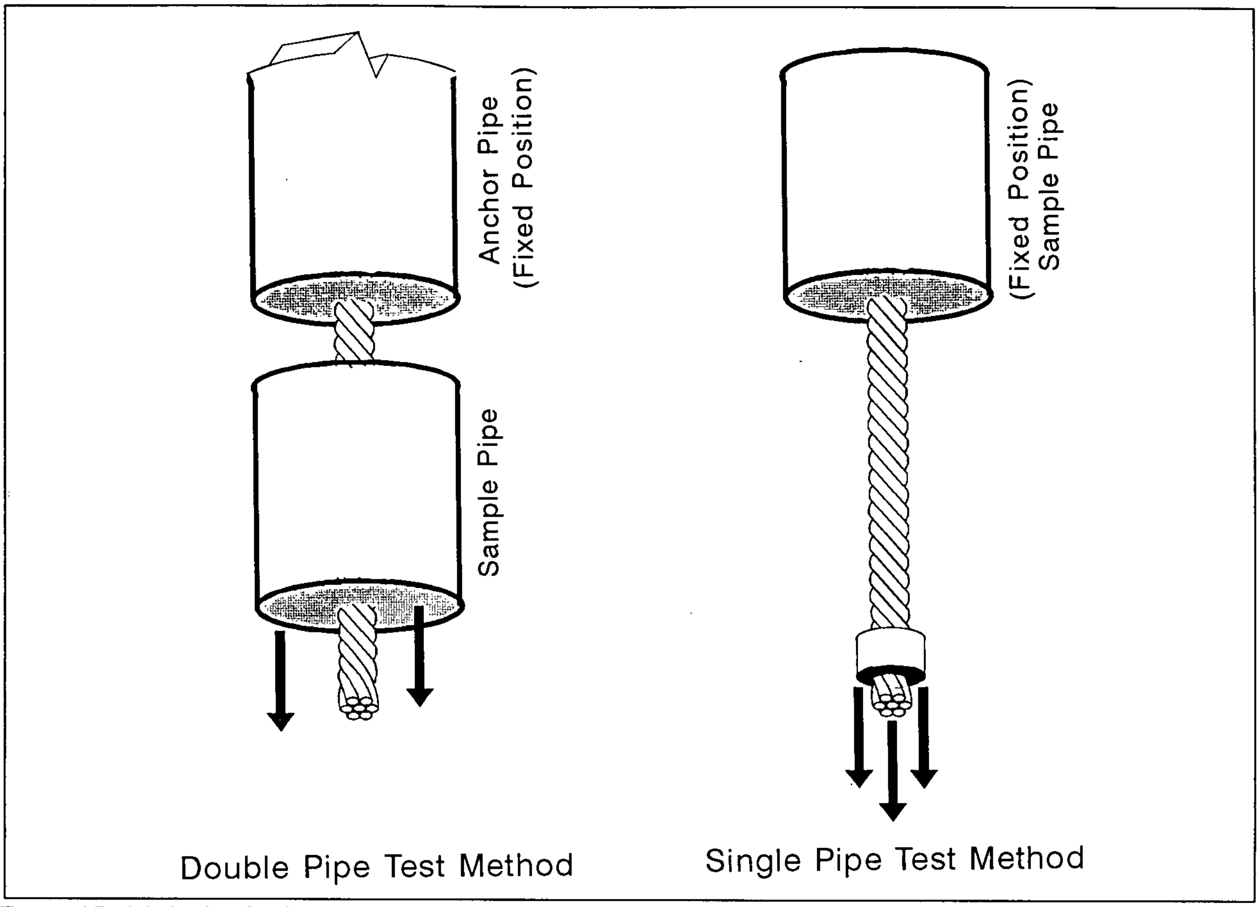


Figure 27. Methods of Laboratory Pull Testing of Cable Bolts

inside of these holes are threaded to increase the bonding capabilities of the resin/steel interface. It is this assembly in which the pull test machine "grasps" onto while exerting a tensile force. This method is primarily used in field pull tests as a result of the machine's compactness.

2) Double Pipe Method (figure 27): A sample is comprised of a cable being grouted into two pipes. One pipe is used as the test length, similar to the single pipe method, while the second pipe is used as an anchor. The anchor section is comprised of a barrel/wedge assembly attached to the steel cable while grouted into a length of pipe. The length of the anchor pipe is greater than the cable's critical bond length to insure that no displacement of the cable/anchor pipe occurs during testing. When composites are being tested, a resin plug is used rather than the barrel and wedge assembly. Each pipe is fitted with a collar, which allows the pull test machine to

"grasp" onto in order to exert a tensile force. A rubber washer (3.1mm) is installed between the pipes to simulate a joint. The double pipe method is adopted by most researchers around the world.

During phase I of composite cable bolt research, a single pipe pull test apparatus was built at the UBC Mining Department (figure 28). At that time, the research dictated the machine had to meet two specific requirements:

1) It could be used in a laboratory setting.
2) It had to be portable to allow for underground field testing.

Figure 28. UBC Pull Test Machine - Single Pipe Method

It was determined that the single pipe method was inadequate for phase II of composite cable bolt research since previous testing did not yield results which were sufficiently accurate. The inadequacy has been contributed to the following:

1) The rods within the cable bolt were not properly anchored, causing differential rod displacement which resulted in premature cable failure.
2) Two hundred and twenty nine (229) millimeters of cable are "free" between the sample and anchored portion of cable. This caused differential diametrical strain within the rods at the air/grout interface (Stillborg, 1984).

The premature cable failure experienced in phase I would not occur if the rods were properly anchored, allowing no differential displacement. Mah (Mah, 1994) documented that a cable bolt sample with identical parameters would fail prematurely when tested with the single pipe method as compared to a double pipe method (Mah, 1990).

The pull test machine at UBC (figure 29) was converted to the double pipe method during the early months of phase II. The pull test apparatus consists of a shaft-mounted load cell, 305kN ram and test pipe housing. The ram is driven by an electric motor (not shown) while the feed is controlled by a needle valve. The 5.7kN load cell and LVDT (linear voltage difference transducer) is connected to separate digital readouts and to a joint x-y plotter.

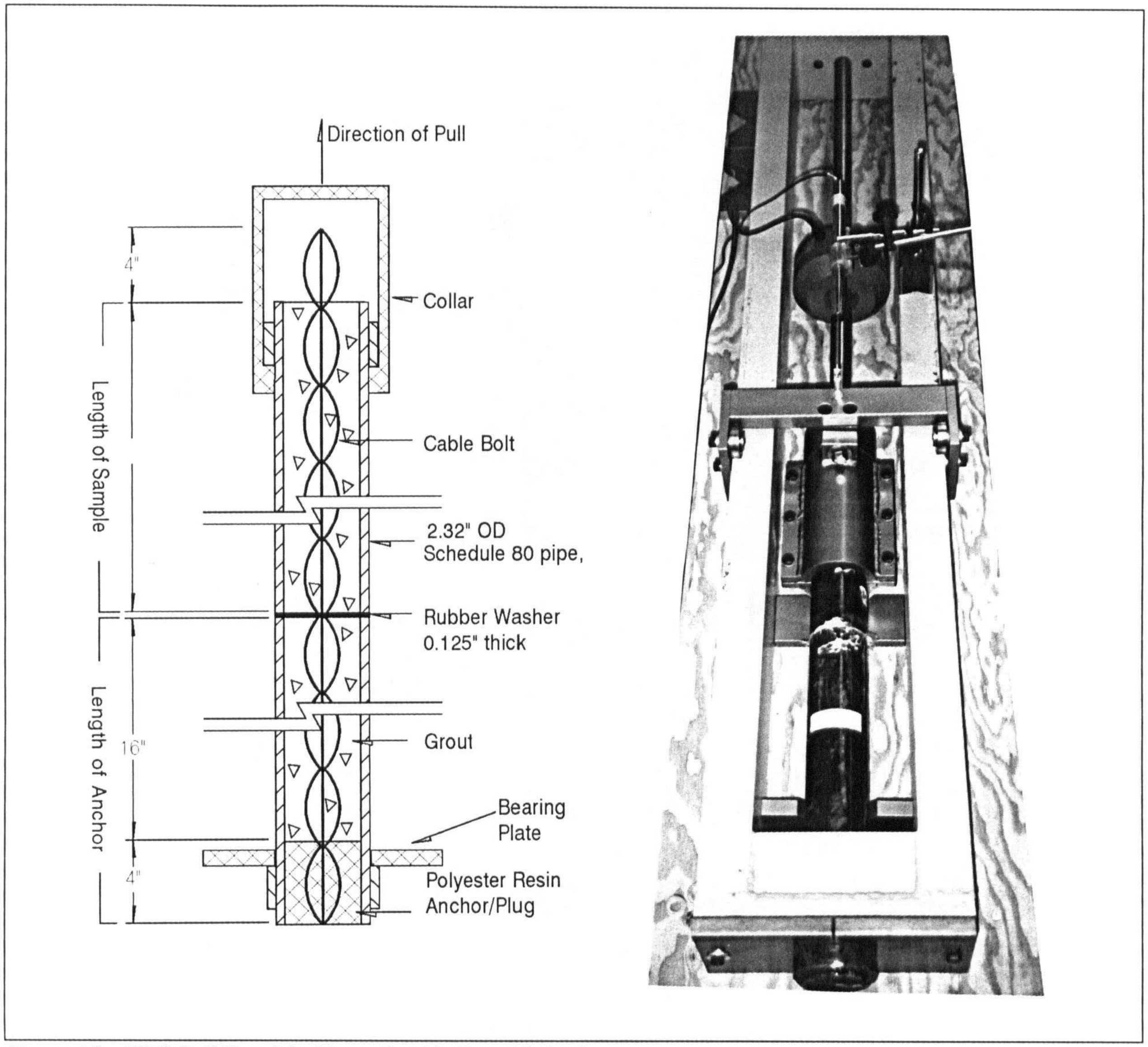


Figure 29. UBC Pull Test Machine - Double Pipe Method

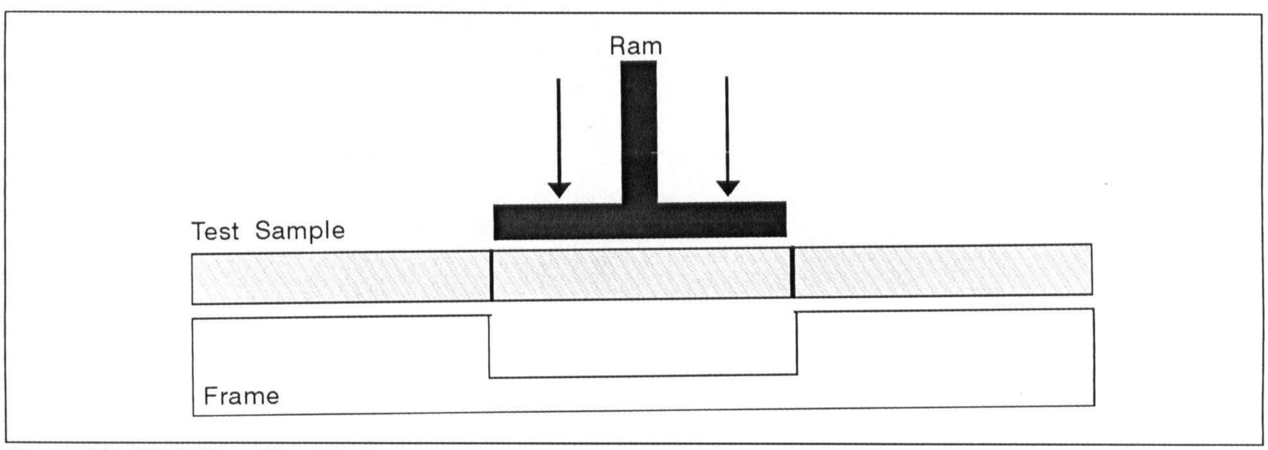


Figure 30. UBC Shear Test Machine

3.1.1.2 UBC Shear Test

The apparatus used for shear testing, loads the cable bolts 90° to their axis (figure 30). A screw type compression machine, 890kN capacity, was used to provide compression in order to shear a sample. When initiated, the bottom of the machine is driven upwards so the top portion of the compression machine contacts the center portion of the sample. The center pipe of the sample is driven downwards, shearing the cable in two locations (at the pipe connections). This results in the lowest shear strength possible, i.e. perpendicular to the axis of the cable.

The sample holder was designed to adapt with a minimal amount of change to the compression machine. However, the load cell, LVDT and data collection system was adapted from the pull test machine to guarantee accuracy. The load cell used has a 507kN capacity and the LVDT has a 102mm +/- 0.01mm stroke. Both are connected to separate digital readouts and to a joint x-y plotter.

3.1.2 SAMPLE PREPARATION

3.1.2.1 UBC Pull Test

Sample preparation for the double pipe method can be seen in figure 31 and figure 32. The cable was placed inside the anchor pipe while ten centimeters of resin was allowed to harden around the bottom of the cable/pipe to form an anchor plug. The cable was centered within the pipe. After 24 hours of curing, a cement based grout was mixed and pumped into the anchor pipe via a grout tube. The grout tube was removed during grouting. The test section of pipe was then lowered down onto the anchor pipe. A rubber washer coated with petroleum jelly was inserted between the pipes to simulate a joint. The pipes were aligned and

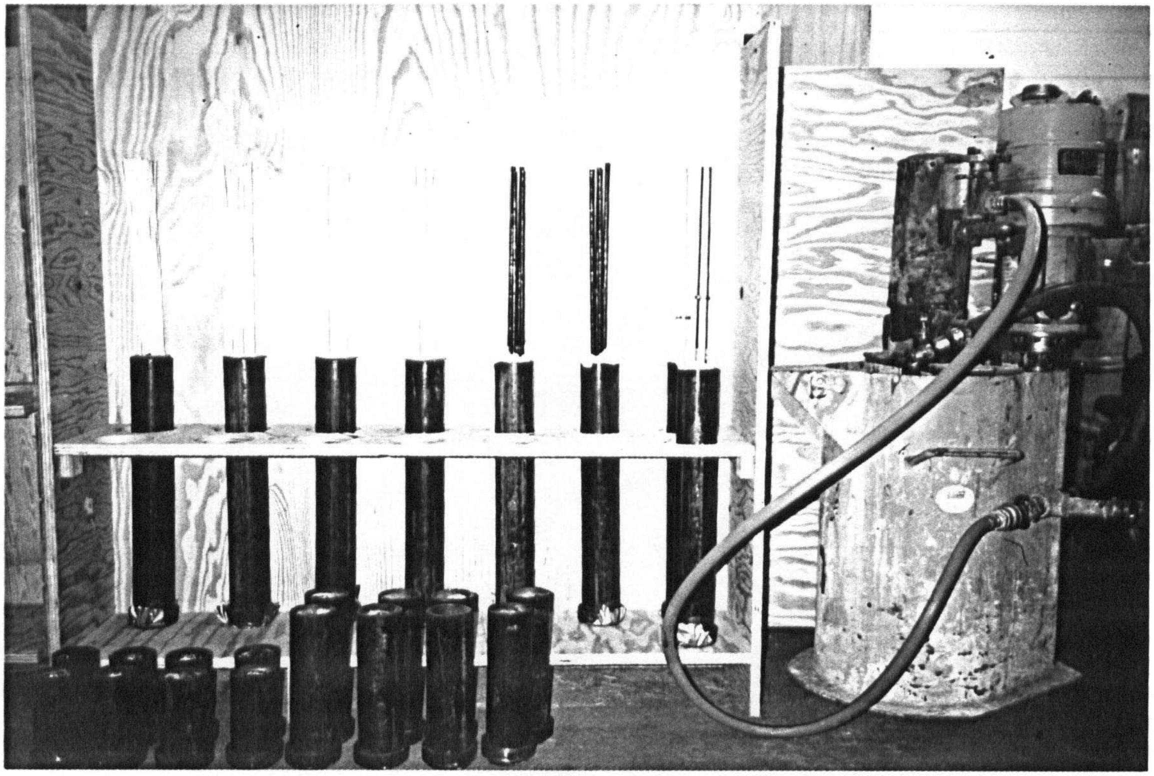


Figure 31. Sample Preparation & Grout Pump

Figure 32. Sample Preparation

temporarily connected through the use of gear clamps and a section of angle iron. Grout was then pumped into the test section of pipe.

The amount of grout sedimentation which took place was dependent on the type of cement/grout mixture used. When sufficient sedimentation took place, additional grout was added to the top of the sample pipe to insure that the correct bond length was created. A plastic bag was placed on top of the test section to reduce water evaporation. The samples were cured at room temperature.

Pull testing of cable bolts at UBC - Mining Department has been modeled from previous testing conducted at the United States Bureau of Mines. It takes approximately eight man hours to construct and test one pull test sample which includes compression testing on the grout. Prior to testing the sample, the grout is allowed to cure for seven days. During this time, other samples are prepared, grouted or tested, resulting in a continuous production of test samples. Testing was generally done in repetitions of one, three, or five samples depending on the test series and the financial constraints of the test program.

1) One Sample: Due to the cost of making the samples and the limiting factor of time, it was determined it would be more efficient (time and cost) to test one sample with no repetitions on parameters which are mostly inferior, but need verification. Samples which were tested with no repetitions were selected after careful consideration. Some samples were tested with no repetitions due to the lack of the composite material on hand.
2) Three Samples: Testing done to define the effects of changing a sample's parameter which is believed not to be the optimum design (e.g. node spacing) is generally established based upon three repetitions.
3) Five Samples: Testing to define the effects of specific parameters which are believed to be used in a final design are conducted with five

repetitions. An example of using five repetitions is when constructing a tensile strength profile for a prototype, such as coated polystal, which is to be installed within a mine.

3.1.2.2 UBC Shear Test

A shear test sample consists of three sections of pipe and a cable. Two anchor pipes, each 508mm in length are separated by the center pipe, which is 381mm in length. A rubber washer coated with petroleum jelly was inserted between the pipes to simulate a joint. All three pipes were aligned and temporarily connected through the use of gear clamps and a section of angle iron. The cable was inserted into the pipe and centered. Grout was then pumped from bottom to top while the grout tube was removed. Several hours after constructing the samples, additional grout was placed on top of the pipe column to compensate for sedimentation. A plastic bag was placed on top of the test section to reduce water evaporation. The samples were cured at room temperature.

3.1.3 TEST PROCEDURES

3.1.3.1 UBC Pull Tests

The procedures of pull testing were modeled after the USBM methods (Goris 1990). Samples are selected at random and installed into the pull test machine. Once the 0.22kN seating load is applied, an increasing tensile force is applied causing the pipes to separate. Since the anchor pipe does not allow cable/pipe displacement, the tensile force causes the cable within the sample pipe to debond on the cable/grout interface. The rate of loading was held constant at approximately 11.1kN per minute. Testing is terminated when either the cable/grout displacement reaches 63.5mm (the limit of the machine), when the cable fails, or when the machine reaches its tensile load limit of approximately 236kN.

3.1.3.2 UBC Shear Testing

Samples tested are selected at random and installed into the pull test machine. The rate of loading is held constant at 11.1 kN per minute. As the load starts to increase, the center pipe is displaced downward, shearing the cable at two locations. Displacement of the pipe and the loading force were continuously monitored throughout the test. Testing is terminated when the cable fails by shearing.

3.1.3.3 Grout Compression Testing

Samples of the grout used in constructing the pull test and shear test samples were extracted and tested to determine the grout strength and to insure grout consistency. The samples taken were cylindrical with a five centimeter diameter and a 2.5 length:width ratio. The ends of the grout samples were machined and unconfined compressive tests were completed on the samples according to ASTM standards.

Cylindrical samples were used since they were representative to what was being used in the mining industry. In order to compare results which used cubed shaped samples, a factor of 1.25 times the UCS strength of the cylindrical samples was applied (Mindess, Young, 1981).

Chapter 4

COMPOSITE EVALUATION

The following chapter discusses Steps 1 & 2, Primary and Secondary Composite Evaluation, in the development of a commercially competitive glass fibre cable bolt. Four types of manufactured composite rods were initially evaluated in Step 1, while the two most prominent composite rods were re-examined in-depth during Step 2. As a result of Step 2, one composite was selected to be used in the development of the commercially competitive glass fibre cable bolt.

4.1 Composite Evaluation

Primary composite evaluation was conducted on four composite materials manufactured in Canada and the United States. The basis of evaluation focused on the products' availability, original surface properties and the quality control exhibited within the manufacturing of the composite (figure 33). This was accomplished through pull tests and observations utilizing the scanning electron microscope (SEM).

4.1.1 STEP 1. PRIMARY COMPOSITE SELECTIONS

The primary composite selection was conducted on the following products:

1) POLYSTAL: The first prototype of a composite cable bolt used in Phase I was comprised of POLYSTAL. The prototype was constructed from a patented composite imported from Bayer Inc. of Germany. The material consists of an E-glass reinforcing fibre bound by a matrix of unsaturated polyester resin along with two helical winds on its perimeter. The composite is manufactured in a "rod" with

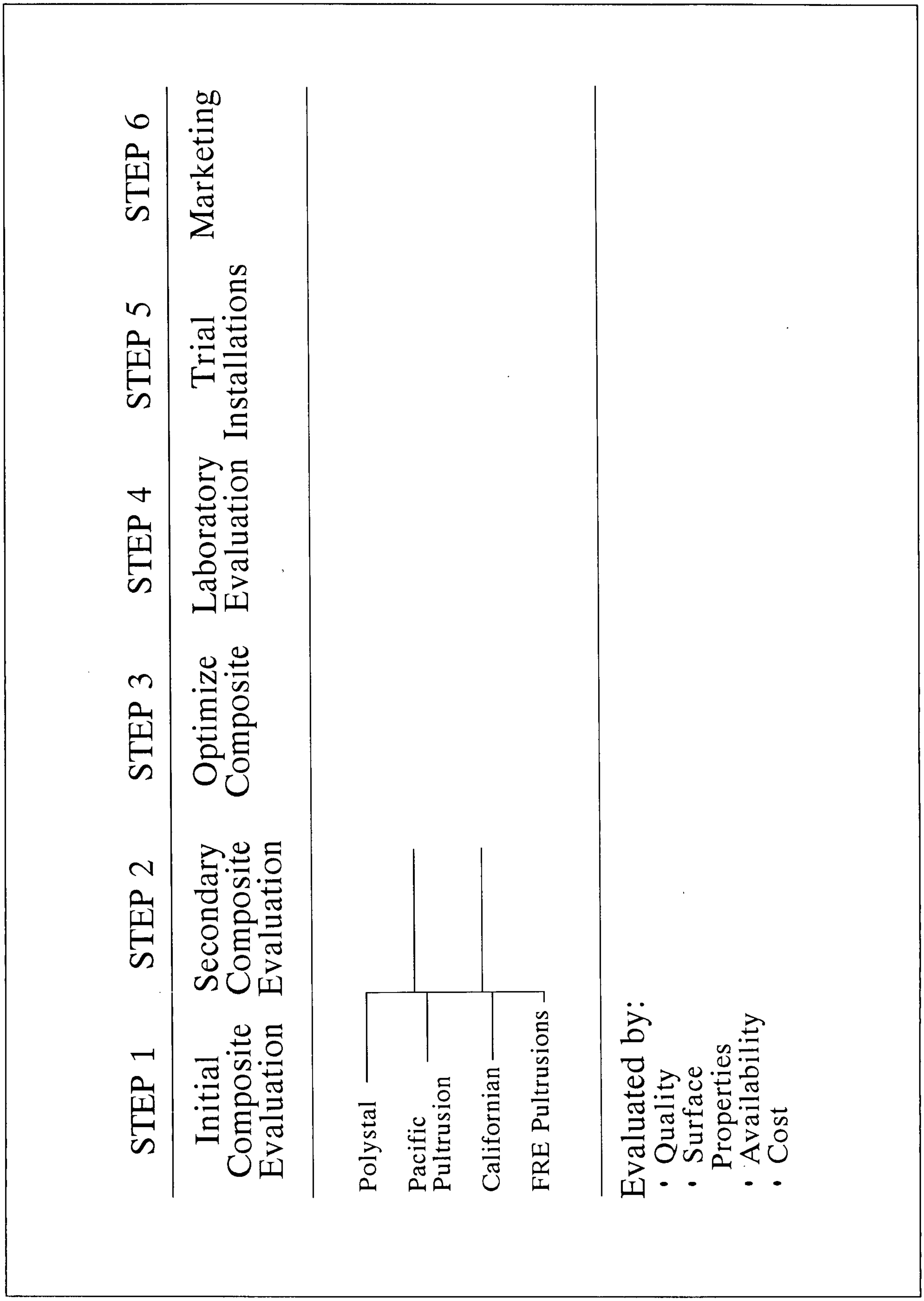


Figure 33. Research Flowchart - Step 1, Initial Composite Selection

a 7.6mm diameter and an optional 1.5mm (0.06 inch) thick polyamide coating. During Phase I, four of these tendons were joined at a node - antinode fashion (lacing) to create a cable bolt (figure 34)(Mah, 1994). The local distributor of Polystal was Con-Tech Systems Ltd.

2) PACIFIC PULTRUSIONS: Located in North Vancouver, Pacific Pultrusions produces custom designed pultruded products for a wide variety of applications. The composite product initially given to UBC Mining Department was made from an E-glass fibre with an unsaturated polyester resin. A low filler content was used in its construction which provided a micro rough surface on the rod. The composite rod's diameter was 6.35mm.

3) CALIFORNIAN: A 7.6mm diameter pultruded rod was submitted to UBC via Con-Tech Systems Ltd. for testing. The rod, produced in Newport, California, was made from E-glass and polyester resin. The finish on the rod was smooth, a result from pulling the composite from the dye at a fast pace.

4) FRE PULTRUSIONS: Located in Edmonton, Alberta, the company is noted for the production of high tensile tendons used as tie downs for oil drilling rigs. The tendon samples were available in an array of sizes and shapes. The rods consisted of E-glass and polyester resin.

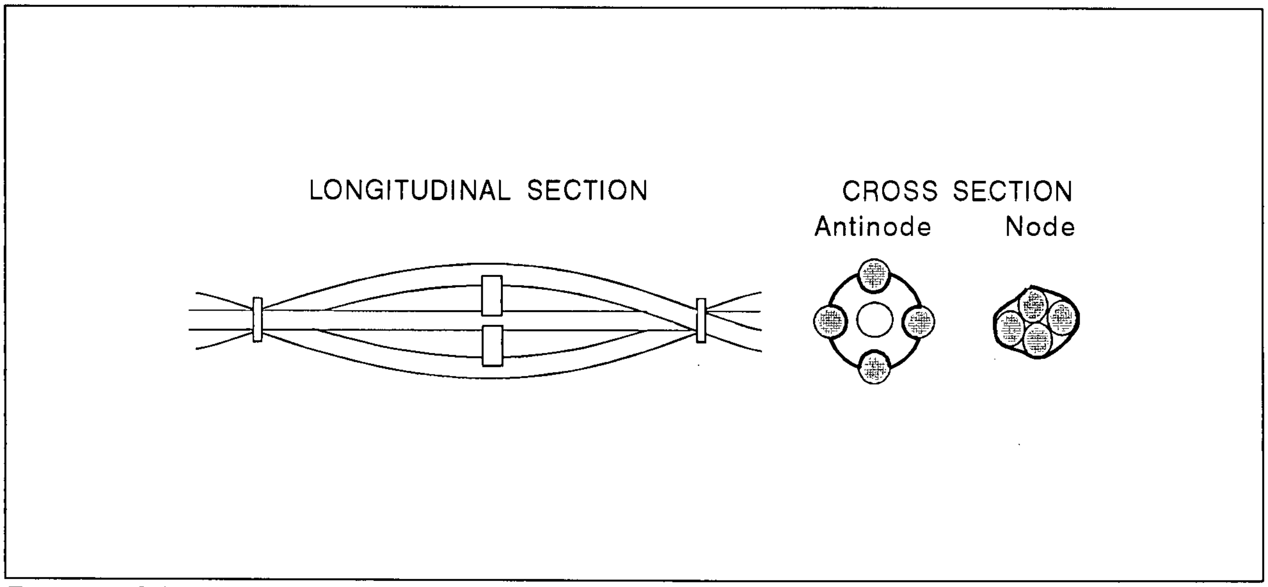


Figure 34. Schematic of Polystal Cable Bolt

4.1.1.1 Quality Control Testing

In concluding Phase I of glass fibre cable bolt research, one of several recommendations made to HDRK was to have experts in the composite industry evaluate and ensure that composites used in the mining industry are of sufficient quality (Mah *et al*, 1991). Quality control measures have been considered critical to the selection of a composite for cable bolting in order to ensure the safety of the operation and for the people working underneath the supported ground. Misaligned fibres, voids within the matrix, volume percent fibre and consistency of the surface coating are among some of the parameters which dictate the physical performance of the composite when utilized as a cable bolt.

Pultruded rod samples from the above four manufacturers were sectioned and their surfaces examined with the aid of the scanning electron microscope (SEM). Figures 35,36,37,38 shows the lay of the fibres along axis for the various pultruded products. All the photographs presented are characteristic of the samples tested. As shown, Polystal has excellent fibre orientation, significantly better than the other samples. The use of high tension applied to the small diameter fibres during manufacturing translated into much less fibre misalignment. Figures 36, 37 and 38 show knots and misaligned fibres in the other manufactures' samples. The high quality Polystal rods are made with smaller diameter glass fibres (13μm), followed by rods supplied from Californian (15μm in diameter), with the other two made from coarser fibres (21μm).

The densities and fibre volume fractions are shown in tables 1. The density was determined by the displacement method according to ASTM D 792 and a burnout test was used to obtain the volume fraction of the glass fibres in the rods (Riahi, Poursartip, 1992). Other than the sample provided by FRE Pultrusions, which is much lower in fibre volume fraction and density, the remaining three products exhibit similar properties. Attention is drawn to the identical fibre volume fractions of the Polystal rods and the rods provided by Pacific Pultrusions.

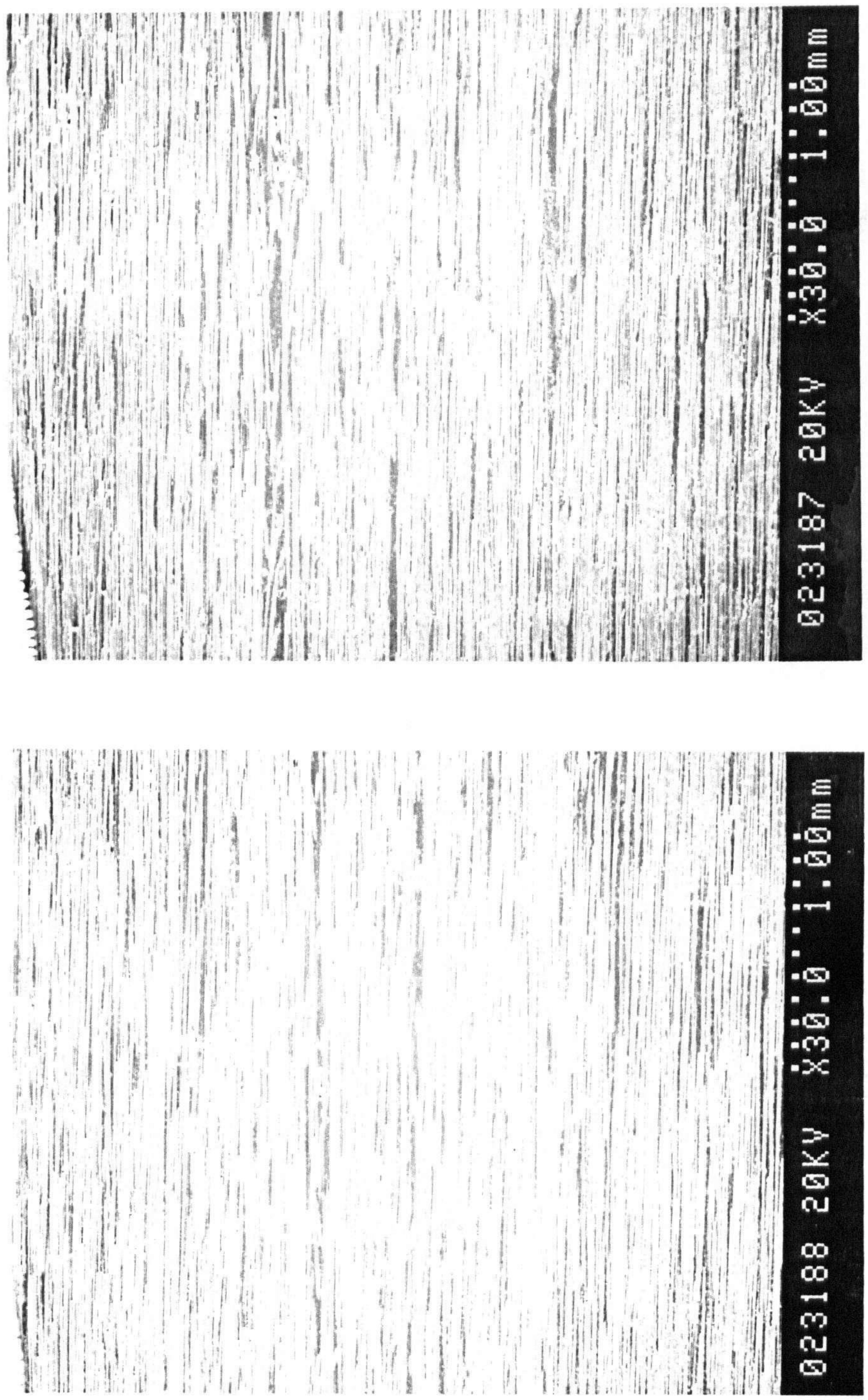


Figure 35. SEM View of Polystal Along Axis of Rod

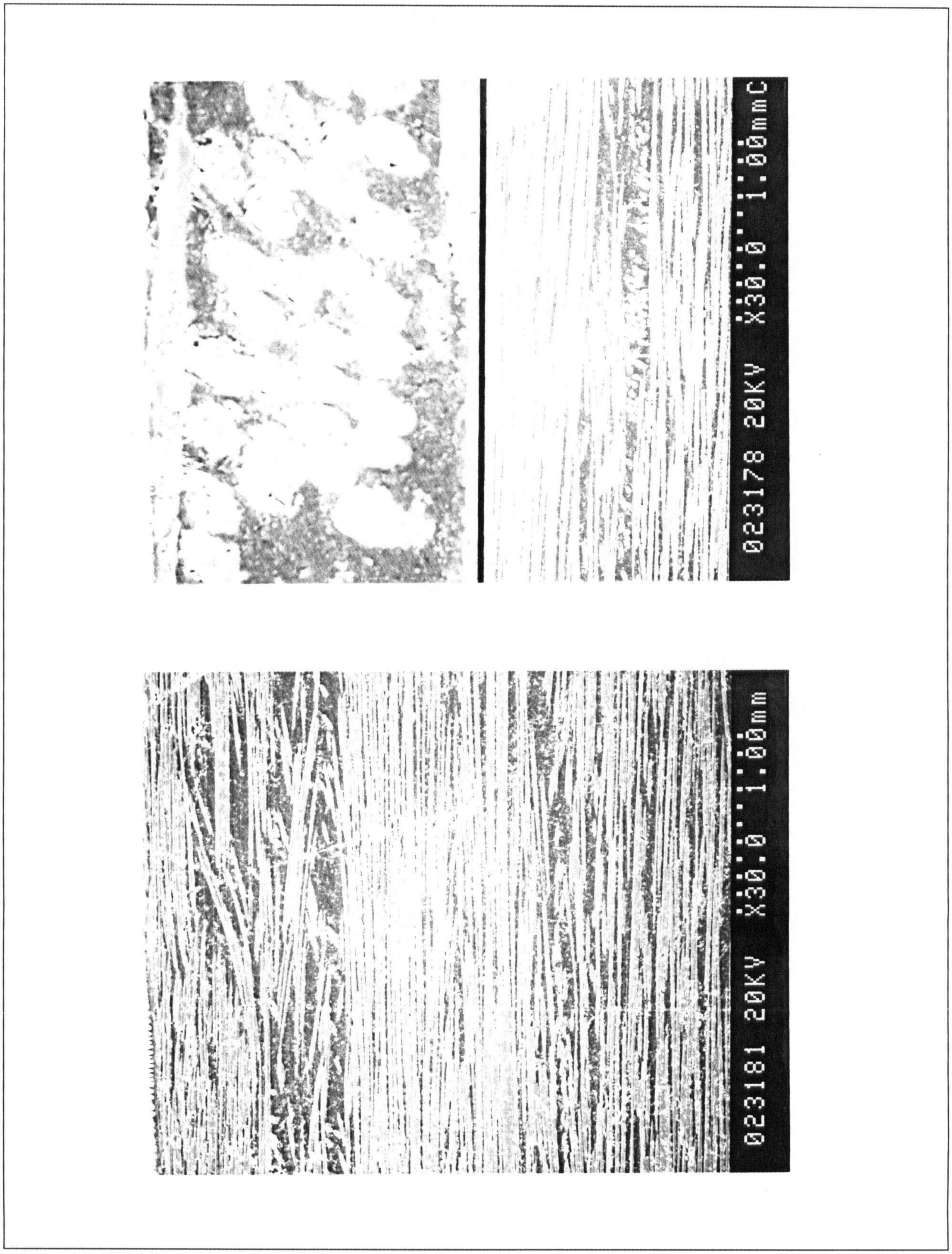


Figure 36. SEM View Along Axis of First Acquired Sample From Pacific Pultrusions

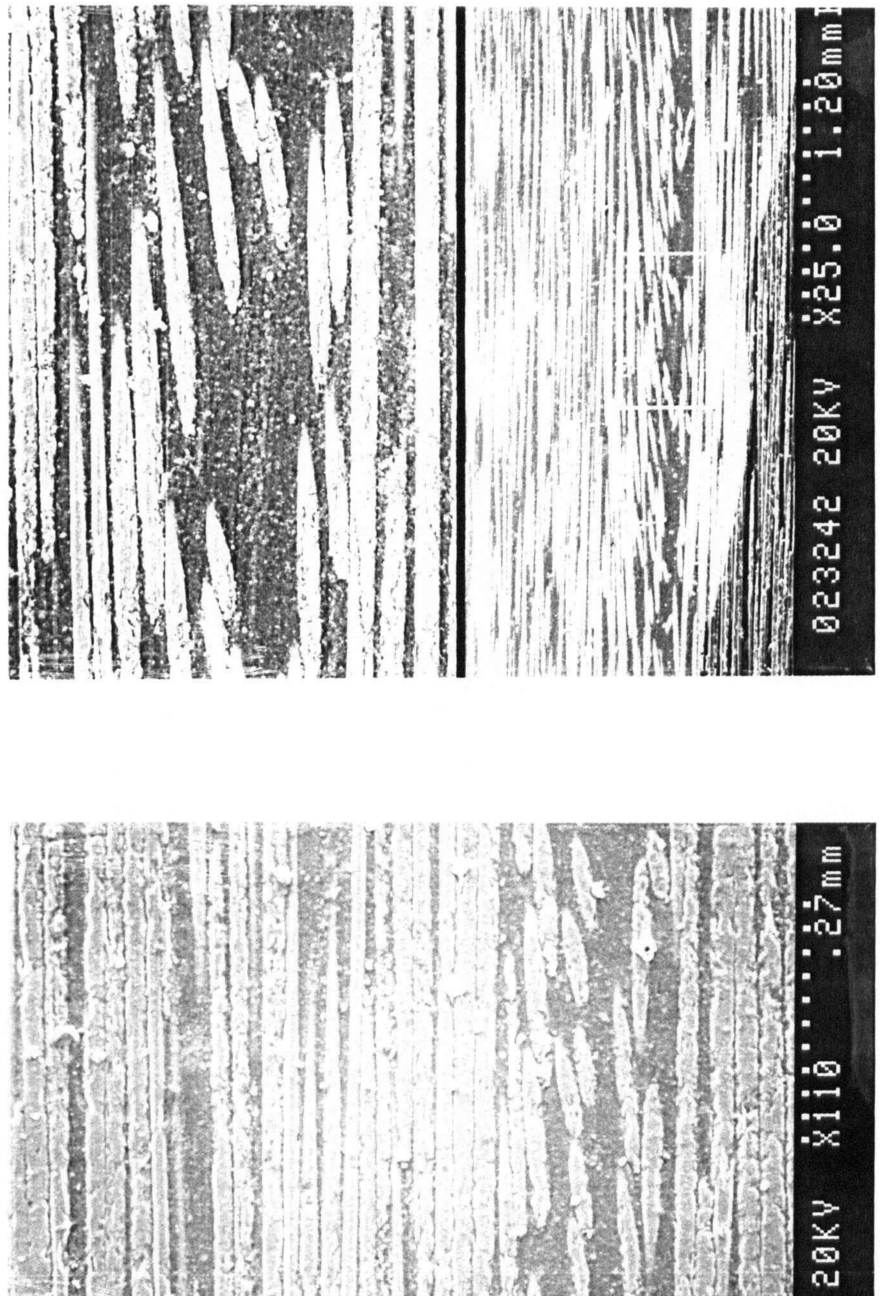


Figure 37. SEM View of FRE Pultrusions' Rod Along Axis

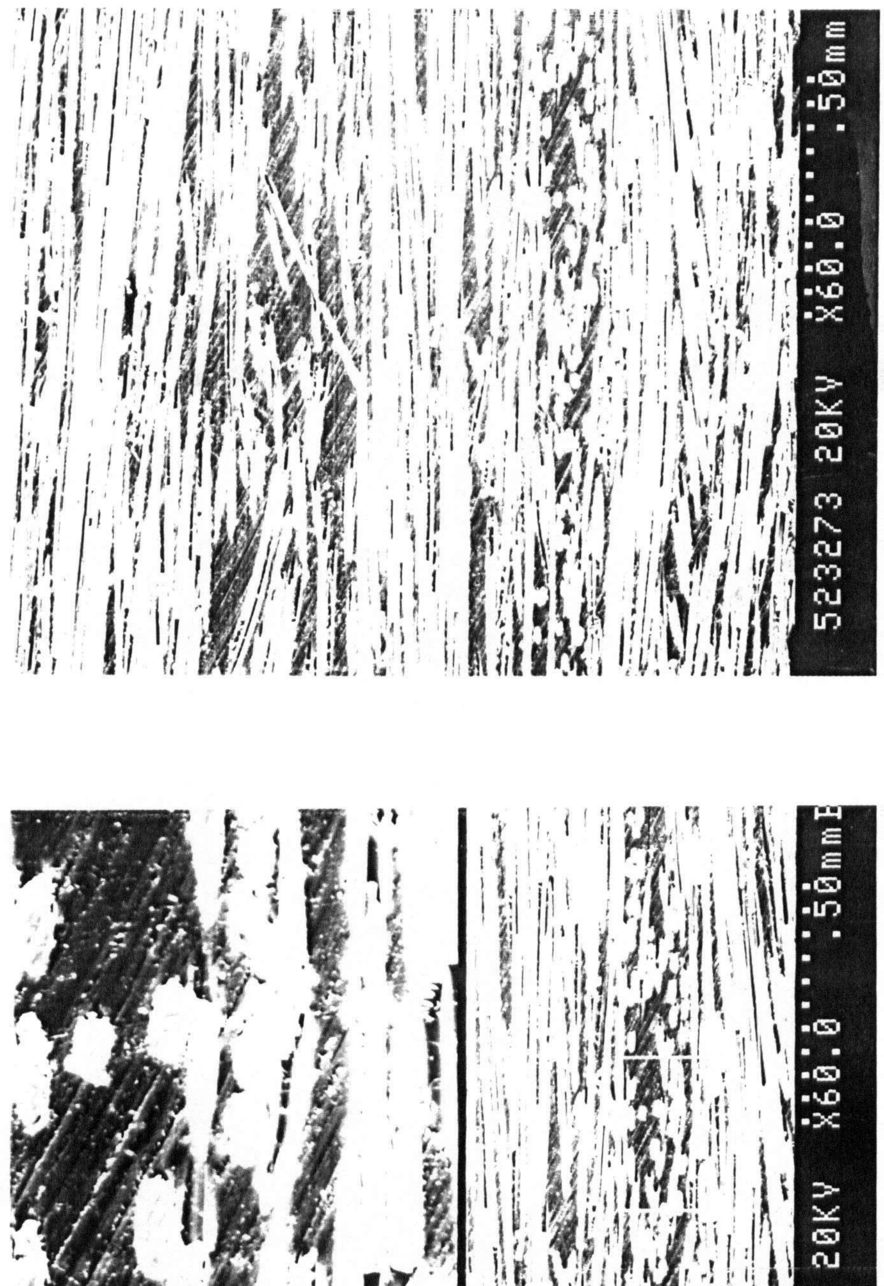


Figure 38. SEM View of Californian' Rod Along Axis

Table 1. Density and Volume Fractions of Selected Composites

Sample Identifications	Weight % Glass Fibre	Volume % Glass Fibre	Specific Gravity @ 21.7°C
Polystal	81.23	64.87	2.0558
Pacific Pultrusions	78.59	64.96	2.1278
Californian	78.58	61.45	2.0132
FRE Pultrusions	73.35	55.94	1.9634

4.1.1.2 Surface Properties

Pull test samples were prepared and tested to evaluate the surface properties of the four composite rods. Each sample had approximately 38,000 mm^2 of surface area embedded within the grout in a straight configuration (figure 39). It was determined that 38 000 mm^2 would yield pull out strengths of all the composites within the margins of the materials strengths, i.e. a larger surface area

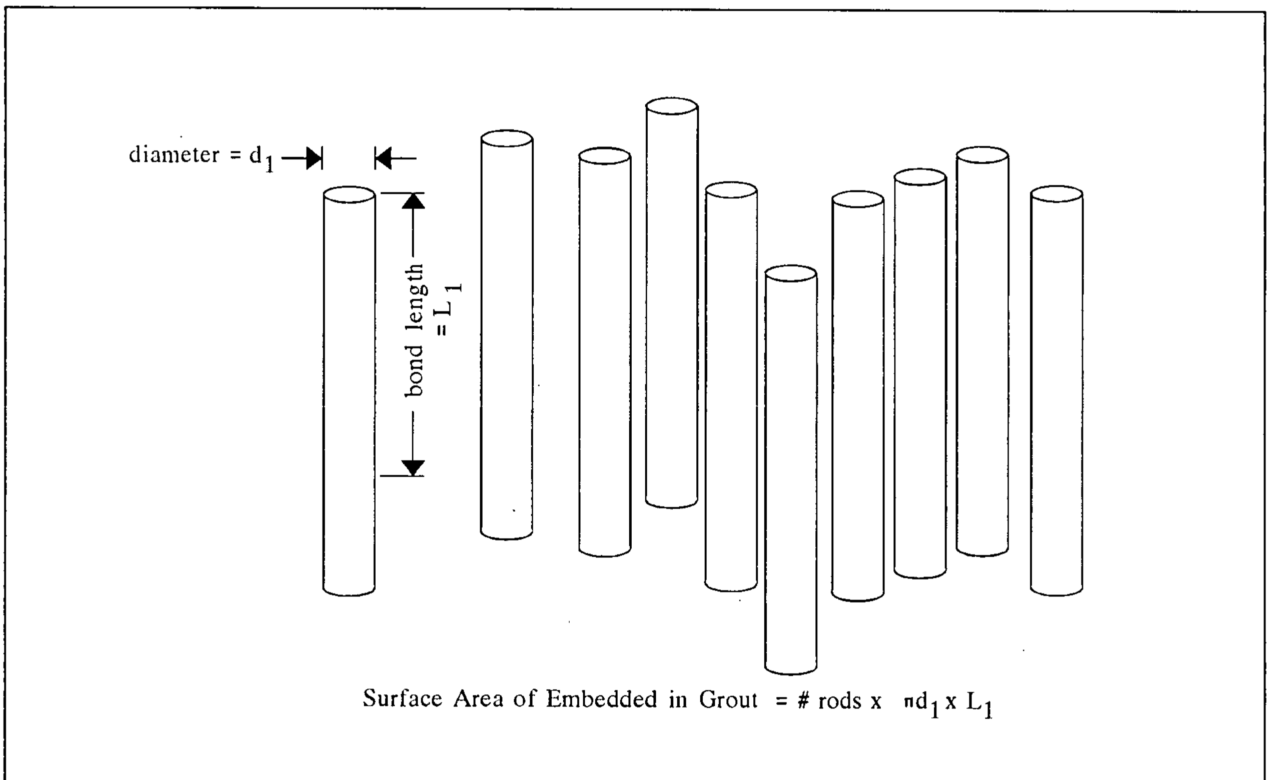


Figure 39. Definition of 38,000mm^2

might exceed a particular composite's critical bond length, while a smaller surface area might cause a particular composite to register a pull out load smaller than preferred. The test samples utilized a type 30 grout with a 7 day cure at a 0.35 water:cement ratio. The grout was hand mixed for ten minutes. Results of the test are shown in figure 40.

The Californian composite had a pull out load considerably lower than the others tested. This was primarily due to the smooth finish resulting from the speed of pultrusion combined with the high filler content used in its construction. Unlike the Californian composite, Pacific Pultrusions used a significantly slower speed combined with a low filler content.

Figure 41 displays typical load vs. displacement curves for each of the composites. The trend of the curve is very important in considering the use of composites for ground support since the pull out resistance offered by a cable bolt is a function of displacement, among other factors. Coated Polystal provides a moderate pull out load with minimal displacement. This is analogous to stiff ground support which does not allow the rock mass to experience significant displacement, causing it to create its own pressure arch which aids in the overall support of the structure. Its pull out characteristics are similar to a conventional steel cable bolt. However, unmodified Pacific Pultrusions provides minimal pull out resistance at small displacements. As the displacement increases (mass displacement), the pull out resistance provided by the composite rod increases. This is useful in burst prone areas. In considering the results from the primary pull tests, only the coated Polystal had sufficient load carrying capacity to be used as ground support without additional surface alterations.

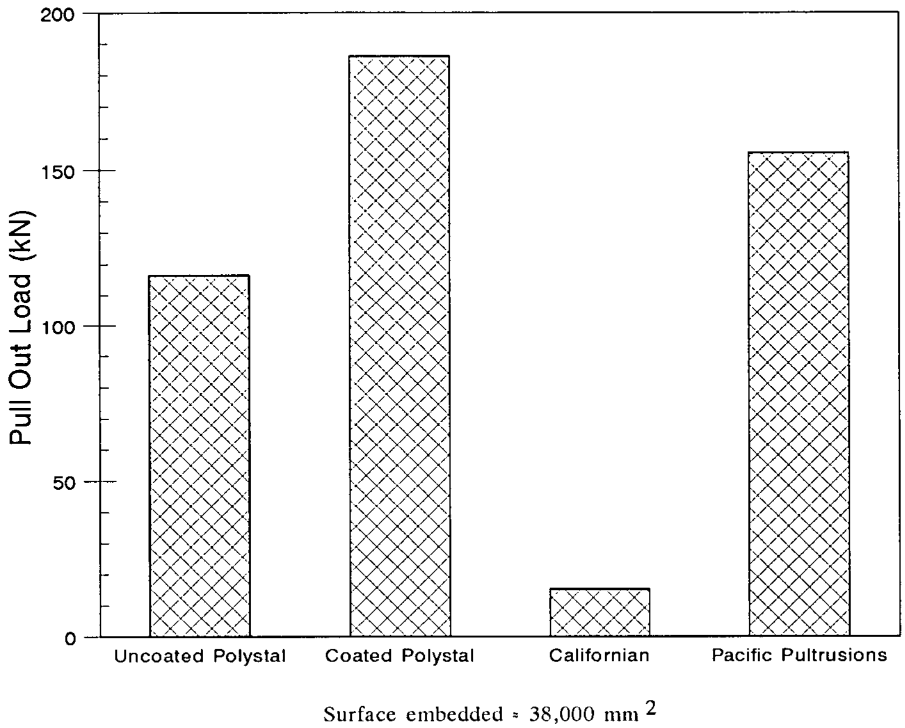


Figure 40. Evaluating Pull Out Loads Generated by Individual Surface Properties

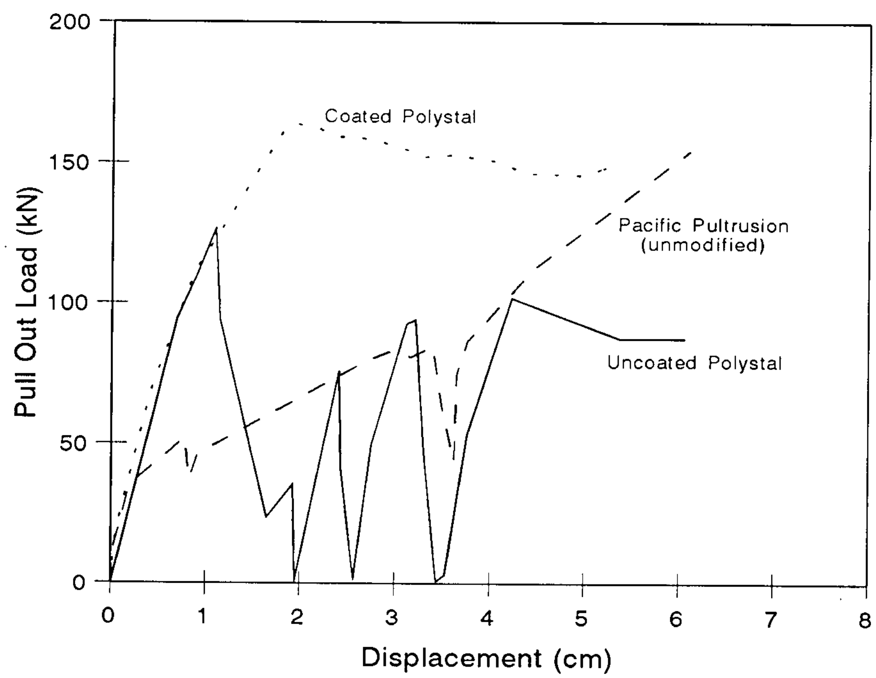


Figure 41. Typical Pull Out Curves (from Surface Properties Test Series)

4.1.1.3 Effect of Cable Configuration on Short Bond Lengths

A primary objective in developing a cable bolt (steel or composite) is to create a support which can sustain high pull out loads under short bond lengths. Configuration of steel cable bolts in the past have had a dramatic effect in reaching this objective. The actual steel strands used in all types of steel cable bolts were identical, with increased performance being achieved through cable configuration (birdcage, nutcage, buttoned, twin strands) and not due to modifications to the surface of the steel strand itself.

Pull tests were done to evaluate the effect of cable configuration (lacing) on short embedment lengths (figure 42). Uncoated Polystal and the Californian composites were tested in two different configurations, (i) straight, and (ii) 254mm node spacing (figure 43). Coated Polystal was not tested due to lack of the composite available at the time of testing.

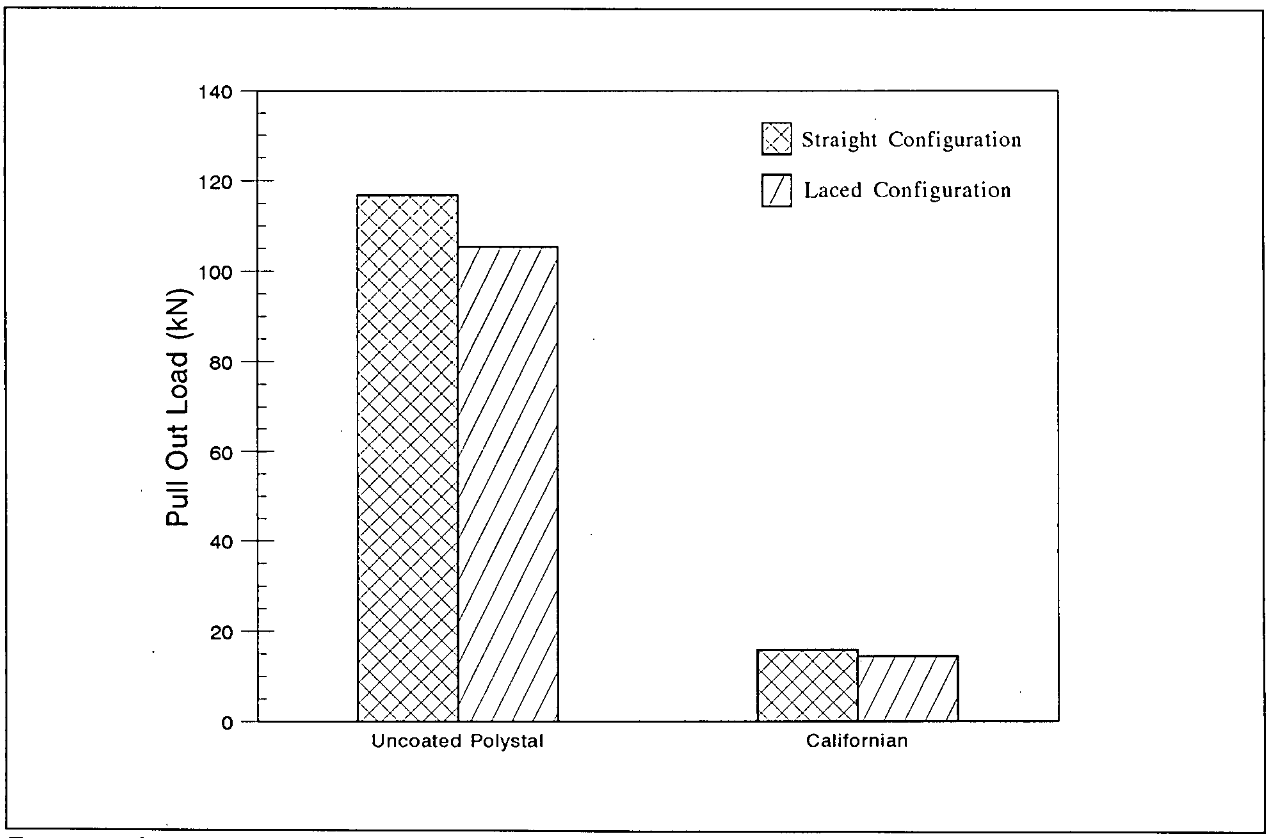


Figure 42. Straight vs Laced Configuration

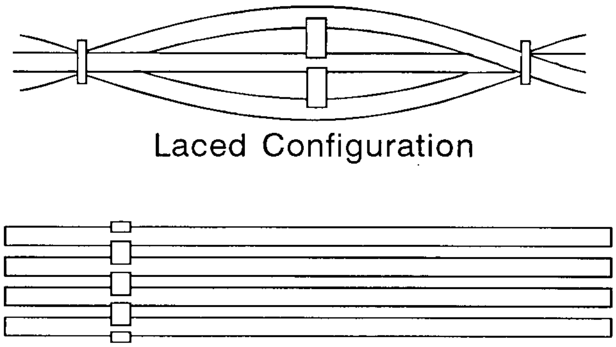


Figure 43. Types of Configuration

In both composites tested, the pull out resistance for the straight configuration exceeded the pull out resistance for laced samples. Lacing of the composite rods is only effective if the bond length (joint spacing) is larger than the node spacing by a certain factor. This factor will vary depending on the type of configuration and roughness of the cable's surface. It is hypothesized by the author that cable bolts which utilize nodes (including steel birdcage, nutcage, etc.) do not have a linear relationship between load and bond length, like conventional steel cable bolts.

It was decided that any future work directed towards increasing the cable bolt's load carrying capacity should focus on the surface roughness and surface area rather than the lacing (configuration) in order to achieve high pull out loads in short bond lengths.

In considering the tests conducted on the four composites, and considering other factors such as availability and company cooperation, it was decided that the products from Bayer (Polystal) and Pacific Pultrusions had the best potential in creating a commercially available cable bolt. Though Polystal is patented and only manufactured in Germany, Con-Tech Systems of Delta, B.C. was interested in pursuing the opportunity to manufacture the material locally. This would decrease the cost by approximately 50% while joint colaboration would easily enable the product to be altered to meet required specifications (Aschenbroich, 1991). Although Pacific Pultrusions has not emphasized quality control in the past due to its product line not requiring high quality control, the company is amenable to improve the quality of its products though interaction with UBC. With improved quality control standards and their convenient location, Pacific Pultrusions is the top competitor for Polystal.

4.1.2 STEP 2. SECONDARY COMPOSITE EVALUATION

Additional testing on Polystal and Pacific Pultrusions' products during Step II of the research program focused on their individual performance, cost and susceptibility for commercial production (figure 44). Since Pacific Pultrusions Ltd. is located in North Vancouver, much interaction between UBC - Mining Department and the company's engineer (C. Gould) occurred. This resulted in several modifications to their product in order to better define a suitable composite for mining applications. In comparison, the availability of Polystal was not very good with only limited composite profiles at the UBC - Mining Department's disposal, and no opportunity of altering the product during the manufacturing process.

4.1.2.1 Surface Alterations to Pacific Pultrusions' Composite

The total pull out resistance provided by the cable is dependent upon three factors, adhesion, friction and configuration. Consequently, the most effective method of increasing a cable's pull out resistance is to induce mechanical locking between the pultruded rod surface and the grout, which in turn results in higher

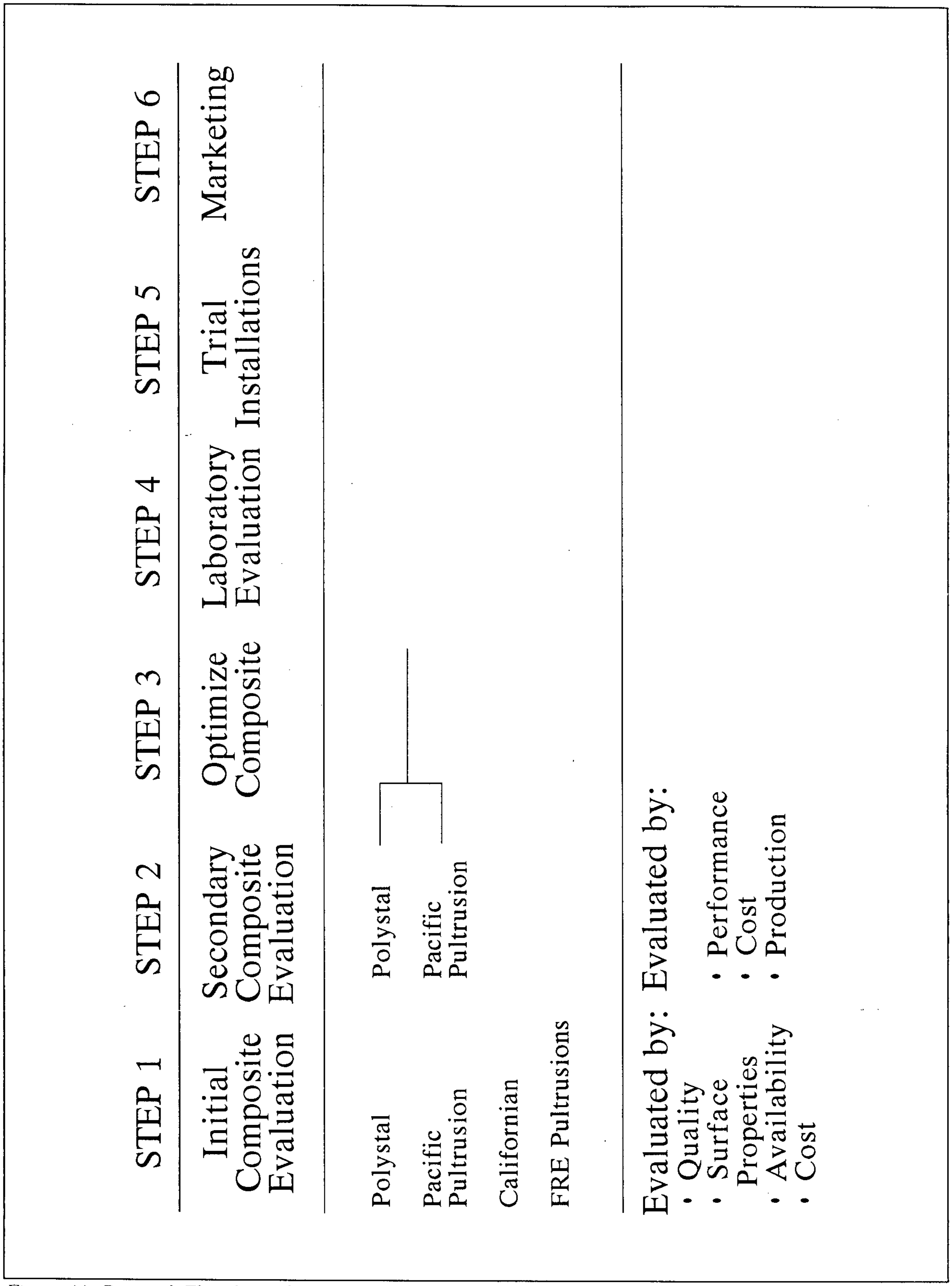


Figure 44. Research Flowchart - Step 2, Secondary Composite Evaluation

frictional forces. One major problem with Pacific Pultrusions' composite is its poor pull out resistance for small displacements. In order to improve this, several modifications were completed in a laboratory setting in an attempt to make the surface of the pultruded rod rougher.

Combinations of three different surface alterations with two different resins were tried (table 2). The surface alterations are (Raihi and Poursartip, 1992):

1) addition of 10% Eco sphere (sand grit)
2) a tow of glass fibre wrapped around the rod, i.e. corkscrew effect
3) two tows of glass fibre wrapped in opposite directions around the rod

Two types of resins were used:

1) polyester resin and 1.5% MEK peroxide catalyst
2) urethane dymeric primer #1 (promotes cement adhesion)

Table 2. Combinations of Surface Alterations Conducted in Laboratory

Rod #	**Surface Modifying Method**
1A & 1B	Polyester resin was loaded with 10% sphere and 1.5% catalyst (MEK) peroxide. This solution was brushed over the rod's surface. To keep the surface homogeneous, the rod was rotated with the aid of a drum winder until the resin was set.
2A	Special urethane primer used in the building industry to promote cement adhesion to other polymers (Dymeric Primer #1) was brushed on the pultruded rod. A drum winder was used to wind primer wetted glass fibre on to this rod. A second coat of this primer was applied to the surface and the rod rotated until dry.
3A & 3B	Same as 2A except that polyester resin was used instead of the primer.
3C	Same as 3A & 3B, with the fibre wound twice.
4A & 4B	Same as 2A, except that two rows of glass fibre were wound
5A & 5B	Same as 1A & 1B, except that Dymeric Primer #1 was used instead of the polyester resin
6A & 6B	Pacific Pultrusions with no surface alterations.

Table 3. Pull Test Results

Rod #	Load (kN)	Type of Failure	Comments
1A	14.28	slip	stick slip
1B	11.52	slip	stick slip
2A	8.36	slip	good residual load
3A	26.91	anchor failed	stick slip
3B	28.56	tendon failure	stick slip
3C	29.31	tendon failure	stick slip
4A	11.21	slip	
4B	16.37	slip	
5A	5.07	slip	
5B	3.96	slip	
6A	10.90	slip	no surface alterations
6B	10.54	slip	no surface alterations

Due to the excessive time in making the above modifications, insufficient rod was produced to construct a cable bolt equal to 38,000 mm^2. Rather, only one rod equal to 3000 mm^2 was pull tested. Pull tests were completed utilizing a 0.35:1 water:cement ratio, type 30 cement with a seven (7) day cure. Results can be found in table 3. All of the tests performed resulted in the surface modifications being stripped from the composite rod by the friction generated at the grout interface. This indicated that the composite/surface modification bond had a lower shear strength than the surface modification/grout bond.

4.1.2.2 Effect of Tendon Size on Pull Out Load

By increasing the surface area of the cable bolt bonded to the grout, an increase in pull out resistance will be experienced given that the sample's bond length is held constant. Pull tests were completed to quantify the increase in pull out resistance for uncoated Polystal samples of 152mm and 254mm bond lengths. Samples of uncoated Polystal were imported and cable bolts constructed using 2mm, 3mm, 4mm and 7.7mm diameter rods. Coated Polystal and Pacific Pultrusions' rods were not available in other sizes at the time of testing. The test samples were designed with a constant ultimate tensile strength (cross sectional area) of 267kN. By changing the diameter of the rods, the number of rods used to create the cable bolt varied resulting in an exponential increase/decrease of surface area. The configurations tested can be found in table 4. Tests were done utilizing type 30 cement with a 7 day cure at a water:cement ratio of 0.35. Each cable configuration was completed in triplicate with the exception of the 2mm and 3mm samples, which were completed in duplicate. This was due to the quantity of Polystal available.

Table 4. Polystal Cable Bolt Configurations Tested

Configuration	Tendon Diameter (mm)	Number of Tendons per Cable Bolt
A	2	63
B	3	28
C	4	16
D	7.7	4

The highest pull out resistance achieved with 15.25cm bond length exceeded the strength of the pull test machine (greater than 220kN) as compared to steel birdcage cables achieving approximately 71.2kN (MRA, 1988) for similar test parameters. Results are shown in figure 45.

As the tendon diameter gets smaller, the surface area of the cable bolt increases exponentially, along with a rapid increase in its pull out resistance (figure 45). Also shown is the cost (imported) of the Polystal cable bolt

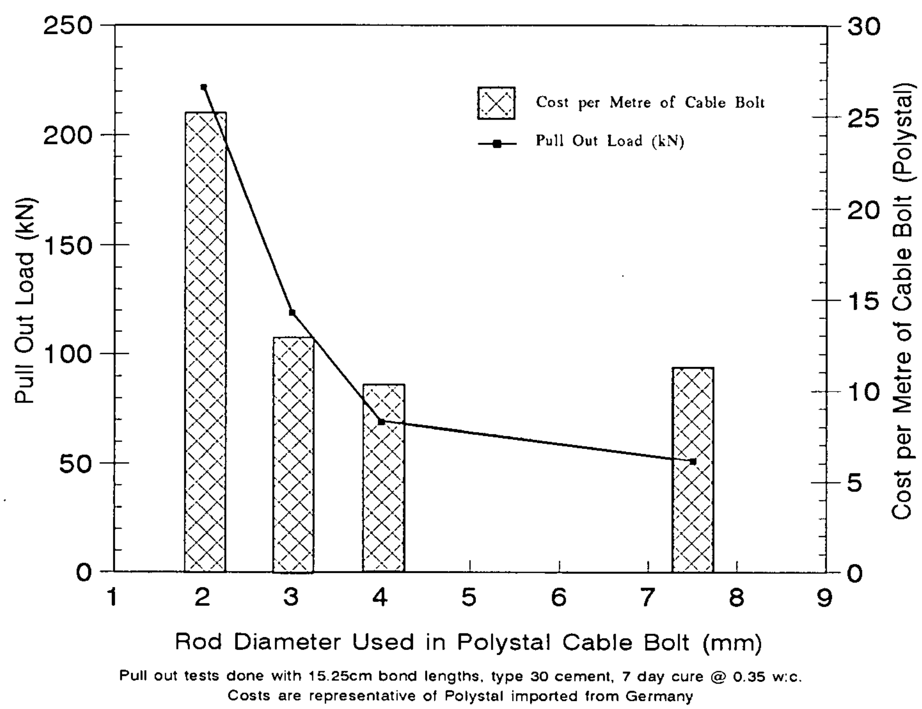


Figure 45. Cost and Pull Out Loads of Polystal

per metre of length. It was estimated that the cost of Polystal would decrease 50% if produced locally (Aschenbroich, 1991). Though the amount of material is the same (with the exception of the helical wind), the cost increases substantially when the tendon diameter decreases. This is a direct result of the time consuming application of the helical wind and surface coating. Regardless of the rod diameter, the maximum number of rods pultruded in a single pull is limited due to the method of applying a helical wind. The machines which apply the wind are bulky, allowing only a certain number of machines to operate per pultrusion machine. As the number of rods increase per cable bolt, so does the man-hours and machine time needed to produce then, resulting in a higher cost.

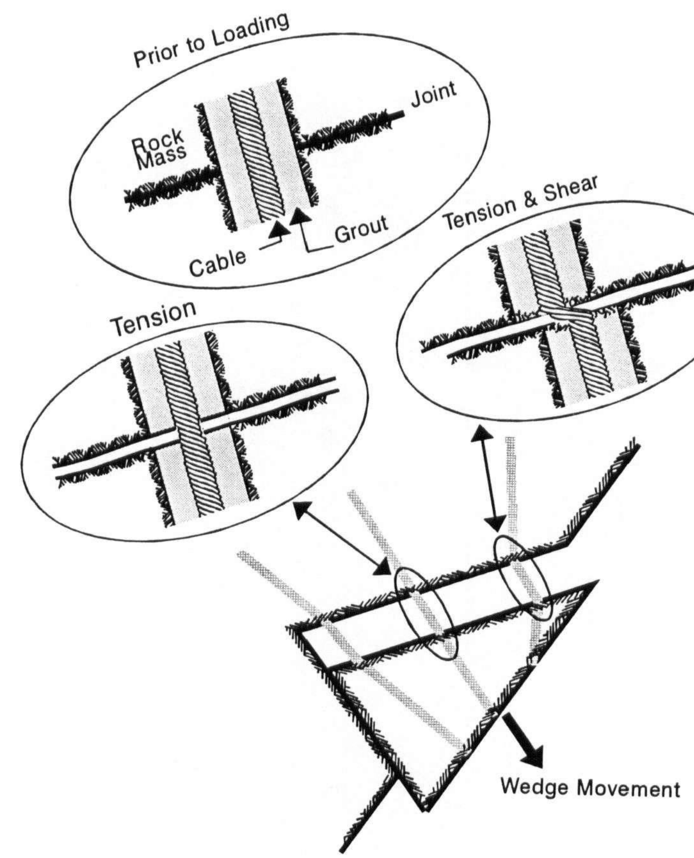


Figure 46. Modes of Loading Cable Bolt Support

4.1.2.3 Shear Strength

A cable bolt can be loaded in tension, shear, torque or a combination of these. Figure 46 shows a common loading sequence of cable bolts involving tension and tension with shear. Preliminary shear testing was conducted on composite cable bolts to determine the worst case scenario, a shear force applied 90 degrees to the cable's longitudinal axis while no tension is applied to the cable bolt. Samples were made using coated Polystal and Pacific Pultrusions' composite and were triplicated. Type 30 cement at a 0.35 water:cement ratio with a 7 day cure was used.

The Polystal cable bolts consisted of four, 7.7mm diameter rods while the sample from Pacific Pultrusions was made from ten, 6.35mm (0.25in) diameter rods. Results can be found in table 5. Polystal has a higher shear strength if the cross sectional area of the cable is .equal to Pacific Pultrusions' composite. However, in comparing cable bolt prototypes, Pacific Pultrusions' cable has a larger cross sectional area due to its lower tensile strength. As a result, Pacific Pultrusions' has the highest tested shear strength for a composite cable bolt prototype.

Table 5. Preliminary Shear Strengths

	Pacific Pultrusions	Polystal
Shear Load (kN)	98.7	62.3
Tensile Strength (kN)	293.0	217.5
Shear Strength as Percentage of Tensile Strength	33.7	28.7
Cross Sectional Area (cm^2)	3.17	1.86
Shear Strength per Cross Sectional Area (kN/cm^2)	31.1	33.5

4.2 Conclusion of Composite Evaluation

In scrutinizing the results of the second step of composite evaluation, it was decided that Pacific Pultrusions could offer the best opportunity in producing a commercially competitive glass fibre cable bolt. Composites previously produced by Pacific Pultrusions have not been used as a reinforcing medium which necessitates a higher quality control. The company's resident engineer acknowledged that a high quality composite with a suitable gritted surface could be produced.

During Step II of the test program, Con-Tech Systems of Delta, B.C., started to import uncoated Polystal and market it in the form of cable bolts (figure 47 & 48) at a price of eleven dollars per metre. Though Polystal has sufficient characteristics as a cable bolt, its cost and availability is not conducive to commercial acceptance within the mining industry. This would change if the patent was purchased allowing Polystal to be produced locally, however, Con-Tech could not financially commit to this until a market of glass fibre cable bolts already existed.

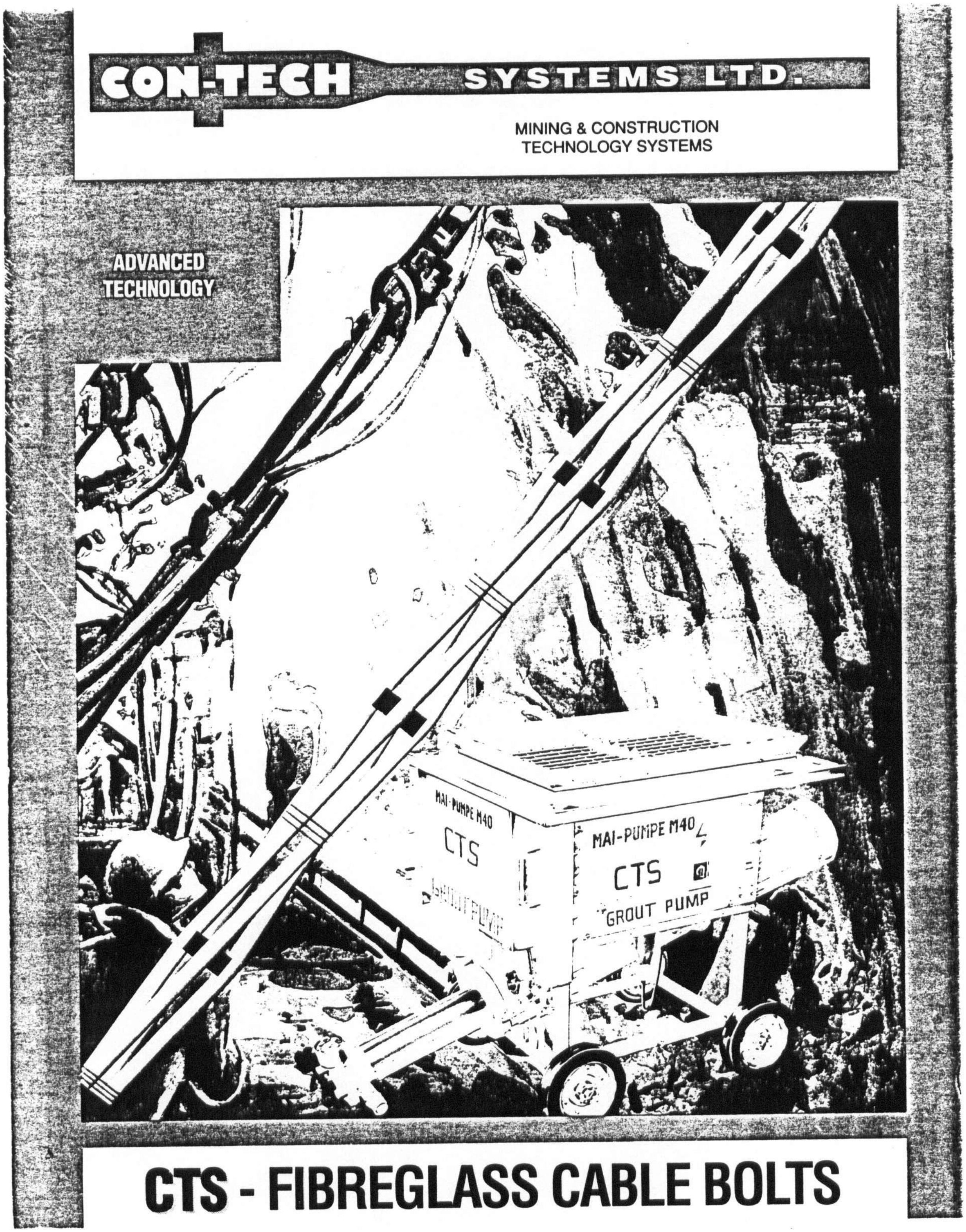


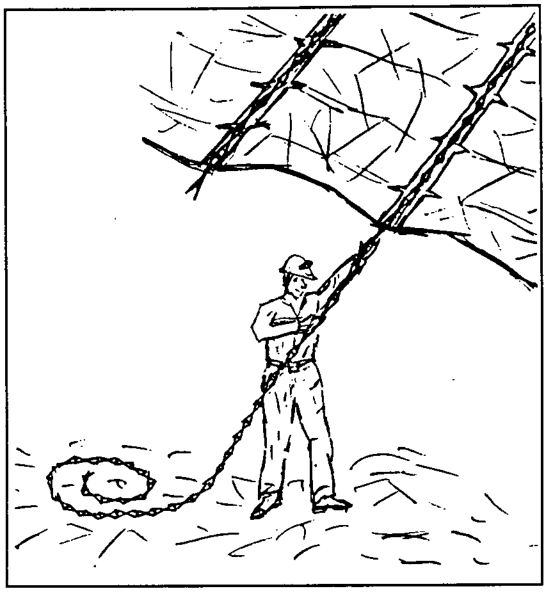
Figure 47. Sales Brochure for Polystal Cable Bolts, Produced by Con-Tech Systems Ltd. (page 1 of 2)

CTS - FIBREGLASS CABLE BOLTS

An extensive research program is currently in progress at the University of British Columbia (UBC) to assess the viability of various continuous fibre reinforced polymer composites for the use of cable bolting in Canadian mines. The program has been divided into two phases.

Phase 1 was sponsored by HDRK. During this investigation, a prototype fibre glass cable bolt (FCB) was jointly developed by **CON-TECH SYSTEMS** using the Polystal material. Its viability was assessed through laboratory testing, field testing and trial installations. During the evaluation of the FCB, many important aspects other than pull out load were investigated. This phase has been completed and served as the frame work for Phase II.

Phase II is currently in progress under the sponsorship of the British Columbia Science Council. This portion of the study will also assess various existing composites as cable bolt reinforcement.



CON-TECH SYSTEMS LTD. fabricates the composite fibreglass cable bolt for the increasing demands of the mining industry for a cuttable rock support for continuous hard rock mining methods.

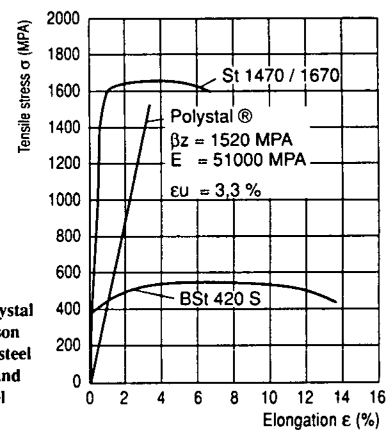
The composite selected to replace steel had to meet the following criteria:

- Must be cuttable
- High tensile and with moderate shear strength
- Flexible
- Does not effect mill process
- Low health and environmental risk
- Non flammable

Polystal material meets all the above criteria and C.T.S. has developed a system using 4/P77 construction profile polystal rods (ultimate load capacity 28 tonnes) which are manufactured into a cable in the C.T.S. plant in Delta B.C.

Property Comparison Between Steel and Polystal

	PRESTRESS STEEL	POLYSTAL
Tensile Strength MPA	1670	1520
Yield Strength MPA	1470	0
Ultimate Strain %	6	3.3
E. Mudulus MPA	210,000	51,000
Specific Weight	7.85	2.0



Stress-Strain Diagram of Polystal (R) in comparison to prestressing steel St 1470 / 1670 and reinforcing steel BSt 420 S

CON-TECH SYSTEMS LTD.

8180 River Road, Delta, B.C. Canada V4G 1B5
(604) 946-5571 Fax (604) 946-5548

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Figure 48. Sales Brochure for Polystal Cable Bolts, Produced by Con-Tech Systems Ltd. (page 2 of 2)

Chapter 5

DEVELOPMENT of DAPPAM

The following chapter discusses Step 3 of the research program. This involves laboratory testing completed on Pacific Pultrusions product to determine the optimum composite structure, cable bolt configuration and surface fixtures. One hundred and four pull tests were completed at UBC to obtain the results presented within this chapter. The chapter culminates by defining the optimum cable bolt configuration, which was used for subsequent testing and in commercial manufacturing.

5.1 STEP 3. Development of DAPPAM

Continued research in Step 3 focused on developing a glass fibre cable bolt prototype utilizing Pacific Pultrusions' facilities. This step of the project strived to increase the performance of the composite produced, increase the quality of the surface coating, while decreasing the cost of the overall product in aid of making it commercially available, competitive and accepted (figure 49).

5.1.1 COMPOSITE STRUCTURE

Laboratory tests were completed to determine the effects of glass fibre quality, resin type and the method of surface preparation for the adhesion of the "grit" surface coating. Two types of glass fibre rods were pultruded. The first type utilized a 13μm diameter, high quality ECR glass bonded with a modified acrylic (methomethacolate) resin (known as yellow), while the second type utilized a 21μm diameter ECR glass and an isophthalic polyester resin (known as blue). Three methods of surface preparation were completed to the two composite types (yellow and blue) prior to the application of a fine sand grit. The types of surface preparation were:

STEP 1	STEP 2	STEP 3	STEP 4	STEP 5	STEP 6
Initial Composite Evaluation	Secondary Composite Evaluation	Optimize Composite	Laboratory Evaluation	Trial Installations	Marketing
Polystal Pacific Pultrusion Californian FRE Pultrusions	Polystal Pacific Pultrusion	Pacific Pultrusion			
Evaluated by: • Quality • Surface Properties • Availability • Cost	Evaluated by: • Performance • Cost • Production	Optimize: • Surface Coating • Cost • Configuration • Unit Performance	Repetative Depending on Performance		

Figure 49. Research Flowchart - Step 3, Optimize Composite

1) Surface of the composite underwent sandblasting and was wiped clean.

2) Surface of the composite was chemically cleaned with 1,1,1 trichloroethane.

3) Surface of the composite was left unaltered after being pultruded.

After the composites' surfaces were prepared, a thin coat of epoxy was applied manually prior to the fine sand grit. Pull test samples were prepared using one rod with a 152mm bond length (equal to 3000mm^2 surface area). The pull test samples utilized type 30 cement with a 0.35 water:cement ratio and were allowed to cure for seven days. Tests were completed in triplicate. All test samples failed by having the surface coating stripped from the composite rod (figure 50).

The highest bond strength tested since the onset of the research program (Phase II) was achieved in this test series. Every sample tested showed an increase in bond strength over the modified samples tested in step 2 of the project, including coated and uncoated polystal. The second best result was using the "blue" rod with no surface preparation

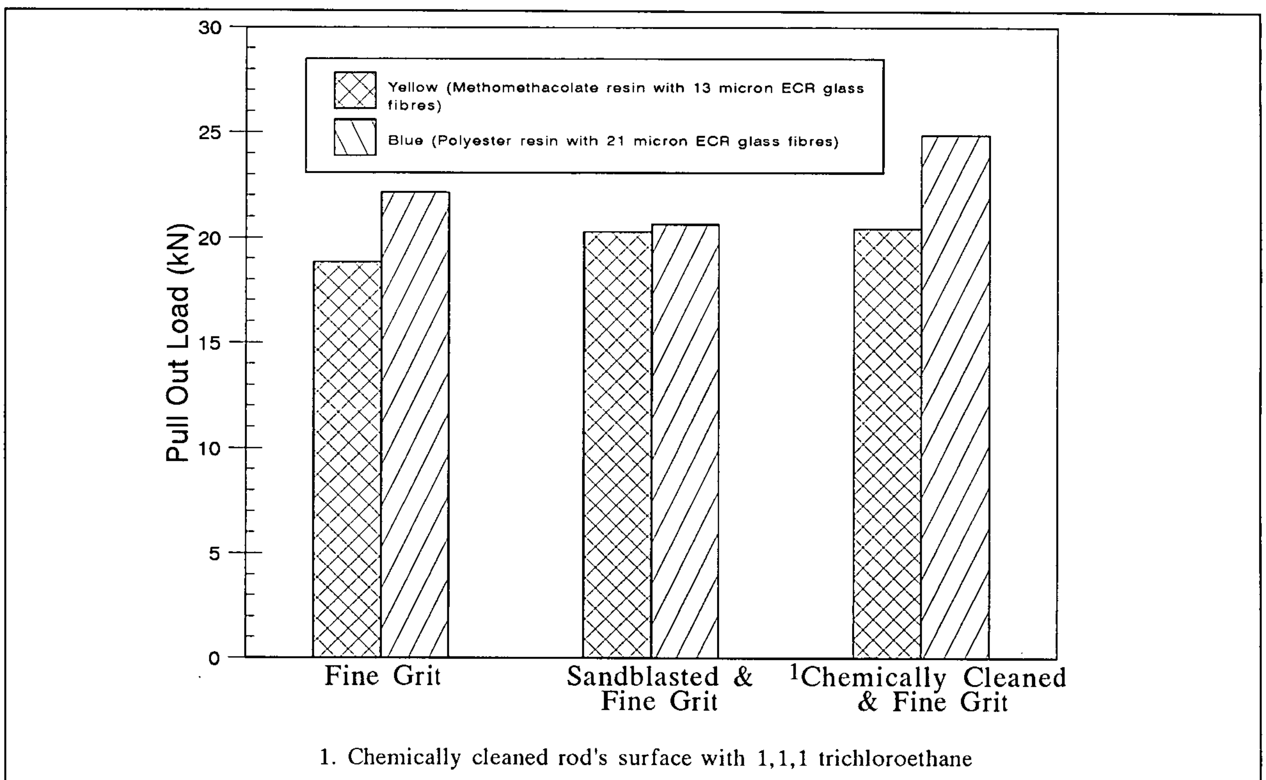


Figure 50. Surface Modifications on Rods

prior to the addition of the sand grit. In conducting the Students T-test, all samples (yellow and blue) which under went sandblasting prior to surface application came from the same sample population, indicating that the type of composite did not influence the bond strength when its surface was sandblasted. In considering the cost and effort in preparing the rod's surface by chemically cleaning, it was determined to be more cost efficient to apply the sand grit directly onto the "blue" rod (21μm ECR glass fibre with isophthalic polyester resin).

Additional tests were conducted to determine the tensile strengths of the altered pultruded products. Figure 51 shows the ultimate tensile strengths achieved by each sample. Included for comparison purposes are Polystal and Pacific Pultrusions "white" sample which is constructed with 21 micron ECR glass fibre and a polyester resin. The white samples were pultruded prior to the onset of the research program. Though five samples were made using the "yellow" composite, four of the samples had their surface

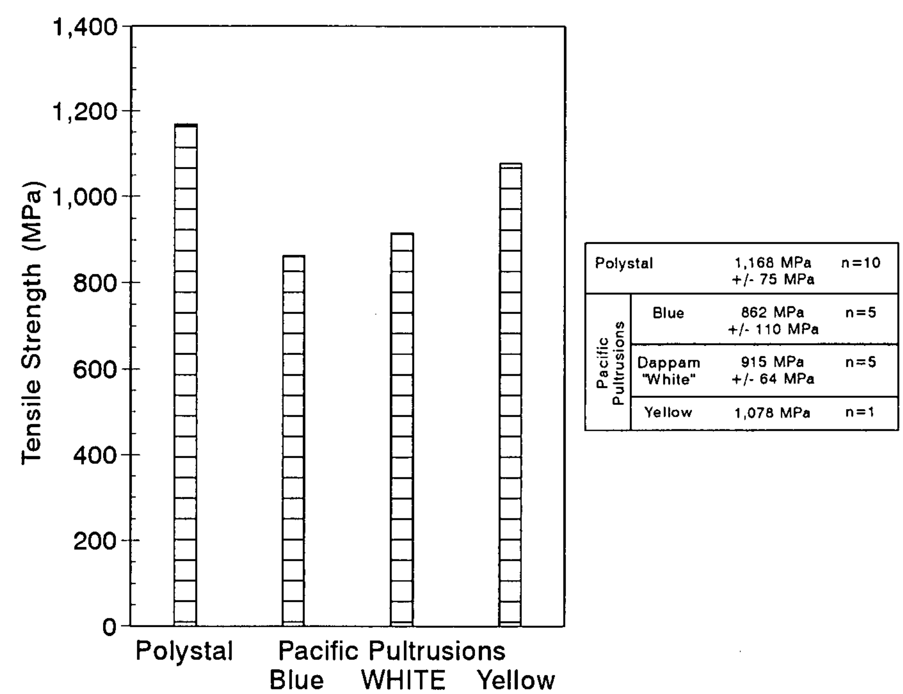


Figure 51. Tensile Strengths

coatings stripped off prior to reaching the rods critical bond length. This occurred even though the samples had an embedment length of 381mm. The bond strength between the "yellow" rod and its surface coating was insufficient.

The test results indicated that using the high quality glass (13μm) had not given the composite a sufficient increase in tensile strength to justify its use. The 13μm quality glass costs approximately twice that of the 21μm glass.

In order to achieve commercial manufacturing of the composite cable bolt, the surface coating must be applied mechanically at the time of rod pultrusion. Early in the research program, all samples had their surface coating applied by hand methods. Pull tests were completed on some of these samples in order to develop a "base" bond strength so comparisons could be made with future samples to evaluate the effectiveness of the mechanical method of surface application. In addition, two types of sand grit were evaluated. Figure 52 displays the results and compares them to Polystal. All samples

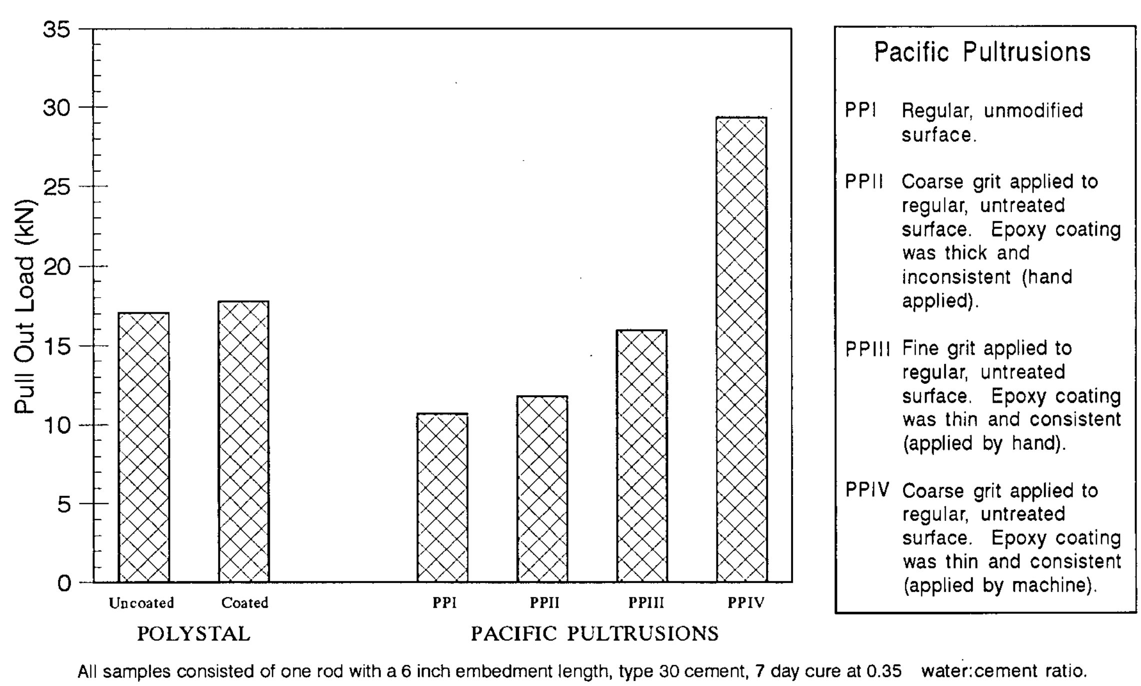


Figure 52. Polystal vs Modified Pacific Pultrusion Rods

consisted of one rod with a 152mm bond length, type 30 cement, 0.35 water:cement ratio and were allowed to cure for seven days. The difference between the test series PPII and PPIV was the consistency and thickness of the epoxy coating which bonds the coarse grit to the composite rod, while the pull out load experienced by each is significantly different. All samples except PPIV failed by the surface coating peeling off from the composite rod. PPIV samples failed by the composite rod reaching its ultimate tensile strength. The surface coating/rod bond did not fail, indicating a sufficient bond strength of the surface coating had been achieved.

Subsequent pull tests were completed in order to evaluate less expensive materials used to adhere the sand grit to the surface of the rod. All previous test samples utilized a modified epoxy. Test series XXV evaluated an Acrylic Polymer (Rhoplex LC-40) and a Polyester Resin, both costing significantly less than the modified epoxy. Three cable bolt samples each consisting of ten rods were tested with each of the resin types tested. A water:cement ratio of 0.35, (ucs = 62.5 +/- 2.7 MPa) was utilized in 15.25cm bond lengths. The tests were done in triplicate with the exception of the Polyester Resin, which had only two samples as a result of grouting problems. The results are shown in figure 53.

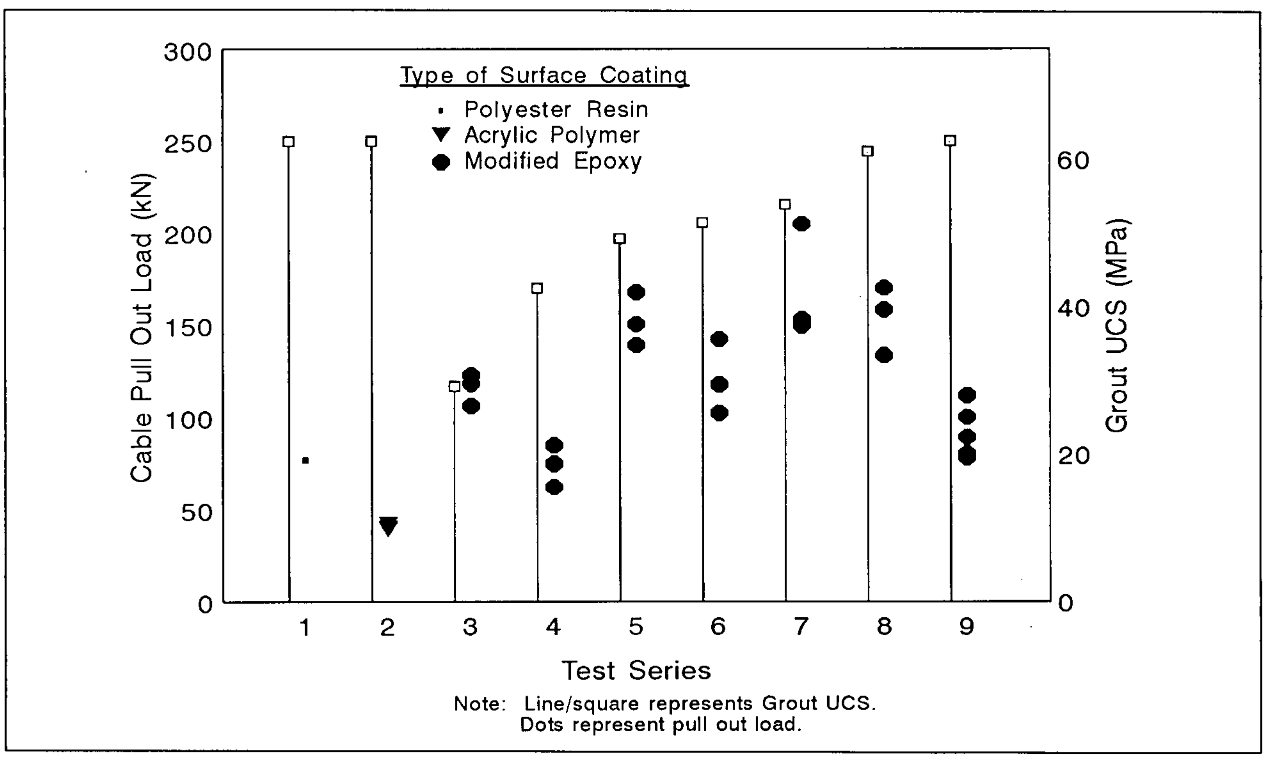


Figure 53. Variance of Surface Coatings - Quality

As the grout strength increases, it is expected that the pull out load achieved by the cable bolt will increase linearly. In figure 53, test series 3 through 9 are tests conducted using the modified epoxy while test series 1 and 2 consist of the Acrylic Polymer and a Polyester Resin respectively. As shown, test series 1 and 2 have a low pull out load compared to the sample's grout strength, significantly lower than most of the test series shown. As a result, the modified epoxy is better suited to adhearing the sand grit to the rod's surface.

5.1.2 CABLE CONFIGURATION

During the early part of the test program it was assumed that the configuration of the cable would play a critical part in determining the performance and cost of the cable bolt. Pull tests were completed to determine the effects of altering the number of rods, diameter of rods and orientation of the rods.

5.1.2.1 Basic Cable Configuration

Due to constraints at the manufacturing stage by Pacific Pultrusions, only two rod diameters were tested, 15.9mm and 6.4mm diameter rods, with minimal samples being available. Six samples were constructed using 6.4mm diameter rods with varying number of rods per sample. A sand grit was applied to the rods manually and the rods were randomly oriented within the pull test samples. Table 6 shows the samples and corresponding pull out loads while figure 54 graphically displays the results.

Table 6. Effects of Bonded Surface Area

Sample	Rod Diameter (cm)	Number of Rods	Area Bonded to Grout (cm^2)	Pull Out Load (kN)	Method of Failure
XX 1a	1.59	1	30.3	78.86	Pull Out
XX 1b	1.59	1	30.3	70.19	Pull Out
XX 2a	0.64	10	49.0	>233.0	Exceeded Machine Test Limits
XX 2b	0.64	10	49.0	>233.0	Exceeded Machine Test Limits
XX 3	0.64	6	29.4	157.9	Pull Out
XX 4	0.64	3	14.7	84.51	Pull Out
XX 5a	0.64	1	4.90	12.77	Pull Out
XX 5b	0.64	1	4.90	10.72	Pull Out

★ Note: Sample length = 15.24cm; Grout UCS = 51.68MPa

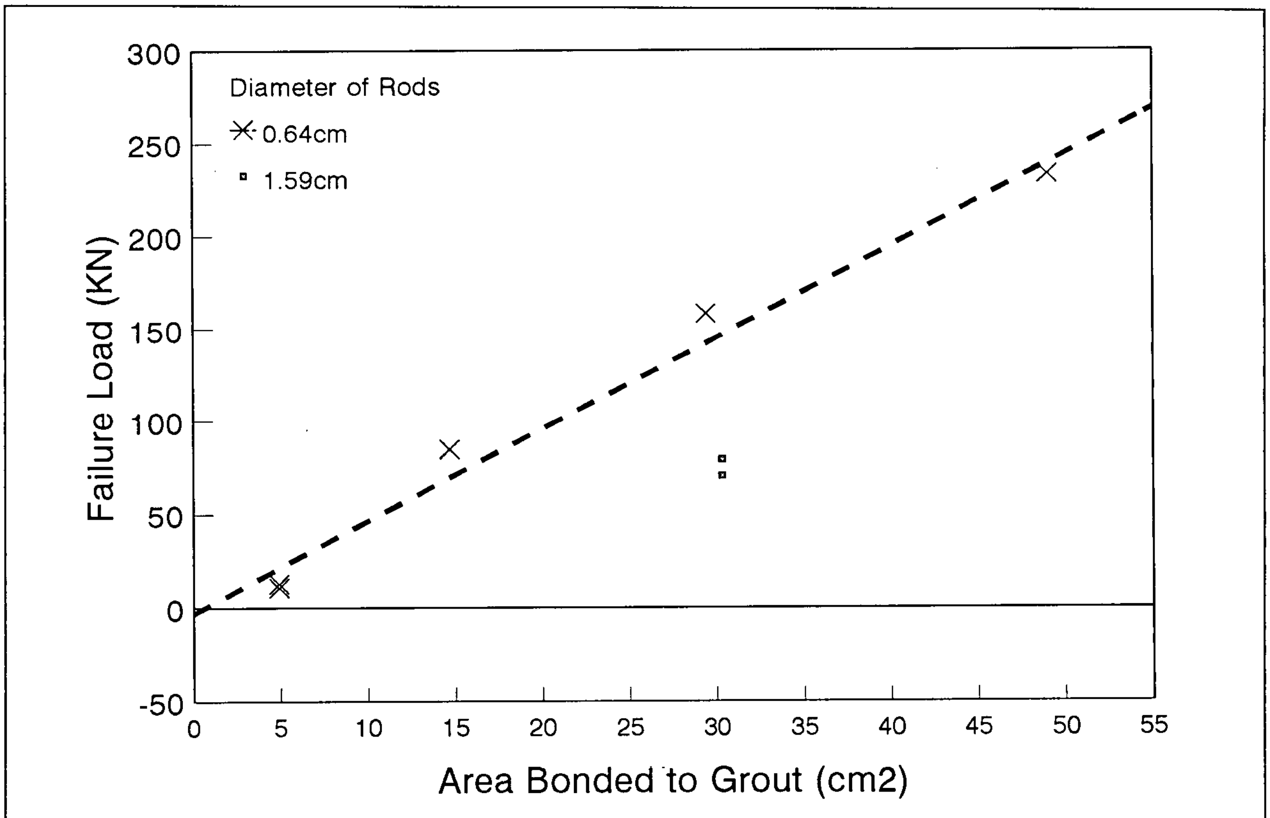


Figure 54. Effects of Rod Diameter on Pull Out Load

In figure 54, the 0.64cm diameter samples are shown with a linear relationship [load=4.94(bond area)-3.14], with the correlation coefficient high at 0.99. It is important to note the low pull out load associated with the 1.59cm diameter rod. Comparing the results to the 0.64cm diameter rods, it is clear that a sample's pull out load cannot be predicted by simply calculating and comparing its surface area which is bonded within the grout. As a result, the line defined by the 0.64cm diameter samples cannot be used to predict pull out loads for samples comprised of rod diameters other than 0.64cm. It can, however, be used to predict the pull out loads for samples with 0.64cm diameter rods, if all other test parameters are considered constant.

To determine the basic cable bolt configuration (number of rods vs. diameter of rod) the material's apparent tensile strength and the cable bolt's projected tensile strength were considered. With the apparent tensile strength of Pacific Pultrusion's modified composite being used (915MPa) and the designed ultimate tensile strength of the cable bolt at approximately 289kN, the cable bolt must have a cross sectional area of $2.917 cm^2$ (Note: the apparent tensile strength was derived from earlier test results achieved through pull testing). Table 7 reveals the possible cable bolt configurations.

Table 7. Cable Configuration

Number of Rods	Diameter of Rods[1] (cm)	Theoretical Minimum Drill Hole Diameter[2] (cm)	Comments
11	0.60	4.46	
10	0.64	4.54	Tight fit into 4.45cm diameter drill hole
9	0.67	4.60	Tight fit into 4.45cm diameter drill hole
8	0.71	4.68	Tight fit into 4.45cm diameter drill hole
7	0.76	4.78	Tight fit into 4.45cm diameter drill hole
6	0.82	4.90	Tight fit into 4.45cm diameter drill hole
5	0.90	5.06	Would not fit into 4.45cm diameter hole
4	1.00	5.26	Would not fit into 4.45cm diameter hole

1 Does not include surface coating
2 Includes thickness of surface coating and 0.64cm gap between cable and drill hole

As the number of rods increase within the cable bolt, the diameter of the rods decrease, which in turn, increases the cable bolt's surface area. This would increase the pull out resistance of the cable bolt. However, as the number of rods increase, the price of the cable bolt increases as a result of increased application of surface coating and lower production rates. The decision to use ten rods per cable bolt was based on:

1) It was the only dye currently available. Construction of another dye would have introduced considerable delays.
2) Using ten rods or less infringes on the 0.64cm gap allowed for clearance between the cable bolt and drill hole.
3) Using eleven rods increases the cost of the cable bolt as compared to ten.
4) Taking into consideration of the drill hole diameter and diameter of grout tube, configuring eleven rods around the grout tube is more difficult as compared to ten rods.
5) The tensile strength of the material used was accurate.

As a result, future cable bolt prototypes would continue to use ten pultruded rods, each with a diameter of 0.64cm given that the composite's tensile strength was 915MPa.

5.1.2.2 Secondary Cable Configuration

Five initial cable bolt prototypes were constructed to determine the influence, if any, of rod configuration on pull out load. The five prototypes can be seen in figure 55, while table 8 describes each prototype. Initial pull tests were conducted on the prototypes in order to observe individual pull out characteristics. Table 9 displays the results, while figure 56 shows the pull out curves associated to each configuration. Observations after testing revealed different types of failures occurred depending on the sample's configuration.

Table 8. Prototype Configurations

Prototype	Comments
Type I	Ten rods bunched together, similar to conventional steel cable bolt
Type II	Random orientation of rods within the drill hole
Type III	Ten rods wrapped around grout tube. Rods touching grout tube.
Type IV	Ten rods wrapped around grout tube. Rods separated from each other and grout tube by using a solid spacer.
Type V	Ten rods wrapped around grout tube. Rods connected using a flexible spacer. Spacer allows the rods to orientate themselves, i.e. rods may touch grout tube or another rod.

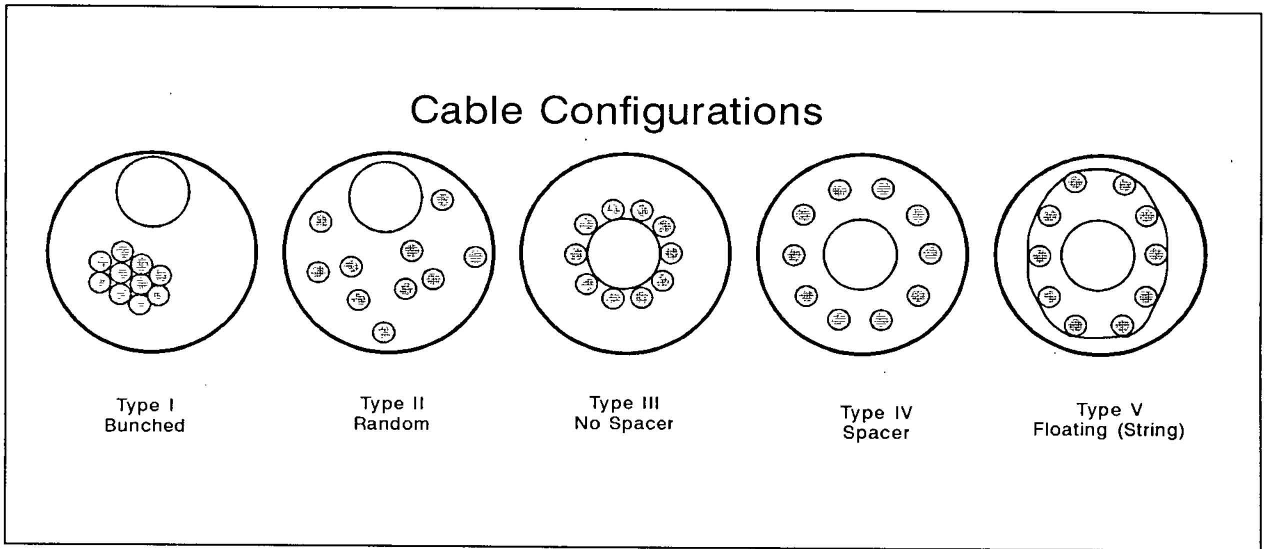


Figure 55. Cable Bolt Configurations

Table 9. Effects of Cable Bolt Configuration

Configuration	Grout UCS (MPa)	Number of Samples	Failure Load (kN)
Type I	53.9	2	133.6
Type II	51.7	2	> 232.0★
Type III	61.1	2	153.7
Type IV	61.1	3	154.0
Type V	61.1	2	174.8

Each sample had a bond length of 15.24cm (6in).
★ Note: Exceeded test machine's load limit

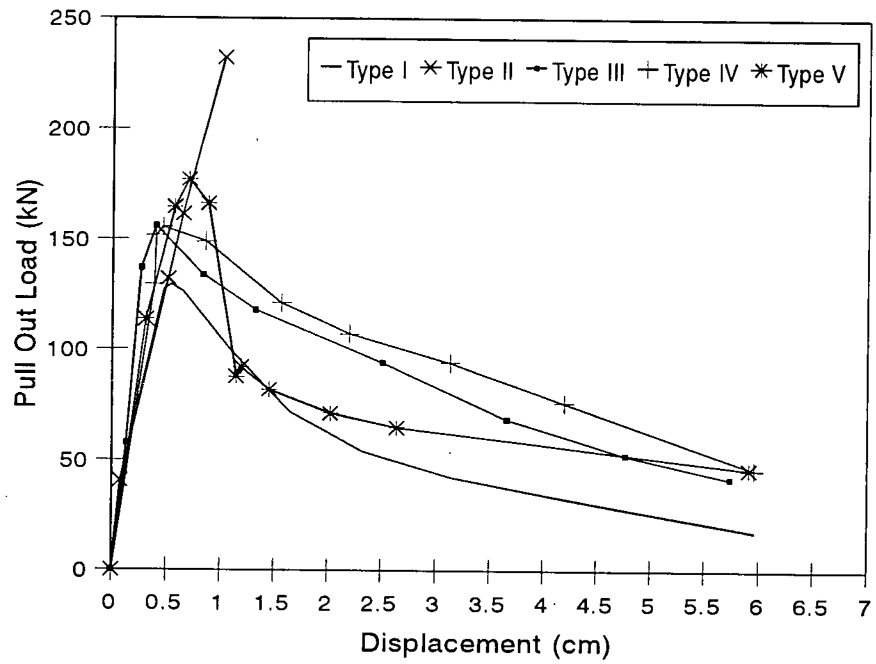


Figure 56. Pullout Curves From Tested Cable Bolt Configurations

The failure surface can be described as the shear surface created when massive cable bolt displacement occurs with respect to the grout. The failure surface is initially thought of being comprised only of the surface of the cable bolt (where the shearing occurs), however, some of the failure surface (shearing) is within the grout. This can be seen in figure 57, which shows the failure surface of each of the prototypes.

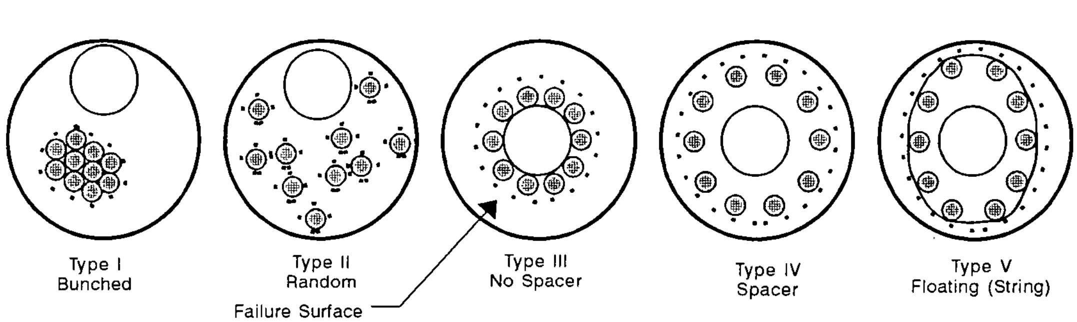


Figure 57. Failure Surfaces

Post failure observations of type I indicated that the grout flutes were crushed and left intact within the cable once the sample had failed. This yields a small and distinct failure surface as compared to type IV, where the shear surface is approximately the outer diameter of the cable bolt. When type IV samples failed, the grout between the grout tube and individual rods remained with the cable bolt while massive cable/pipe displacement occurred. The grout between the rods and grout tube was sheared off and displaced with respect to its original position within the pipe. Unlike all other configurations, type II's failure surface could not be examined since the sample's applied loads reached the limits of the pull test machine without causing the sample to fail. It is hypothesized that the load transfer from the rods to the grout is better distributed throughout the grout in this configuration, increasing the size and shear strength of the failure surface.

In review of the test results, it was decided to conduct additional testing on configurations type III, IV and V. Though the load generated by samples configured with random rod orientation (type II) exceeded the limit of the test machine, random positioning of the rods within the drill hole is not practical from an installation perspective. Type I orientation would be the least expensive to manufacture, however it leads to bleeding of the grout and does not take full advantage of the cable bolt's surface area.

Test series XXIII and XXIV were developed to test configurations III, IV and V using two cement grout compressive strengths and two cable bond lengths. The samples were completed in triplicate. Table 10 displays the series' test parameters.

Figures 58, 59 and 60 display the load carrying capacity of each cable configuration for two grout compressive strengths. In conducting a statistical analysis on the data, the Students T-test revealed that each data group tested were from different populations using a 5% significance level. In observing figure 59 (type IV), the difference of failure loads between 51.4MPa and 61.1MPa grout is

Table 10. Pull Test Parameters

Cable Configuration	Water:Cement	Bond Length	# of Samples Tested
Type III (no spacer)	.35	15.25	3
	.35	22.90	3
	.45	15.25	3
	.45	22.90	3
Type IV (spacer)	.35	15.25	3
	.35	22.90	3
	.45	15.25	3
	.45	22.90	3
Type V (string)	.35	15.25	3
	.35	22.90	3
	.45	15.25	3
	.45	22.90	3

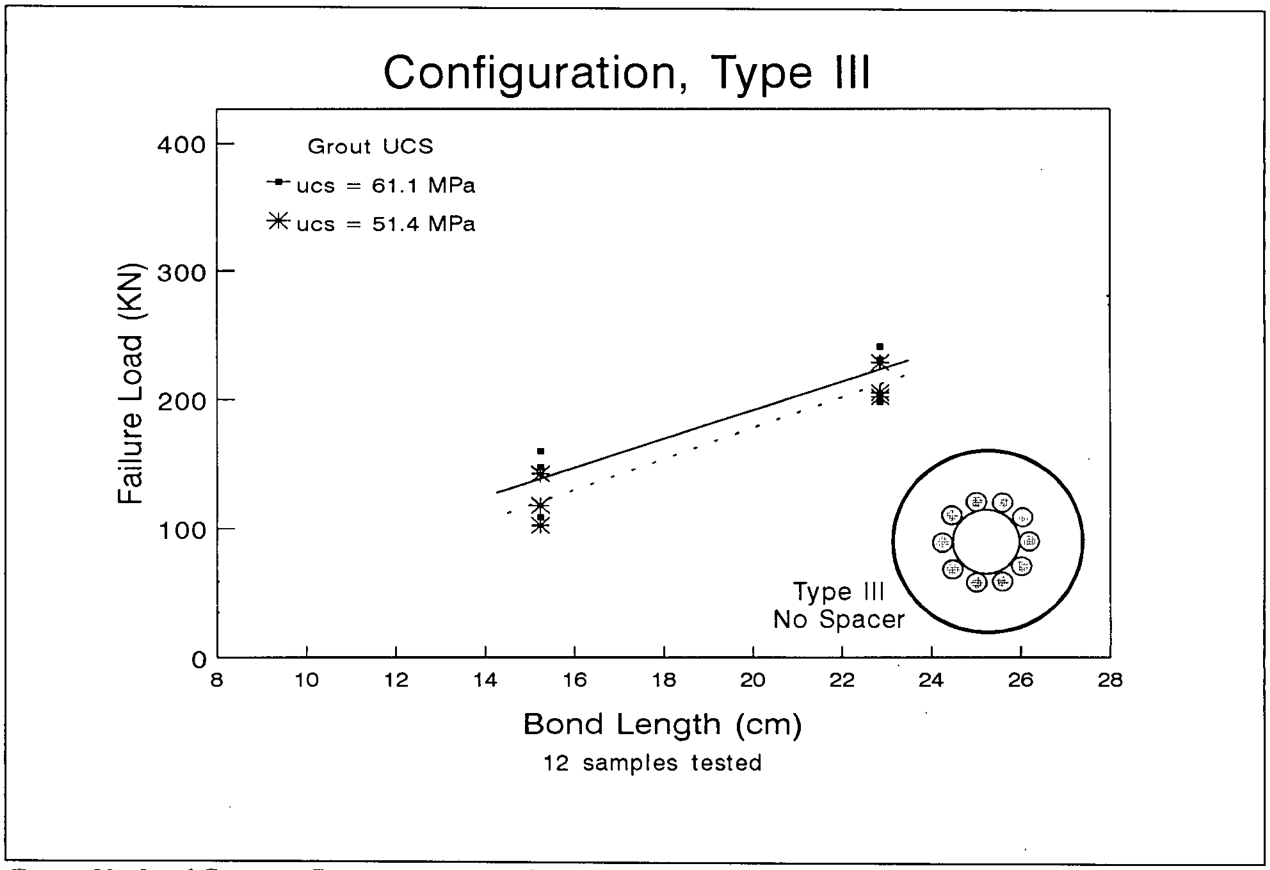


Figure 58. Load Carrying Capacity - Type III Configuration

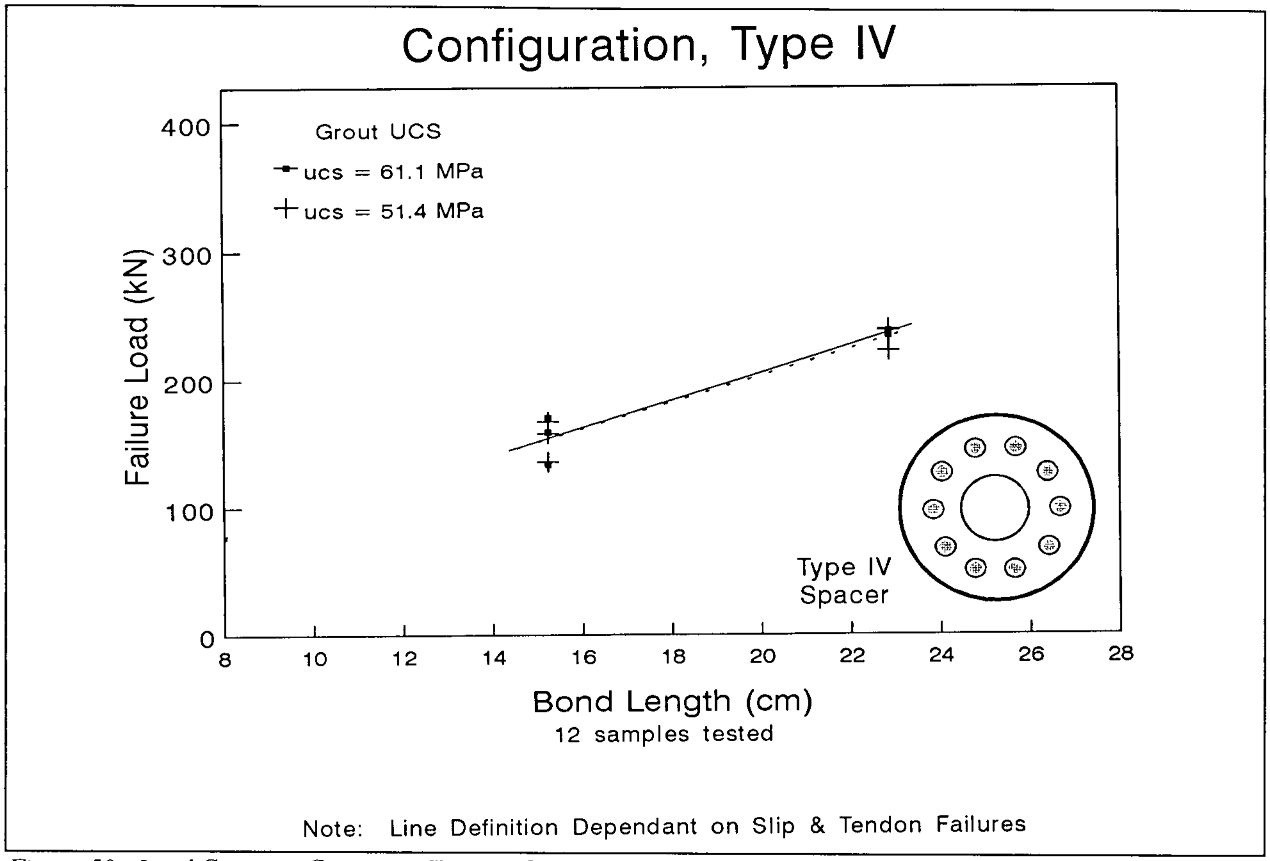


Figure 59. Load Carrying Capacity - Type IV Configuration

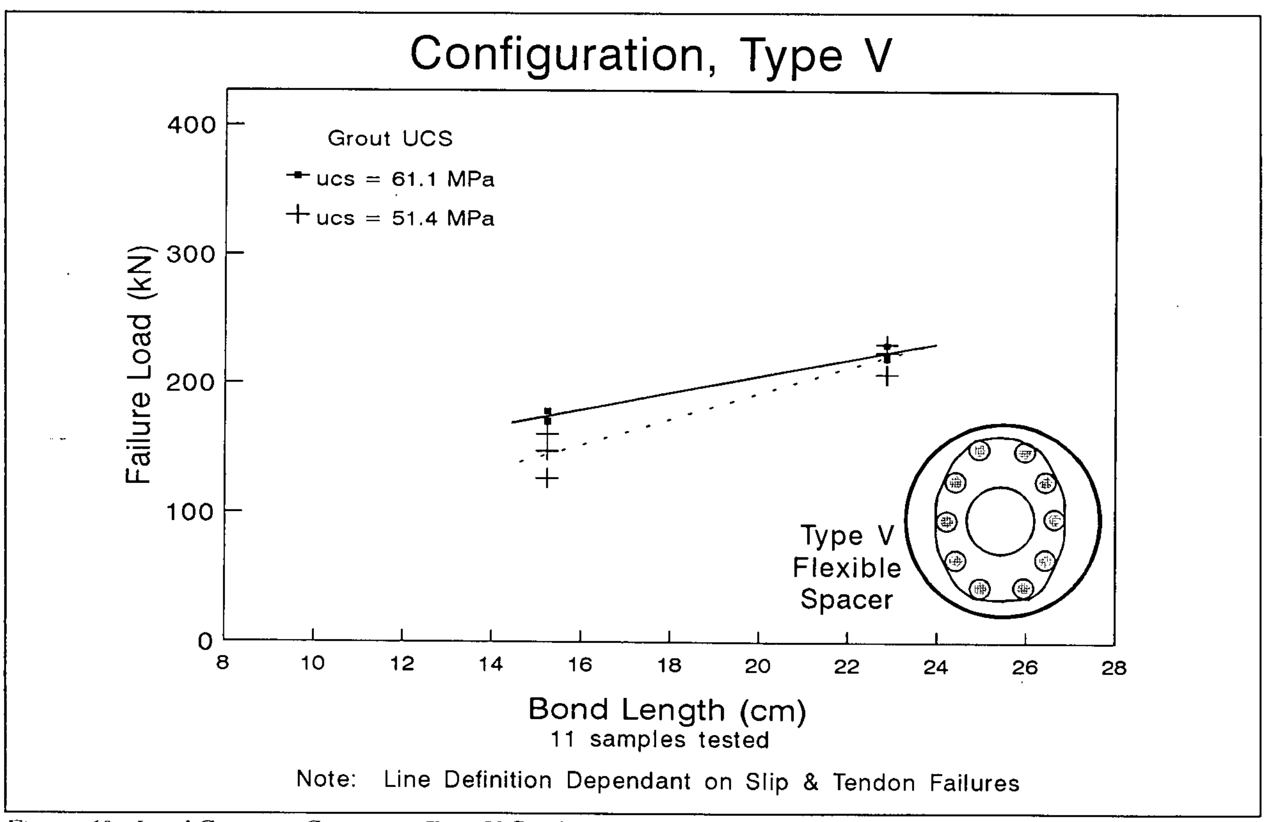


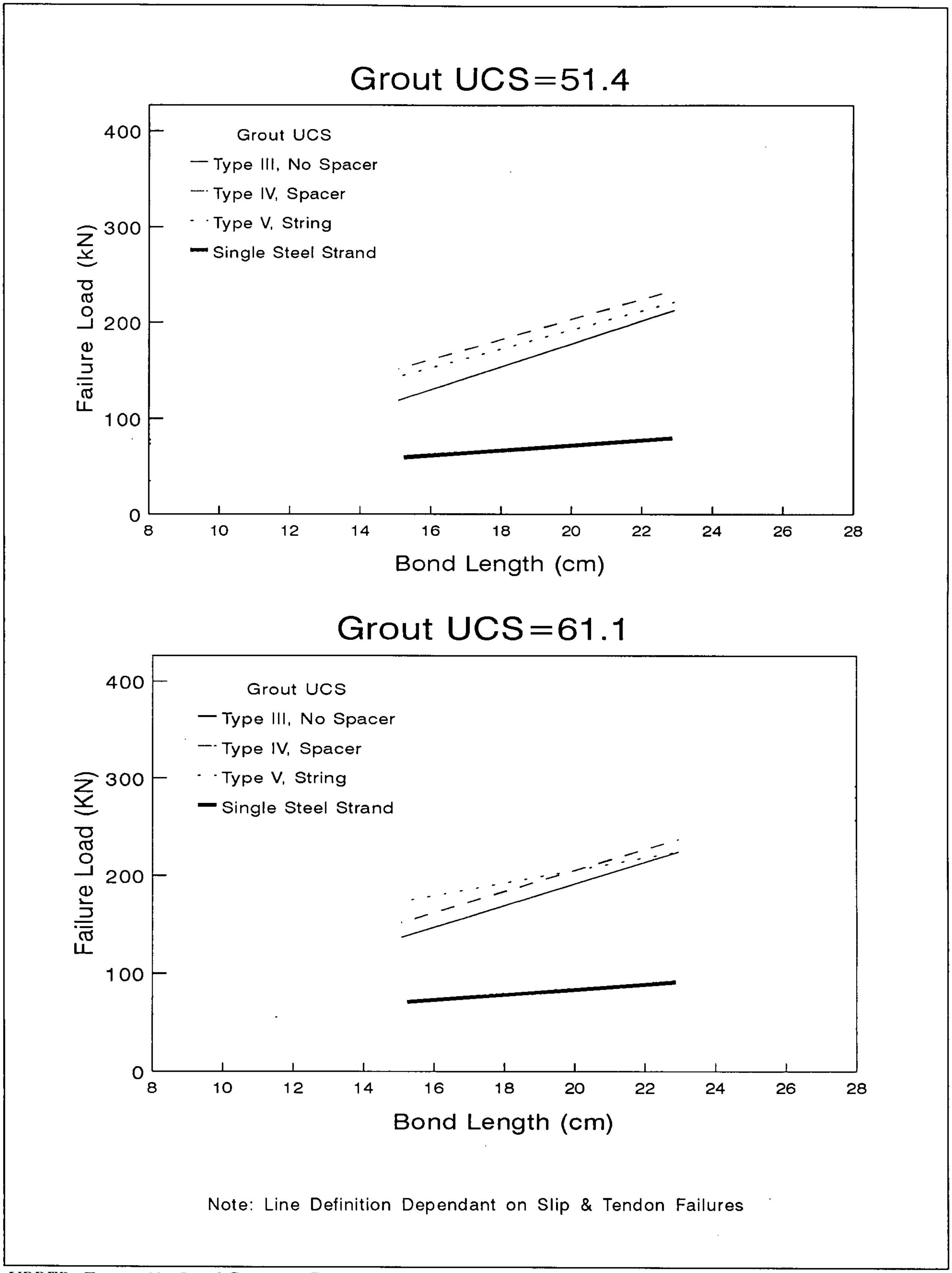
Figure 60. Load Carrying Capacity - Type V Configuration

minimal. In conducting the Students T-test using a smaller confidence interval (1%), the sample populations for the 15.24cm bond lengths are considered to be from the same population. This does not hold true for the samples having a bond length of 22.86cm (type IV). Regardless, the overall trend of type IV is evident in figure 59. The effects of varying the grout compressive strength (water:cement ratio) for type IV is minimal, especially when compared to regular steel cable bolts.

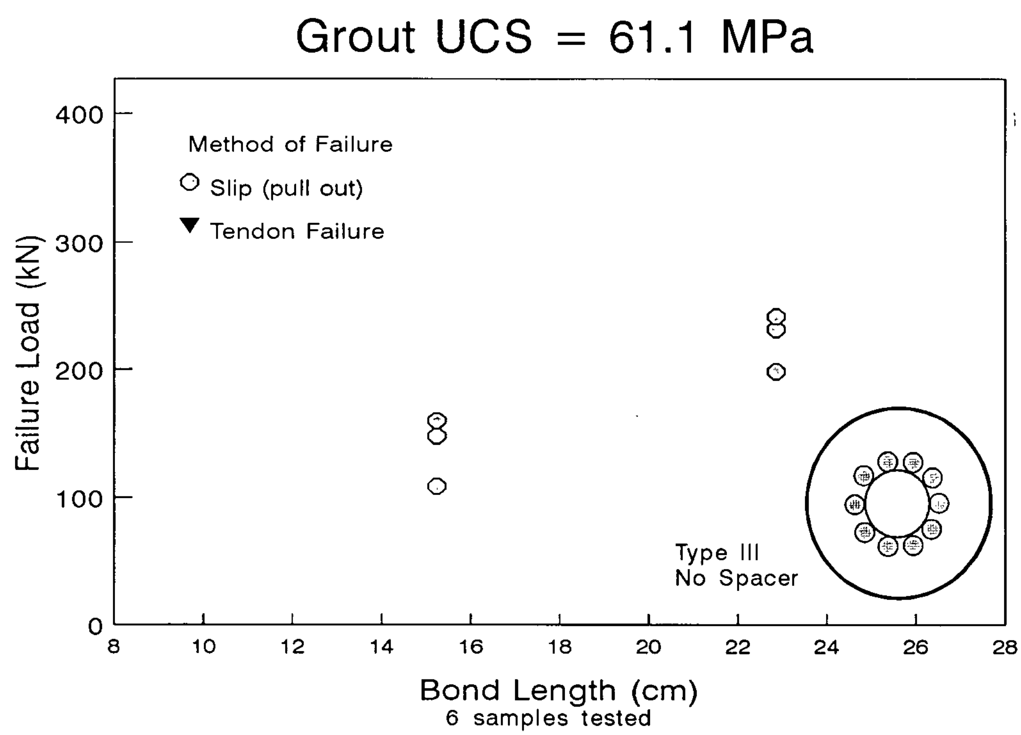
Figures 61 and 62 displays the load carrying capacities of the three prototypes compared to a conventional steel cable bolt. The line definition for the steel cable bolt is defined by test series XIX. It is evident that the configuration of the rods within the cable bolt does influence the load carrying capacity of the glass fibre cable bolt.

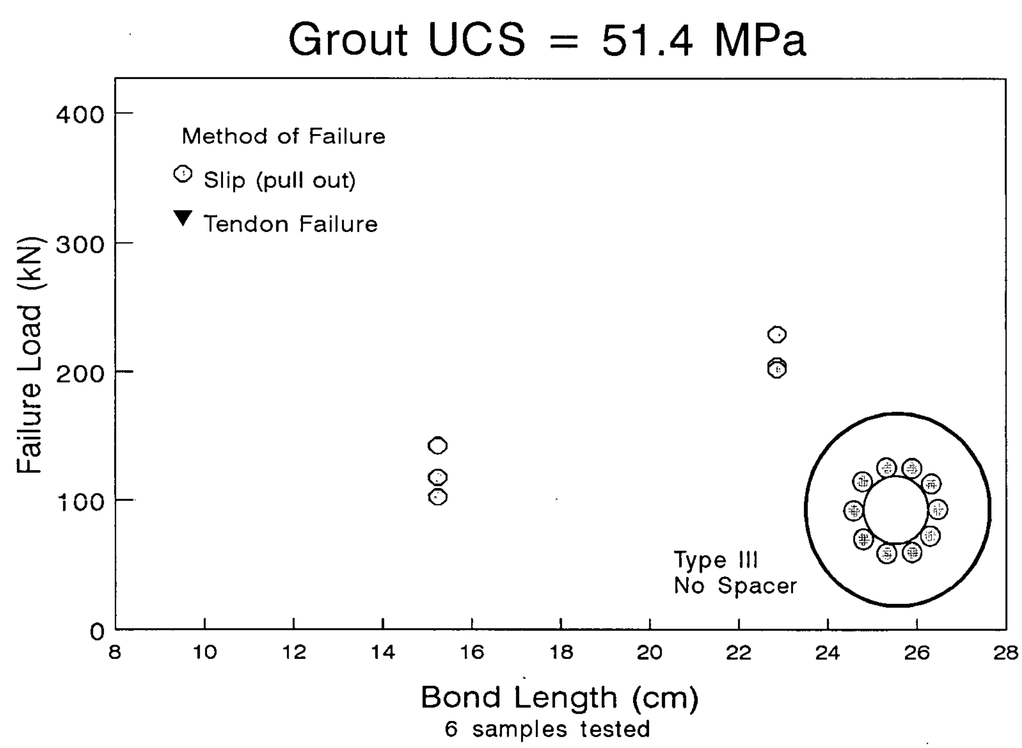
In addition to the load at which a cable bolt fails, the method of failure is also of importance. If the sample length is less than the cable's critical bond length when testing regular steel cable bolts, the sample will fail by the cable pulling out of the grout through massive grout/cable displacement. It was assumed that this would also occur for the glass fibre cable bolt samples. In observing the results of test series XXIII and XXIV and the methods of failure in which the test samples failed (figures 63-68) it is evident that the method of failure in the glass fibre prototypes is different than that of steel cable bolts.

Two types of failure were experienced in testing the two test series. The first type of failure can be seen in figure 63 and 64 (type III). All samples failed by pulling out of the grout through massive cable/grout displacement. This is the same type of failure as experienced in testing steel cable bolts (Goris 1990), and the type of failure expected to occur in all glass fibre cable bolt samples which had a bond length less than its critical bond length. However, in observing figures 65-68, some samples (type IV & V) experienced violent rod failure within the cable bolt. The number of rods failed within the cable bolt varied

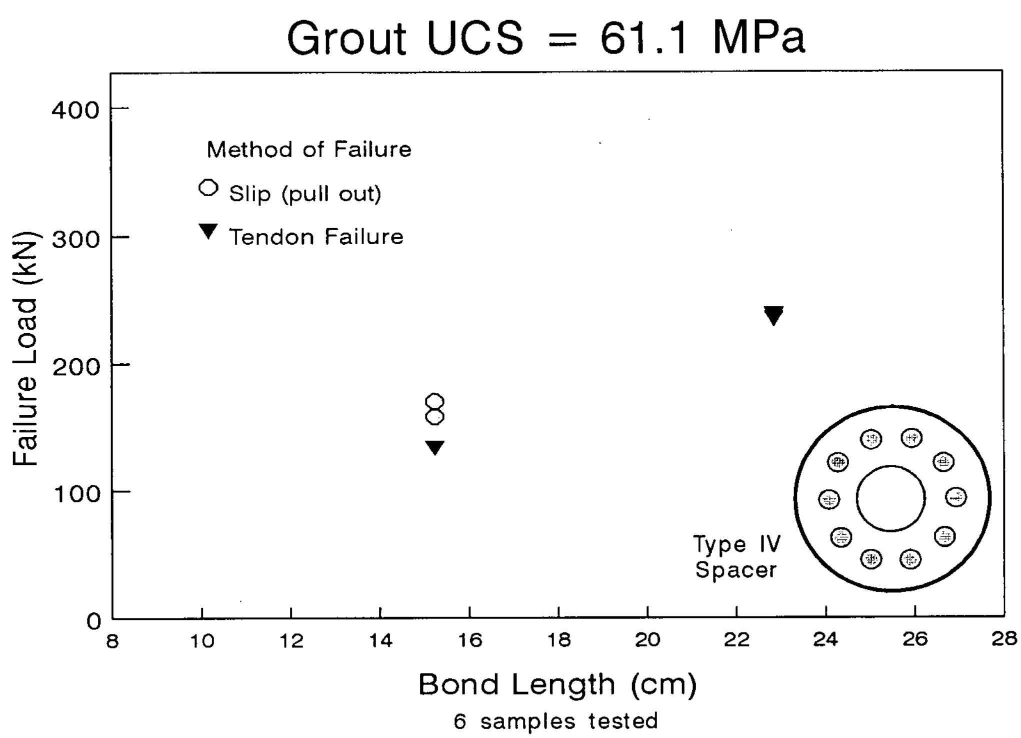


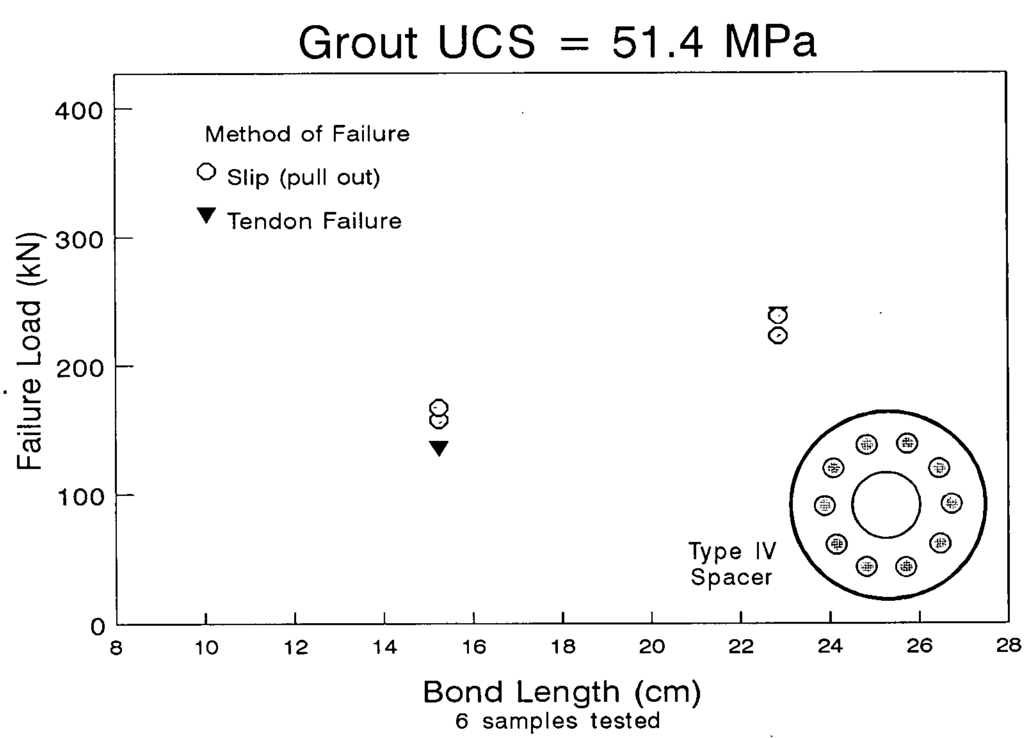
UPPER: Figure 61. Load Carrying Capacity at 0.45 water:cement
LOWER: Figure 62 Load Carrying Capacity of 0.35 water:cement



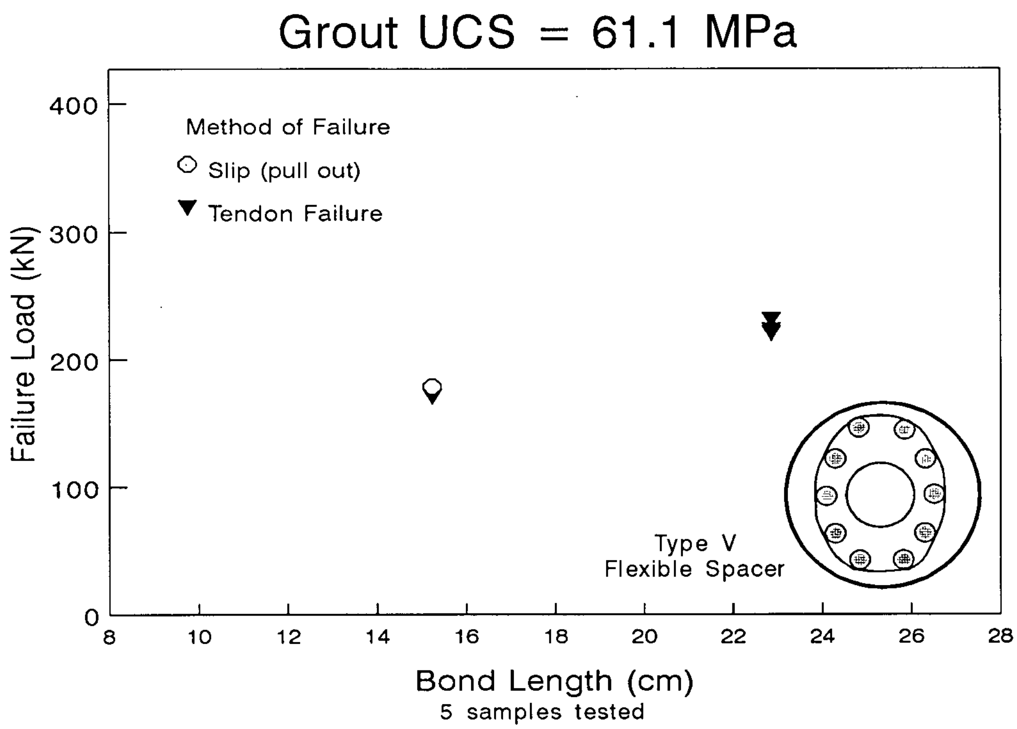


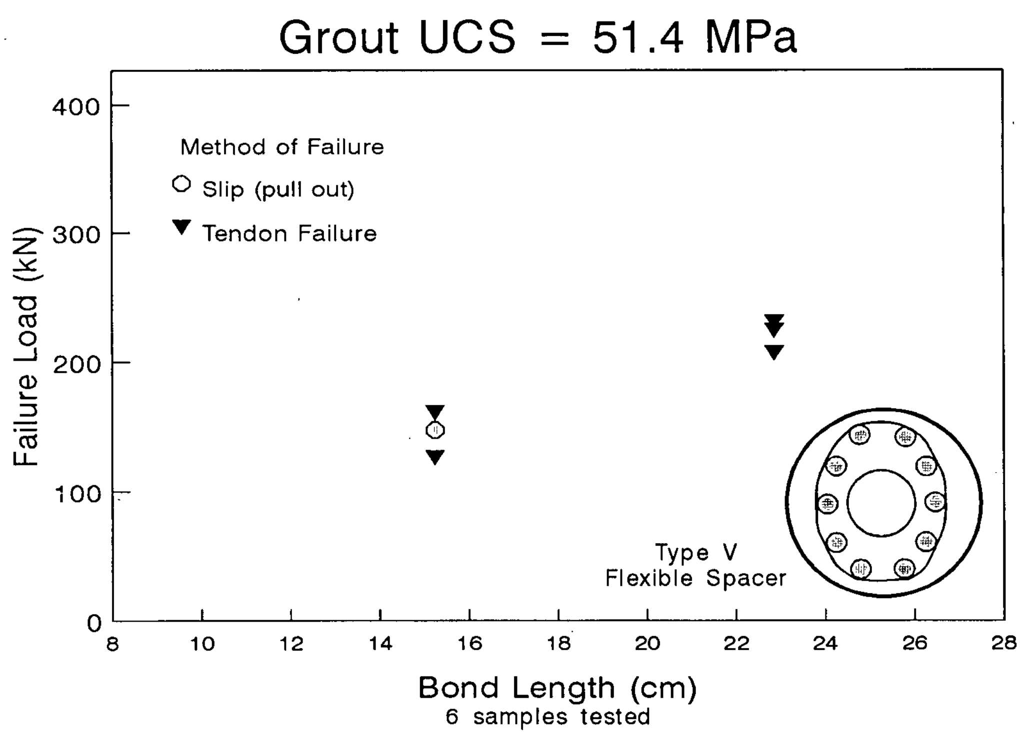
UPPER: Figure 63. Type of Failure, 0.35 w:c, Type III
LOWER: Figure 64. Type of Failure, 0.45 w:c, Type III





UPPER: Figure 65. Type of Failure, 0.35 w:c, Type IV
LOWER: Figure 66. Type of Failure, 0.45 w:c, Type IV





UPPER: Figure 67. Type of Failure, 0.35 w:c, Type V
LOWER: Figure 68. Type of Failure, 0.45 w:c, Type V

between one to nine. This type of failure can be explained by differential rod loading. Figure 69 shows the pull out curves for two samples. As shown, one sample experienced differential rod loading while the second sample did not.

When a load is applied to the cable bolt, it is assumed theoretically that the load is distributed among the ten glass fibre rods evenly. When the test sample reaches the load at which it fails by pulling out of the grout (massive grout/cable displacement) the ten rods should equally displace with respect to the grout, each rod carrying the same measure of load. This occurred in the samples represented in figures 63 and 64 (type III). However, due to variations within the surface coating and/or configuration, each rod does not always equally displace with respect to each other (type IV & V). As a result, the rods which do not show mass displacements experience an increasing load as compared to the rods which are experiencing mass displacement and hence a decreasing load. This continues until the rods which are not mass displacing exceed their individual tensile strength and fail violently. This continues until all rods which did not experience mass displacement fail and the remaining rods (which are undergoing mass displacement) pull out of the grout.

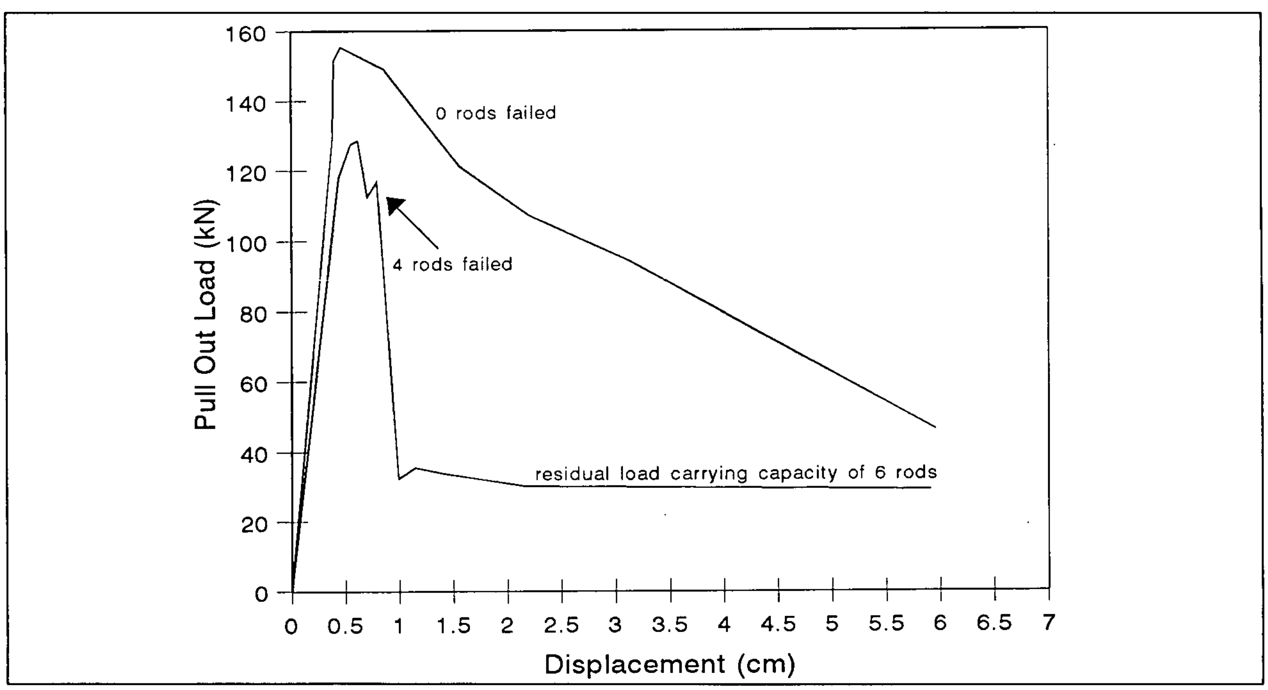


Figure 69. Pullout Curves Showing Two Types of Cable Bolt Failure

Type III configuration did not experience premature tensile failures, unlike type IV and type V configurations. The reason for this is unknown, however, it is hypothesized that the failure surface created in type III is more uniform and smaller with respect to the surface area effected on the cable bolt. The only disadvantage of having the cable bolt experience a tensile failure is that the cable bolt has a significantly lower (if any) residual load carrying capacity. However, as a result of premature tensile failures it was determined that the most ideal configuration for the glass fibre cable bolt is type III. As a result, future laboratory testing focused on this configuration, called DAPPAM (figure 70).

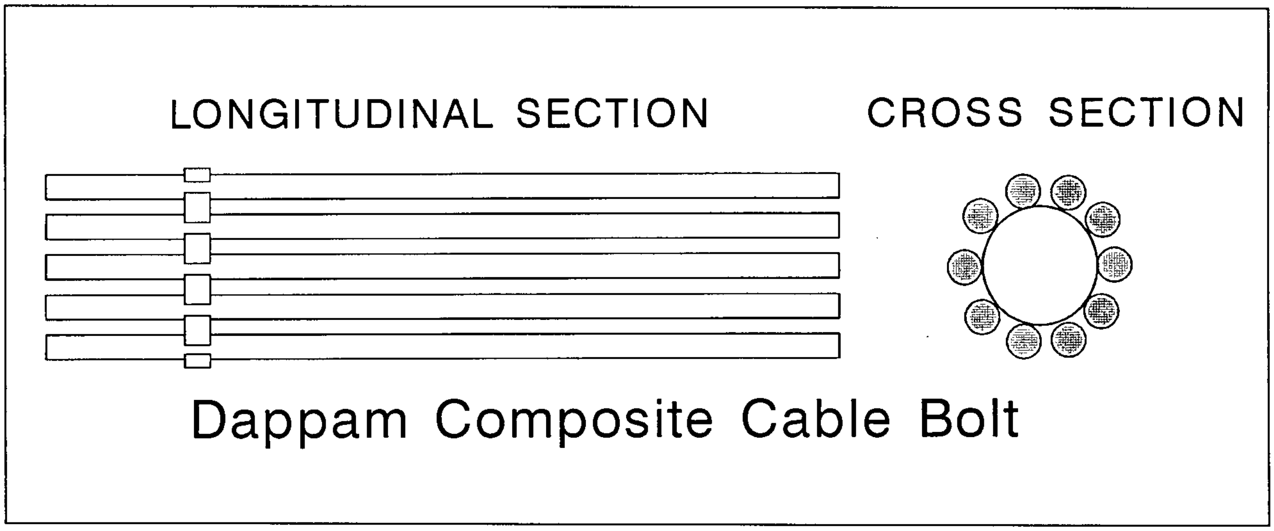


Figure 70. DAPPAM Cable Bolt

5.1.3 SURFACE FIXTURES

Two types of barrel and wedges were designed and tested as to provide anchors for surface plates on the DAPPAM cable bolt. The general trend in the mining industry is to install face plates. Though the DAPPAM cable bolt has a high bond strength, it was concluded that if the option of face plates was not available, that the sales of DAPPAM would suffer.

Figure 71 shows a diagram of prototype BW1, providing ten individual holes for each tendon to pass through the barrel. The prototype was installed and pull tested three

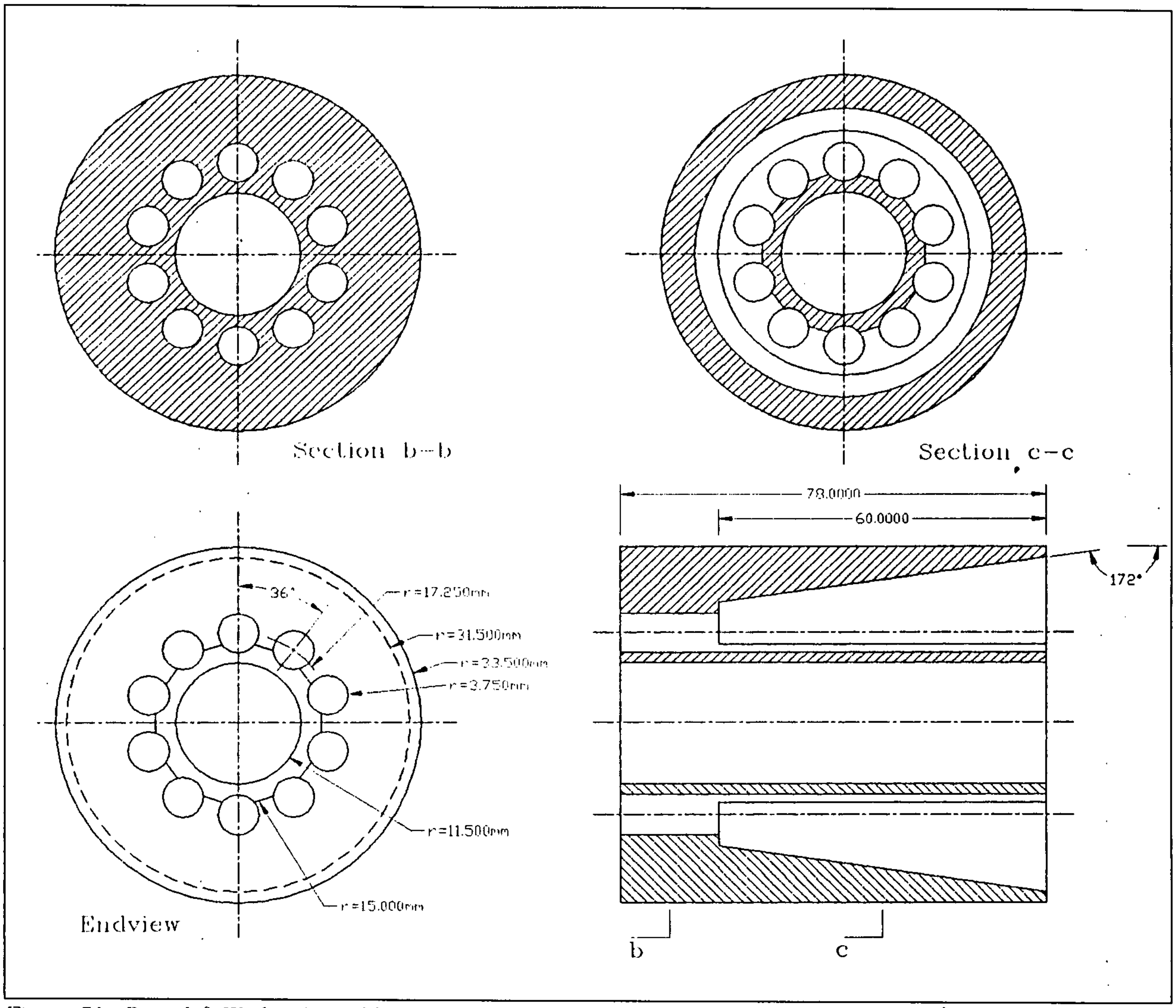


Figure 71. Barrel & Wedge Assembly, Prototype BW1

times on the DAPPAM cable bolt. The average load at failure was 162kN. Failure occurred when the tendons were physically crushed and pulled apart. Prototype BW2 (figure 72) consisted of the same arrangement, though, rather than having ten holes, the barrel simply pressed the rods toward the grout tube. The prototype necessitated that the grout tube be filled with grout. The average failure load of the three samples tested was 111kN. Two types of failure occurred when testing the BW2 prototype. The first being the same as encountered when testing BW1 prototype, crushing of the glass fibre rods. The second mode of failure consisted of the cable bolt being pulled through the barrel and wedge (through 10cm of displacement). This was a result of the grout within the grout tube being crushed and ejected from the tube, causing the glass fibre rods to be pressed into the grout tube. Figure 73 shows a typical pull out curves from the pull tests. It is evident that the peak load and residual load carrying capacity of the barrel and wedges are not satisfactory for commercial development.

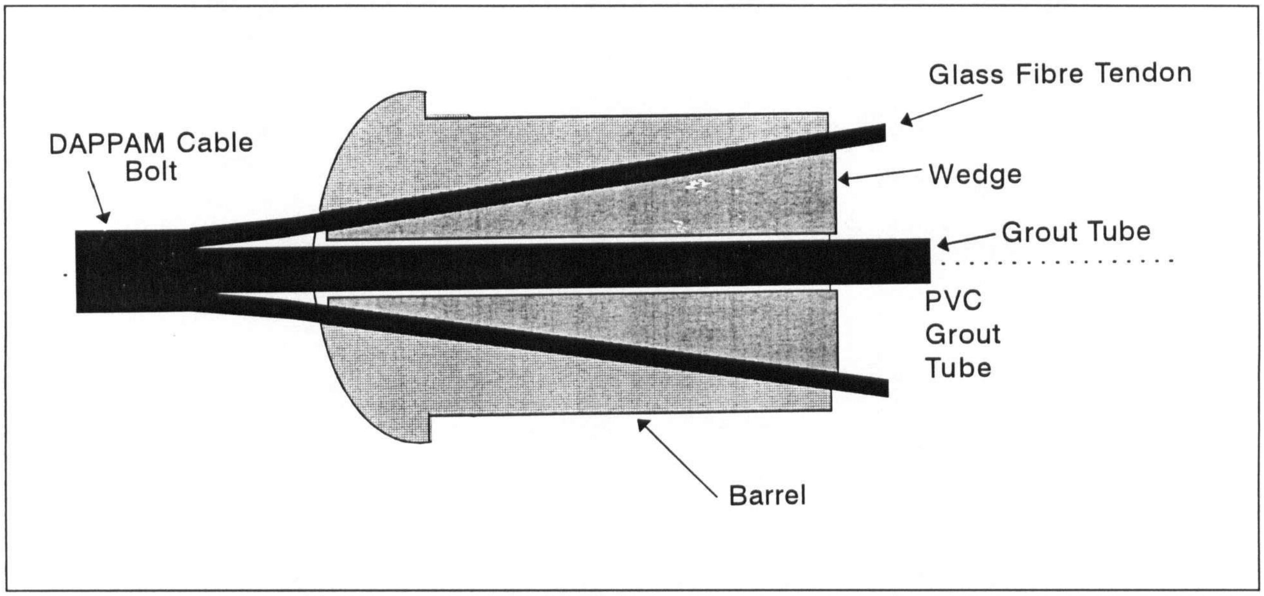


Figure 72. Barrel & Wedge Assembly, Prototype BW2

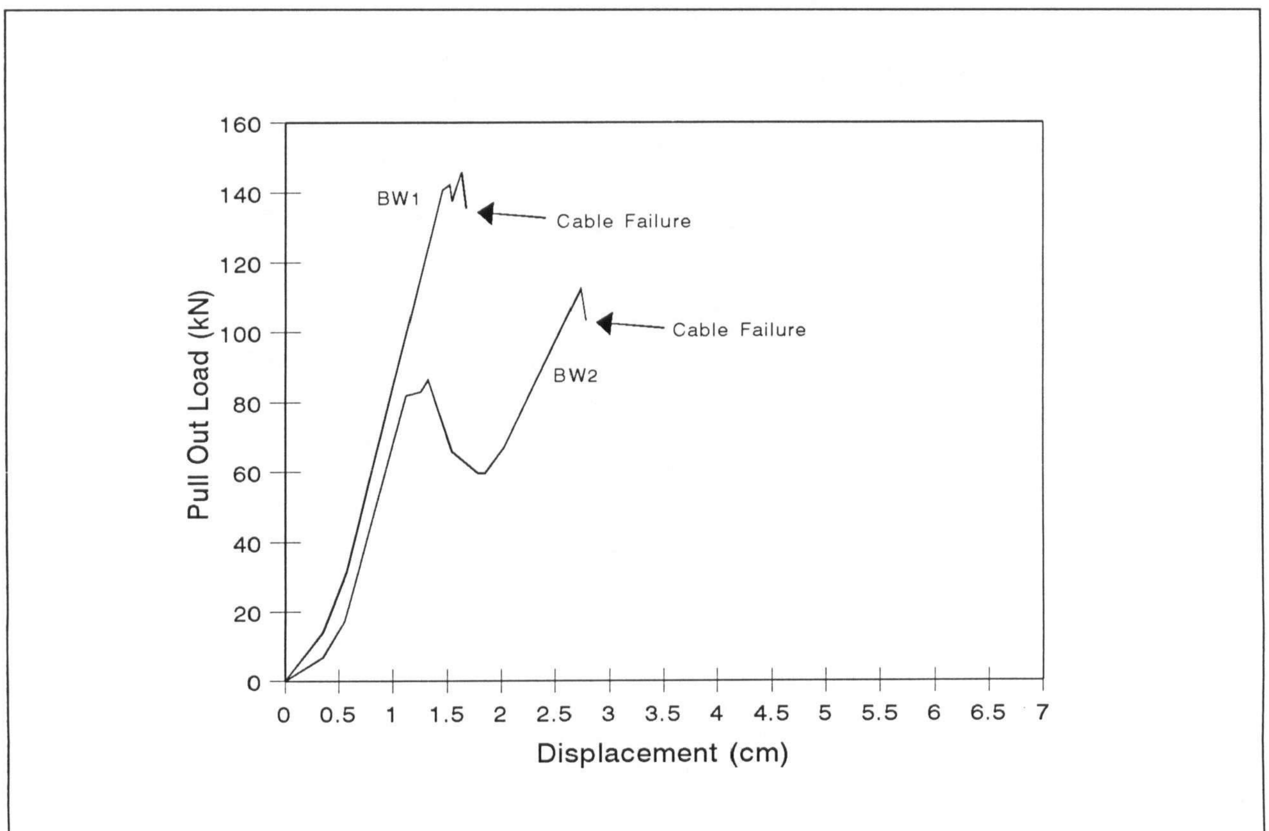


Figure 73. Typical Pullout Curves for Barrel & Wedge Assemblies

Chapter 6

LABORATORY EVALUATION of DAPPAM

The following chapter discusses the results from laboratory evaluation of the DAPPAM cable bolt. The chapter introduces testing completed on steel cable bolts for the purpose of data comparison.. The load carrying capabilities of DAPPAM are defined, including physical properties of the cable bolt. Corrosion resistance and failure observations are also discussed.

6.1 Laboratory Evaluation of DAPPAM

Once the optimum configuration of DAPPAM was determined, a laboratory evaluation of the prototype was undertaken (figure 74). The prototype of DAPPAM consisted of ten (10) individual 0.64 cm diameter rods enveloping a 2.2 cm O.D. high density polyvinyl grout tube (type III configuration). The individual rods were constructed with 21μm diameter ECR glass fibres within a isophthalic polyester resin. A surface coating consisting of a fine silica grit adhered to the glass fibre rod through the use of a modified epoxy was applied to the individual rods (figure 75).

The laboratory evaluation consisted of pull testing, modified shear testing at the USBM, tensile testing and grout column testing. Observations utilizing the scanning electron microscope were also completed. The testing was aimed to fully define the characteristics of the DAPPAM cable bolt and where practical, comparing them to conventional steel cable bolts.

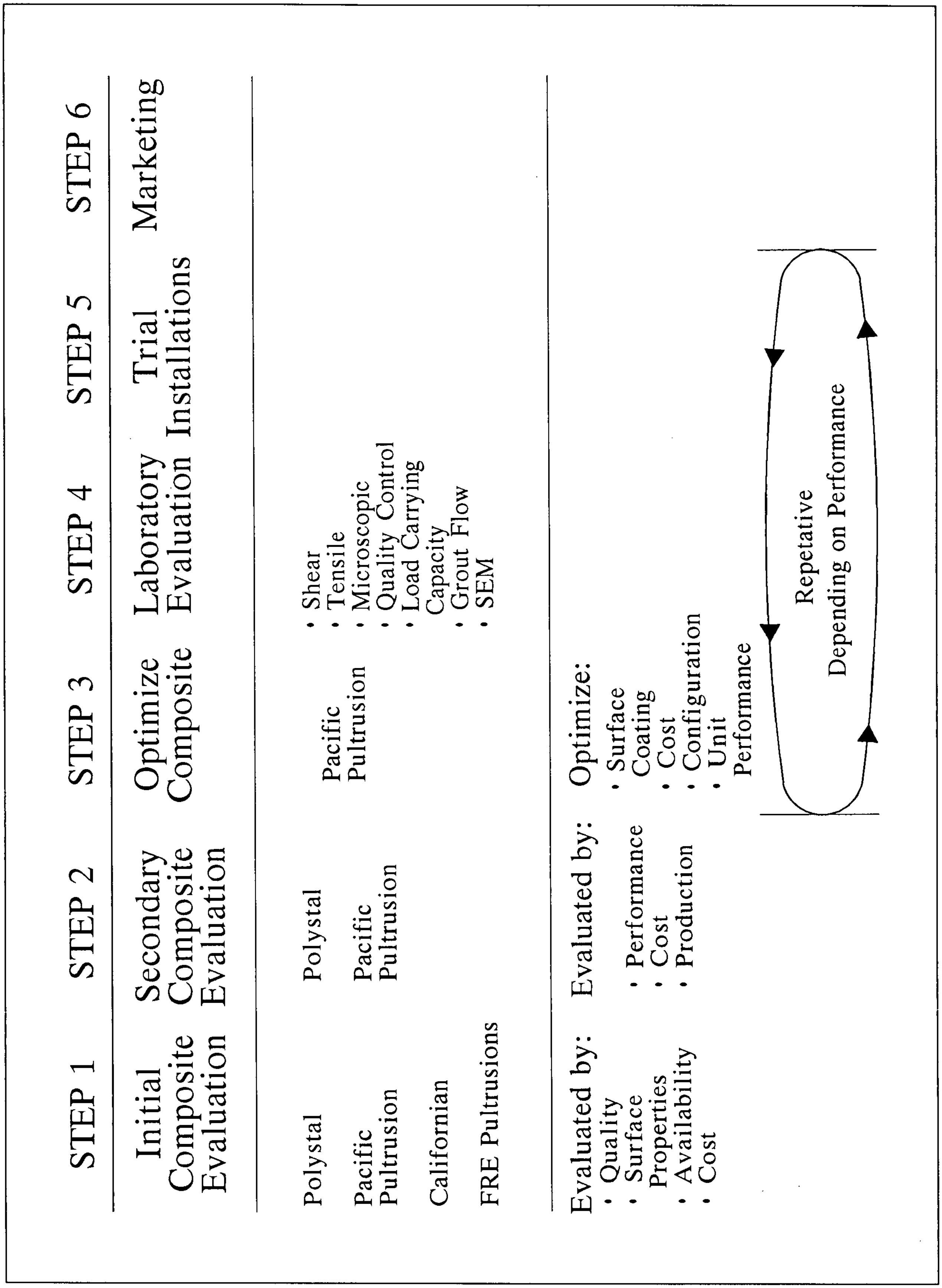


Figure 74. Research Flowchart - Step 4, Laboratory Evaluation

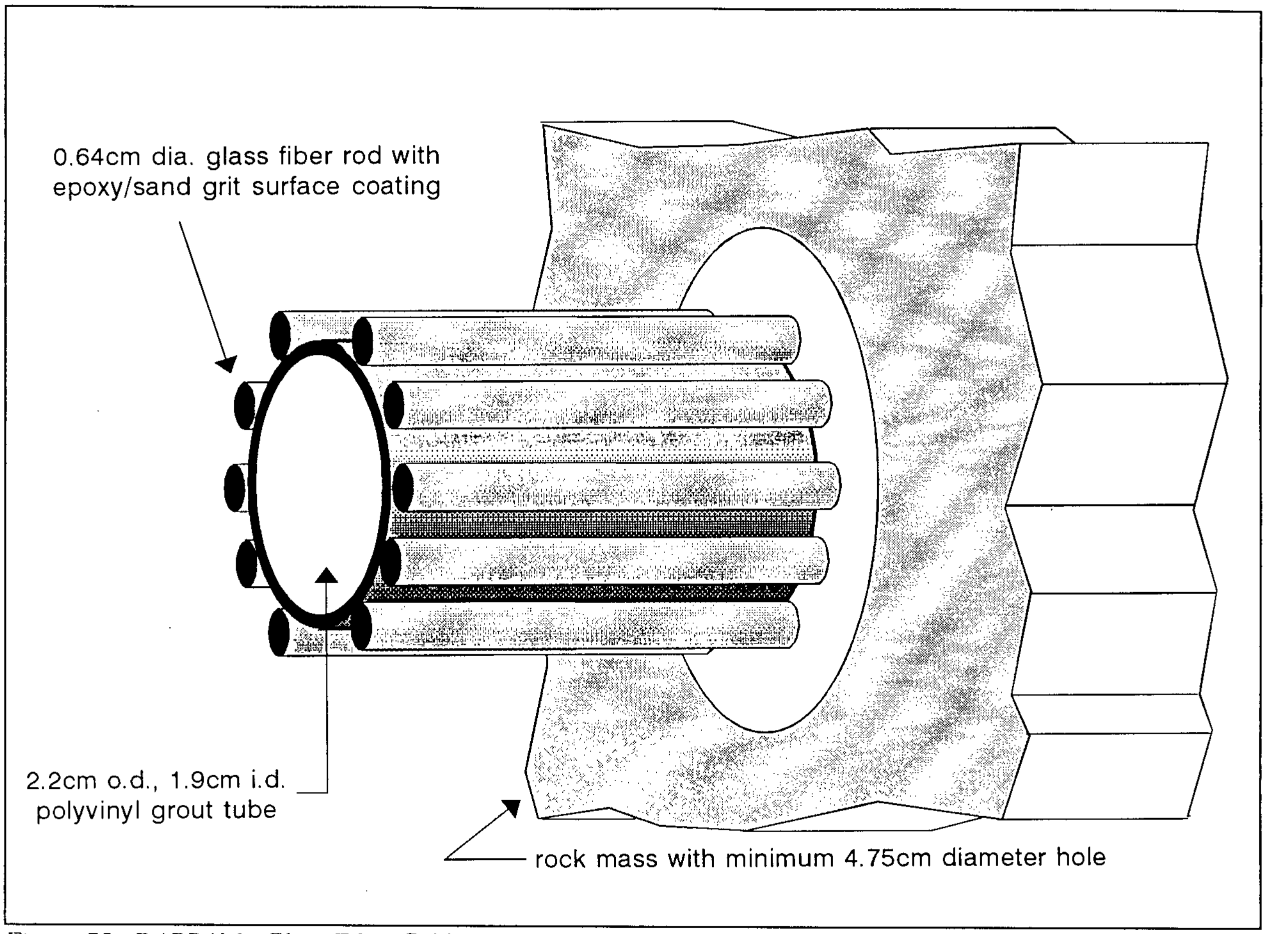


Figure 75. DAPPAM - Glass Fibre Cable Bolt

6.1.1 TESTING OF STEEL CABLE BOLTS

In order to fully evaluate a composite cable bolt prototype, a comparison must be made to conventional steel cable bolts which currently dominate the mining industry. Pull out tests on steel cable bolts conducted by other researchers have yielded quantitative results under specific test parameters (Goris 1990) (MRA 1988) (Stillborg 1984), but not to the extent which will allow flexibility in parameter input needed for comparing test series. The parameters which influence the cable's pull out load the most are its bond length, cement strength and confinement of the sample. Testing by Goris from the United States Bureau of Mines (figure 76) has produced a graph and equation which will estimate the pull out load for various bond lengths when tests are conducted in a schedule 80 steel pipe and at a water:cement ratio of 0.45 (ucs ≈ 50 MPa as tested, ≈ 40 MPa adjusted due to UCS sample shape [see section 3.1.3.3])(Goris 1990). However, when grout is mixed

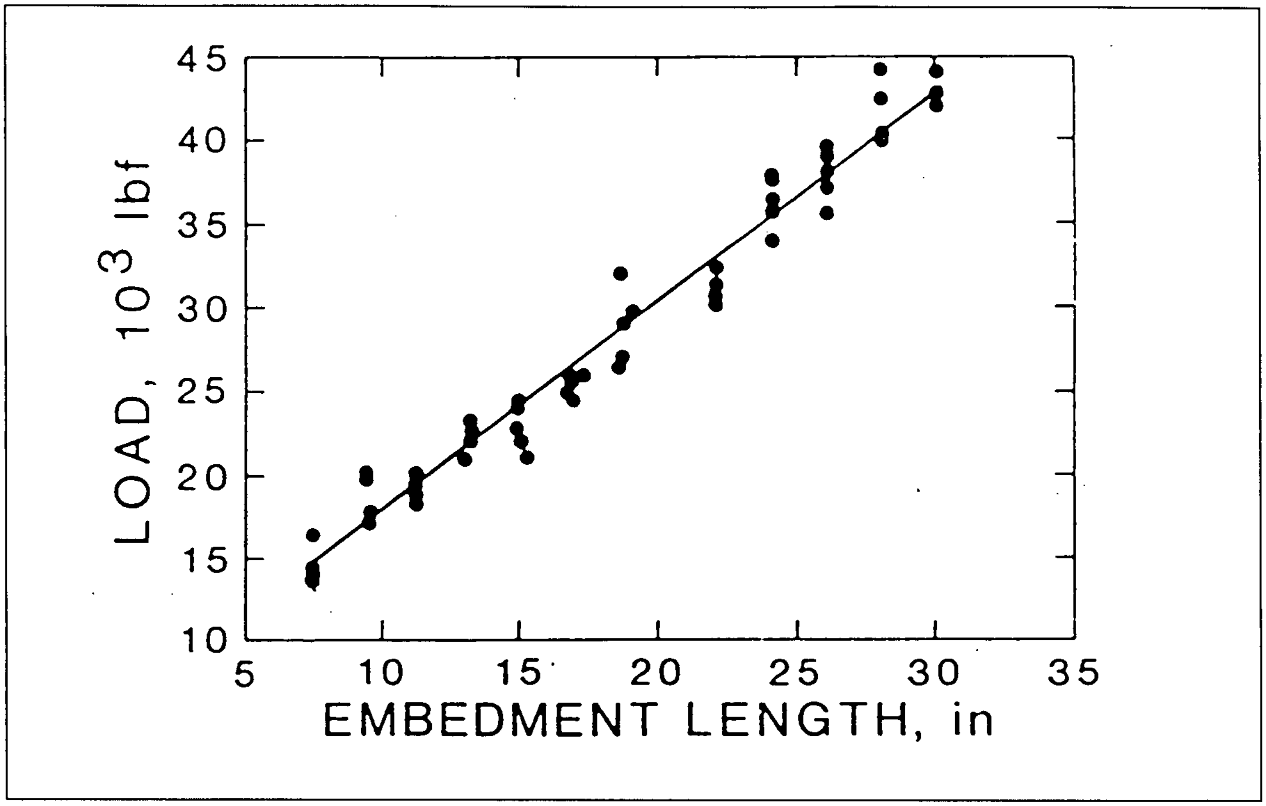


Figure 76. Bond Length vs Load as Defined by Goris, 1990

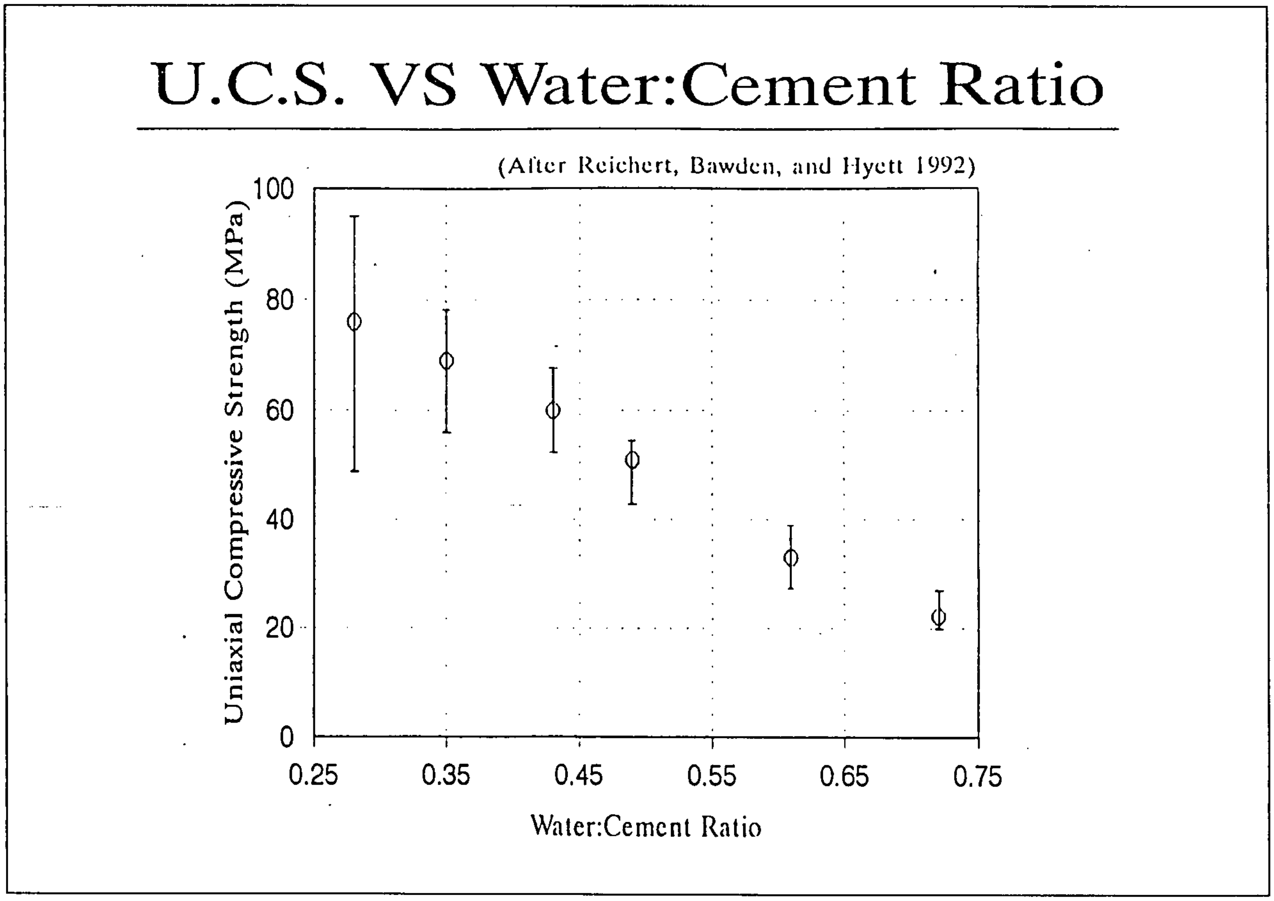


Figure 77. Variation of Cement Based Grout (Reichert 1992)

and cured at a 0.45 water:cement ratio, a variance in its strength is inevitable due to the number of variables involved (mix time, method of mix, cure characteristics, chemical composition of cement, etc.) (figure 76).

In holding one of three main parameters constant (the confinement) by using a standard schedule 80 steel pipe, a graph and equation was developed from results produced by pull out tests on single steel strand cable bolts. The resulting equation allows one to compare composite cable bolt pull test results (as long as the test samples utilize schedule 80 steel pipe) to conventional steel cable bolts, regardless of bond length and cement strength.

To increase accuracy of the test program, the samples tested used parameters to make them (near) orthogonal. Due to the variance in cement strength, true orthogonality is not possible. Figure 78 shows the variance in the grout strength associated to the test. If true orthogonality was achieved, the line through the points would have been linear. In addition, the samples' parameters used for testing were created to minimize the variance in defining the plane by choosing the samples parameters so the plane would be defined within the center and the four corners. The equation of the plane is:

(1) $$\text{Load} = -9535.4 + 1.84(\text{grout}) + 1531.1(\text{EL})$$

Load = pull out load (lbf)

grout = unconfined compressive strength (psi)

EL = embedment length of sample (inch)

The data fits the equation with r = 0.917 while the standard error of the equation is 10.3kN. Having completed a pull test on a composite cable bolt, one would enter the sample's embedment length and grout strength into equation 1 to determine the pull out load of a single steel strand cable bolt using the same test parameters. The equation is valid for bond lengths between 10.2cm and 35.6cm.

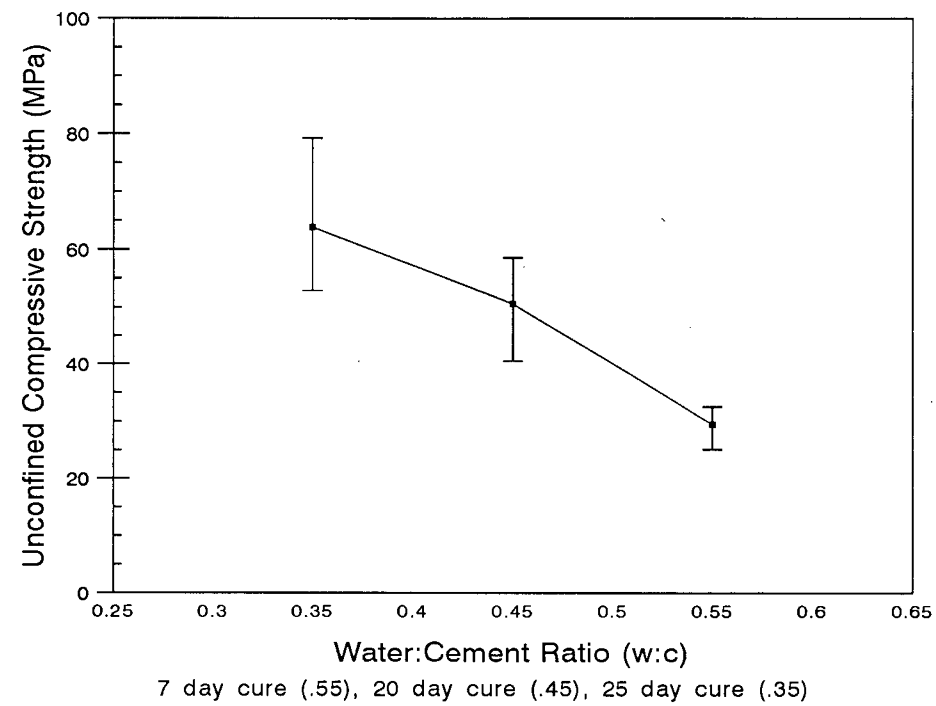


Figure 78. Variance of Grout UCS on Steel Cable Bolt Test Series

Figure 79 displays a graphical representation of equation 1.

It is stressed that the testing of steel cables was for the purpose of comparison. For this reason, the accuracy of the equation 1 when compared to results derived from USBM (figure 80) are acceptable. It is hypothesized that the difference of results lies within testing procedures and equipment.

6.1.2 LOAD CARRYING CAPACITY

Previous tensile testing conducted during Step 3 of the research program utilized the double pipe pull test machine which required the samples to be embedded in grout. Previous results indicated that the tensile strength of Pacific Pultrusion's composite was 915MPa, resulting in the cable bolt's theoretical load carrying capacity to be 293kN (as compared to 267MPa for steel cable bolts). Confirmation of the tensile strength was

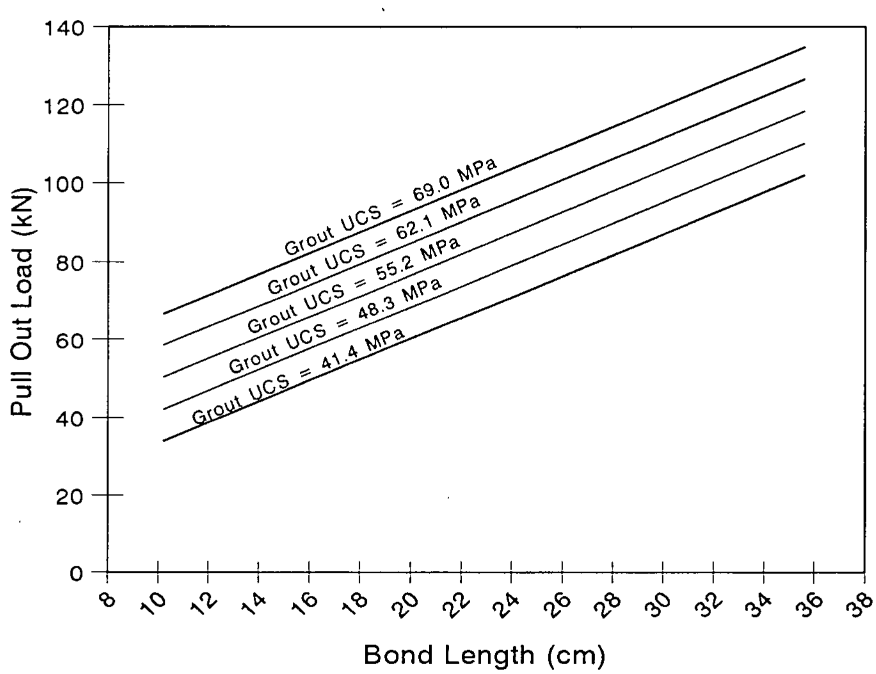


Figure 79. Effects of Grout & Bond Length on Steel Cable Bolts

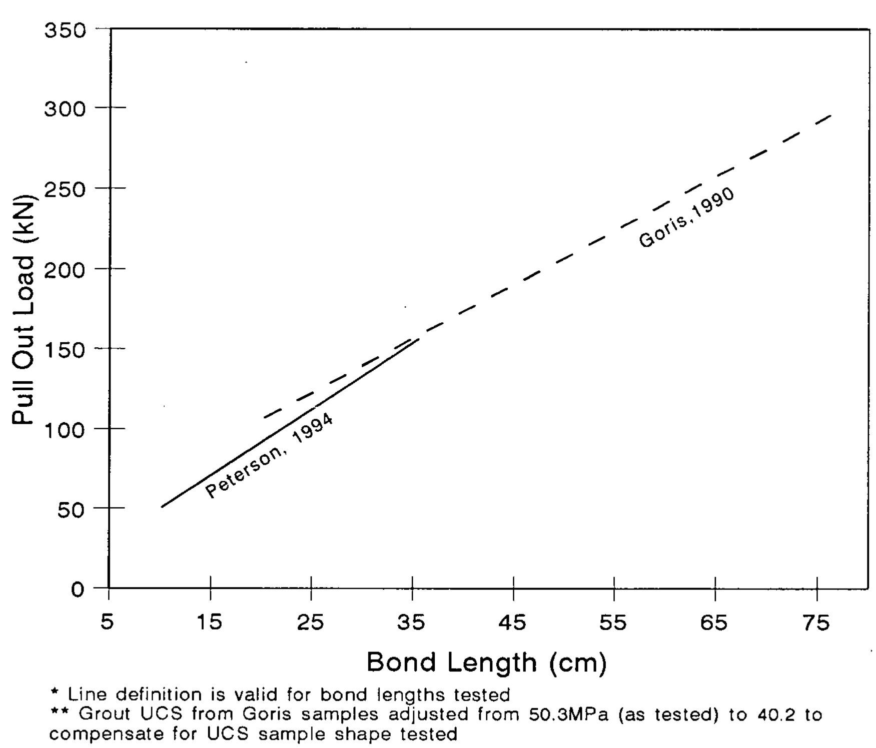


Figure 80. Bond Length vs Pull Out Load on Two Data Sets (Adjusted Grout UCS values)

warranted so additional testing was completed using an Instron machine by the Department of Metals and Material Engineering at the University of British Columbia.

Seven samples, each consisting of one rod with a 6.55mm in diameter and 86.4 cm in length were tested in the Instron machine (figure 81). Each end of the rod was anchored in a sleeve using an epoxy for 25.4cm, leaving 35.6cm of rod unconfined. The rate of displacement was 0.085 mm/s. The mean value of the sample's tensile strengths was determined to be or 35.0 +/- 1.2 kN (Delfosse, 1993). This yields the cable bolt's theoretical tensile strength (ten times one tendon) of 350kN, higher than previous estimations by approximately 57kN.

The difference in tensile strengths can be attributed to several reasons:

1) Methods of Testing: The obvious difference is the method of testing. The double pipe method has 100% of the sample confined within the cement grout, while the Instron method has 35.6cm of sample unconfined. The effects of confinement are unknown.
2) The samples tested using both methods were not from the same pultruded batch. The samples acquired for the Instron testing had modified manufacturing practices performed, resulting in a higher quality product.

The exact influence of testing method and sample originality is not known.

The pull test apparatus at UBC had a maximum load of approximately 245kN. As a result, cable bolt samples could not be tested to failure as to determine the cable bolt's maximum load carrying capabilities. Subsequently, cable bolt samples were sent to the United States Bureau of Mines for destructive pull testing.

Five pull tests were completed at the USBM under the direction of John Goris in order to determine the ultimate tensile strength of the DAPPAM cable bolt. The test samples utilized type III cement at a water:cement ratio of 0.40 and allowed to cure for 7

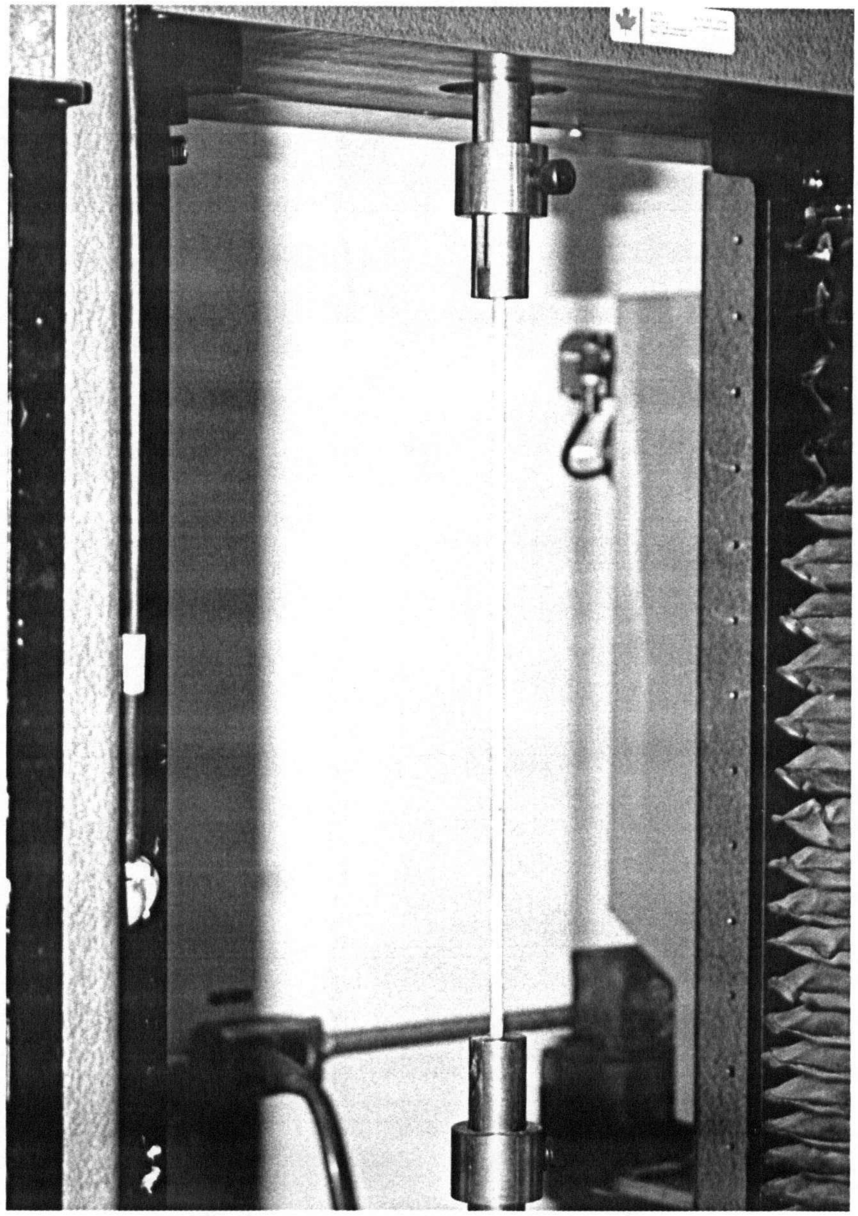


Figure 81. Tensile Testing in Instron Machine

days. The samples were stored in 100% humidity after the first day. Each sample consisted of two pipes, each 50.8cm in length.

Testing irregularities were experienced as a result of the method used to anchor the sample (pipe) in the pull test machine. As a result, the sample slipped within the machine's jaws, causing displacements of approximately 8cm between the sample and machine. For the first three samples, the recorded displacement included this movement (jaw slippage), including the true displacement between the two pipes. For this reason, the displacement recorded for the first three samples is exaggerated (as shown in figure 82). The potentiometers were moved for tests four and five in order to measure the true displacement, only between the two pipe segments. Figure 82 shows the difference in pull out curves.

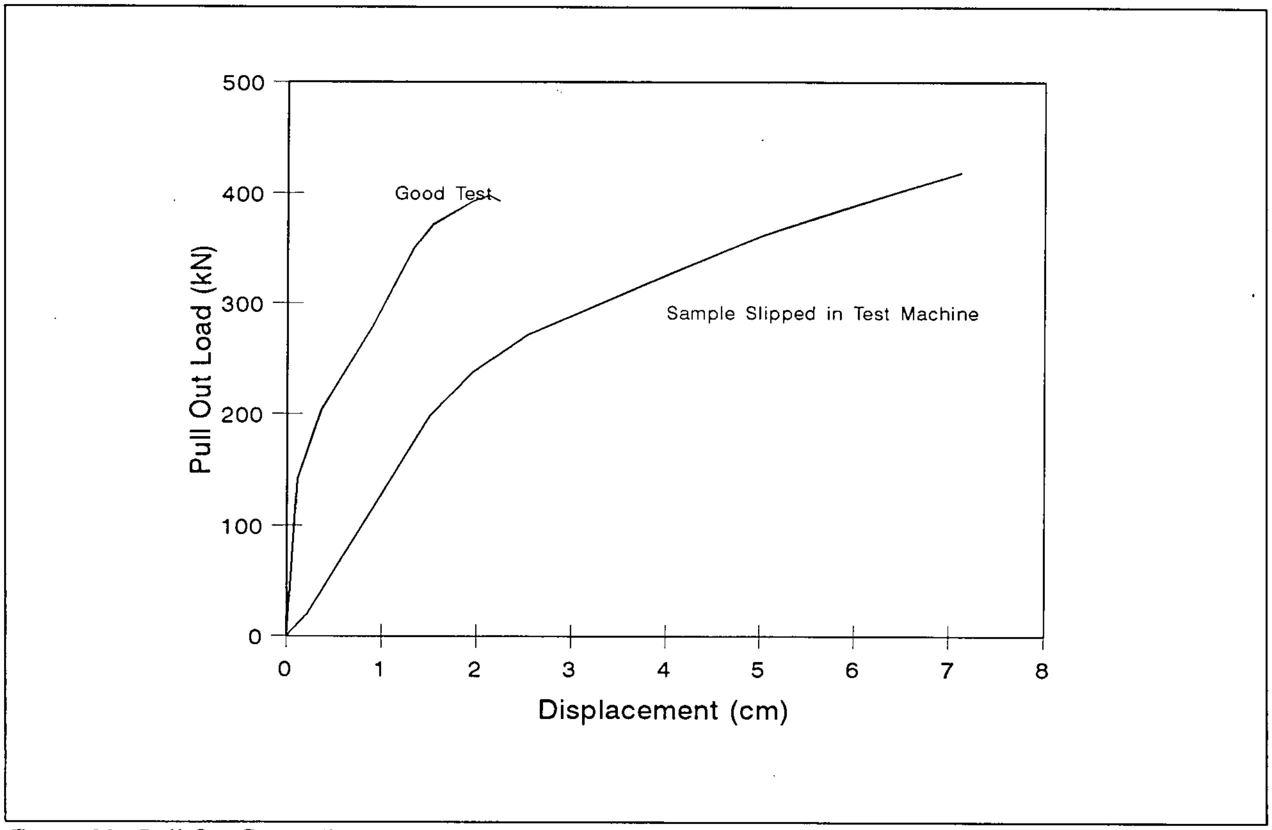


Figure 82. Pull Out Curves From Destructive Tests at USBM

All five samples were tested to failure. As reported by Goris, none of the failures were catastrophic, rather, the individual fibres broke and the load decreased to near zero within several seconds. Figure 83 displays a sample after testing.

The average tensile strength of the cable bolt was tested at 409 +/- 8kN, resulting in a theoretical material strength of 1,212MPa, significantly higher than what was previously predicted. This is primarily a result of increased quality control during manufacturing (chapter 8).

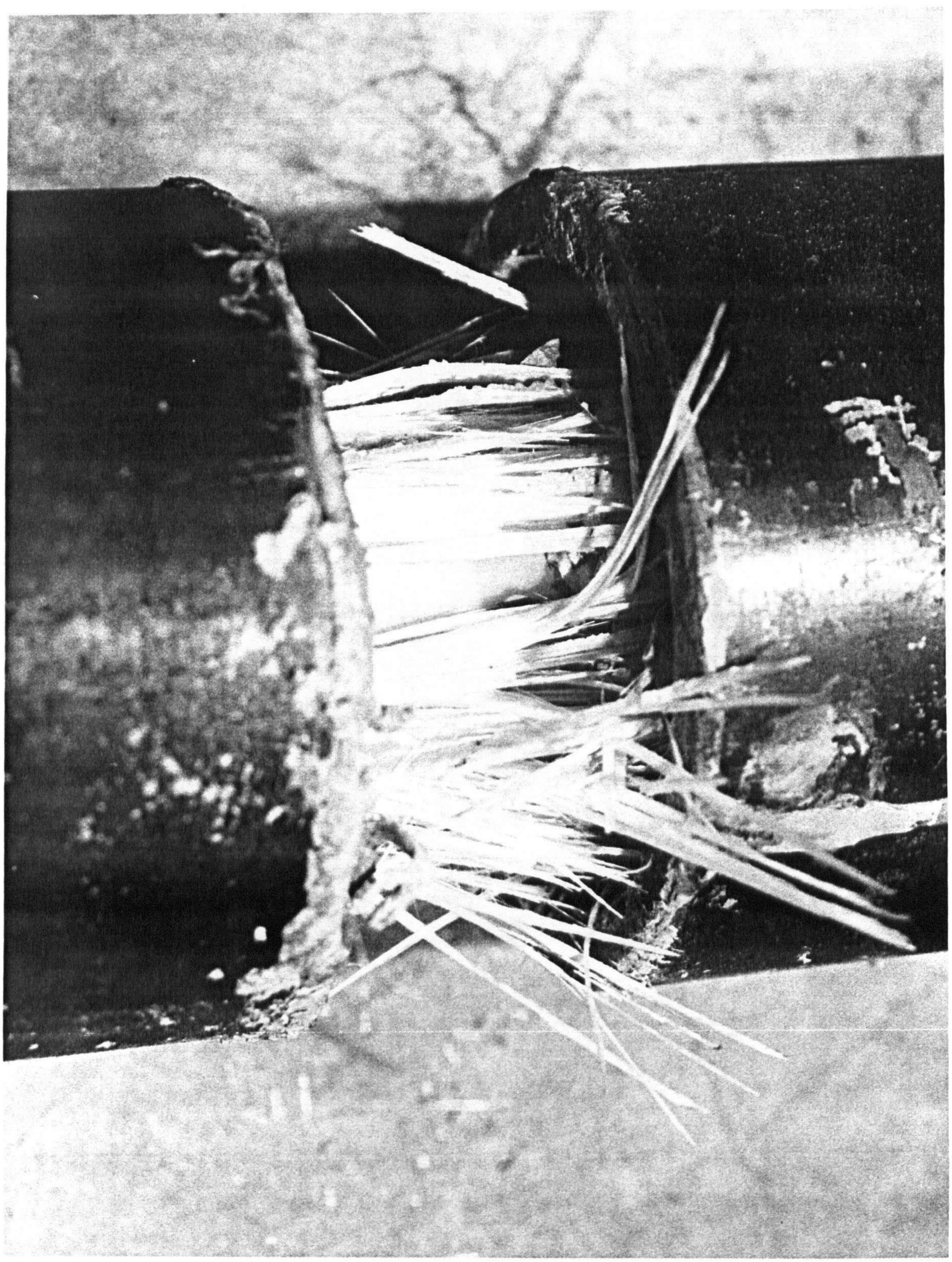


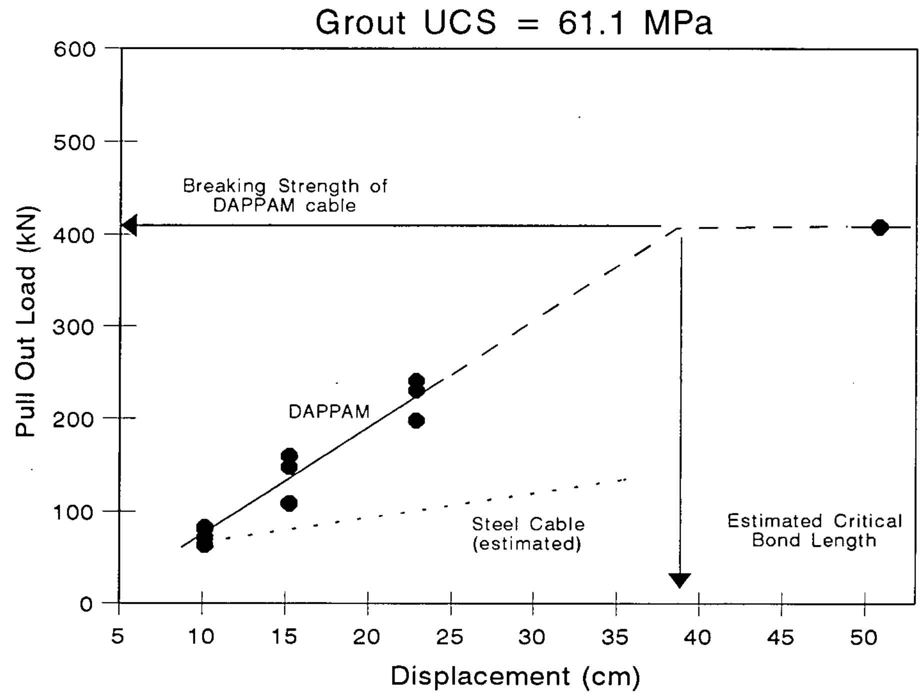
Figure 83. Sample of DAPPAM After Destructive Pull Test (USBM)

One of the primary purposes of utilizing ten 6.35mm rods in the construction of DAPPAM was to construct the cable bolt with an estimated ultimate tensile strength of 289kN, comparable to a conventional steel cable bolt. This was based on early tensile tests completed on the less refined composite material. Primarily through modifications to the composite material throughout the research program, the final tensile strength of the DAPPAM cable bolt exceeded the earliest estimates. As a result, consideration into decreasing the number of rods within the cable bolt to seven can be made. This would produce a cable bolt with an approximate tensile strength of 285kN, a satisfactory strength. With the reduction of rods, the cost of the cable bolt would decrease proportionately, making the price of the cable bolt more competitive. However, the shear strength and bond strength of the cable bolt will also decrease proportionately. With the time and financial constraints the research program was experiencing, a test series to determine the load carrying capacities of other prototypes utilizing less than ten composite rods could not be completed. A test program to determine the full effects of using between seven to nine rods within the cable bolt should be completed prior to commercially retailing a new configuration of DAPPAM (other than type III configuration).

6.1.3 INFLUENCE of BOND LENGTH & GROUT STRENGTH

Pull tests were completed to determine the load carrying capacity of DAPPAM when the bond length of the sample is less than its critical bond length ($\approx$ 39cm). Tests were completed in triplicate, using two grout strengths. Type 30 cement was used in a water:cement ratio of 0.35 and 0.45 and allowed to cure for seven days yielding grout strengths of 61.1MPa and 51.4MPa respectively.

Figures 84a and 84b compares the results to a single steel cable bolt using the same grout strength. The dashed portion of the line interpolates the load carrying capacity at bond lengths untested. Table 11 introduces the equation of the lines found in figure 84



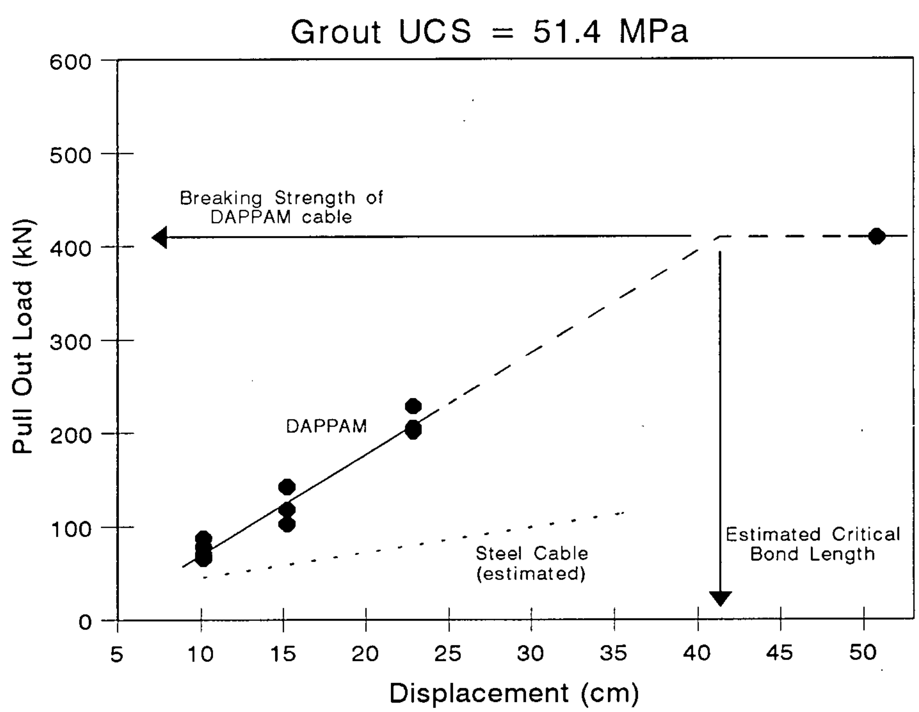


Figure 84a. Load Carrying Capacity of DAPPAM - Grout UCS = 61.1 MPa
Figure 84b. Load Carrying Capacity of DAPPAM - Grout UCS = 51.4 MPa

and their corresponding correlation coefficient. Figure 85 displays a typical pull out curve associated with a pull test and compares it to a conventional steel cable bolt. It can be interpolated that the critical bond length of the DAPPAM cable bolt is between 39cm to 41cm, depending on grout strength (ultimate tensile strength of cable = 409kN) (figure 85).

Table 11. Load Carrying Capacity of DAPPAM

Grout Strength	Equation of the Line (metric)	Correlation Coefficient
51.4 MPa	Load=10.82(BL)-37.8	r=0.977
61.1 MPa	Load=11.61(BL)-41.0	r=0.968

★BL = Bond Length in centimeters
★Load = Failure Load in kilonewtons

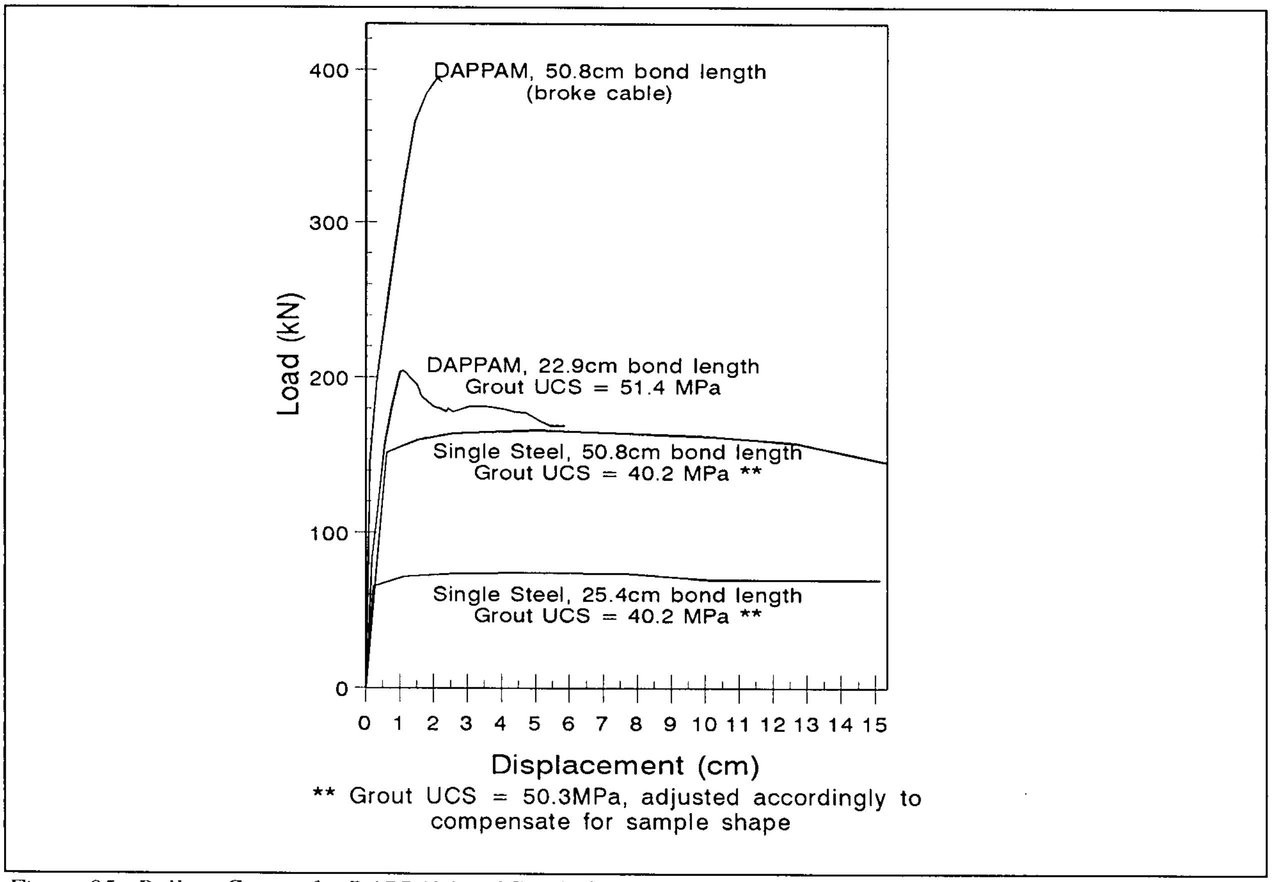


Figure 85. Pullout Curves for DAPPAM and Single Steel Cable Bolts (Steel Cable after Goris, 1990)

During testing of the series, it was observed that the pull out curves created two trends, in testing two similar samples with equal test parameters (figure 86). The primary difference in pull out curves is that curve "B" has very little residual load carrying capacity. Observations of the samples after testing concluded that none of the samples had failed composite rods. The different residual loads can be attributed to the failure of the bond between the rod and surface coating. The importance of residual load is arguable, depending on the design engineer's philosophy.

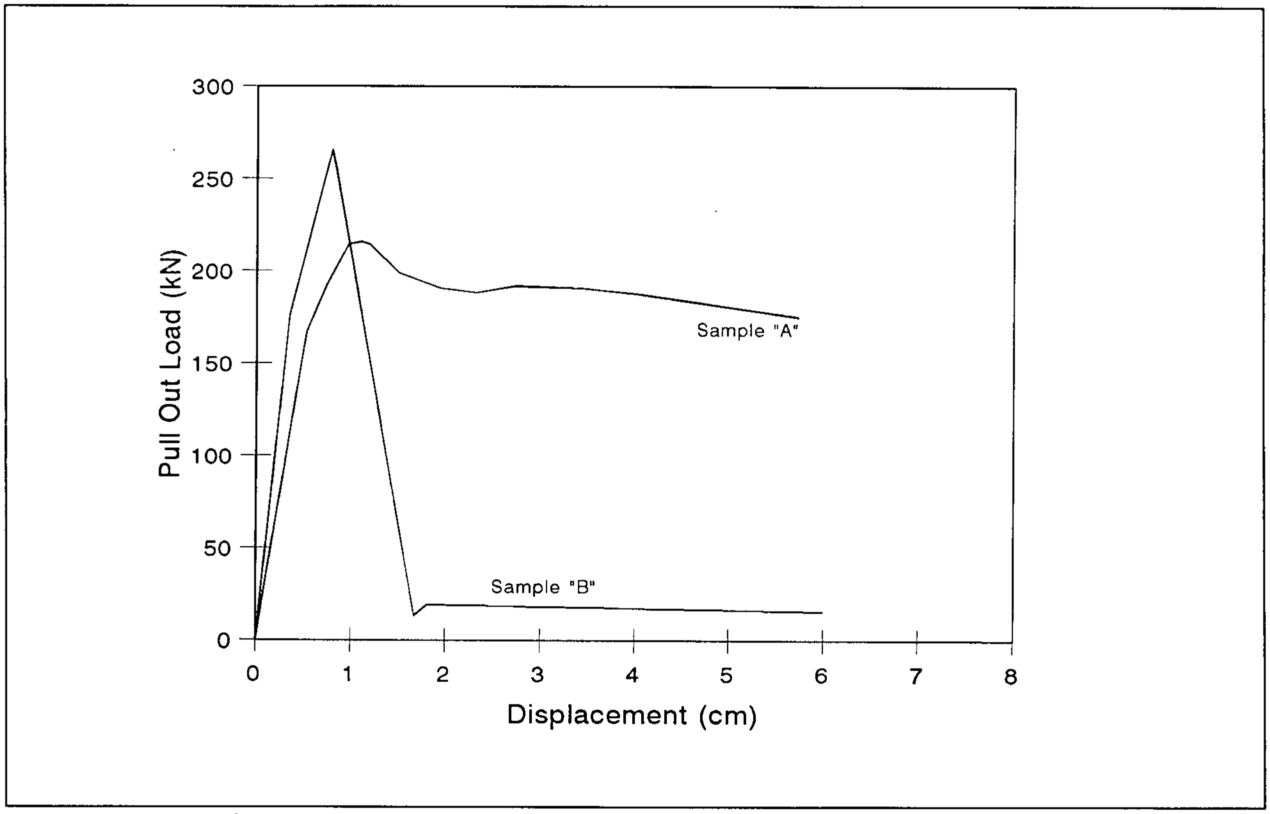
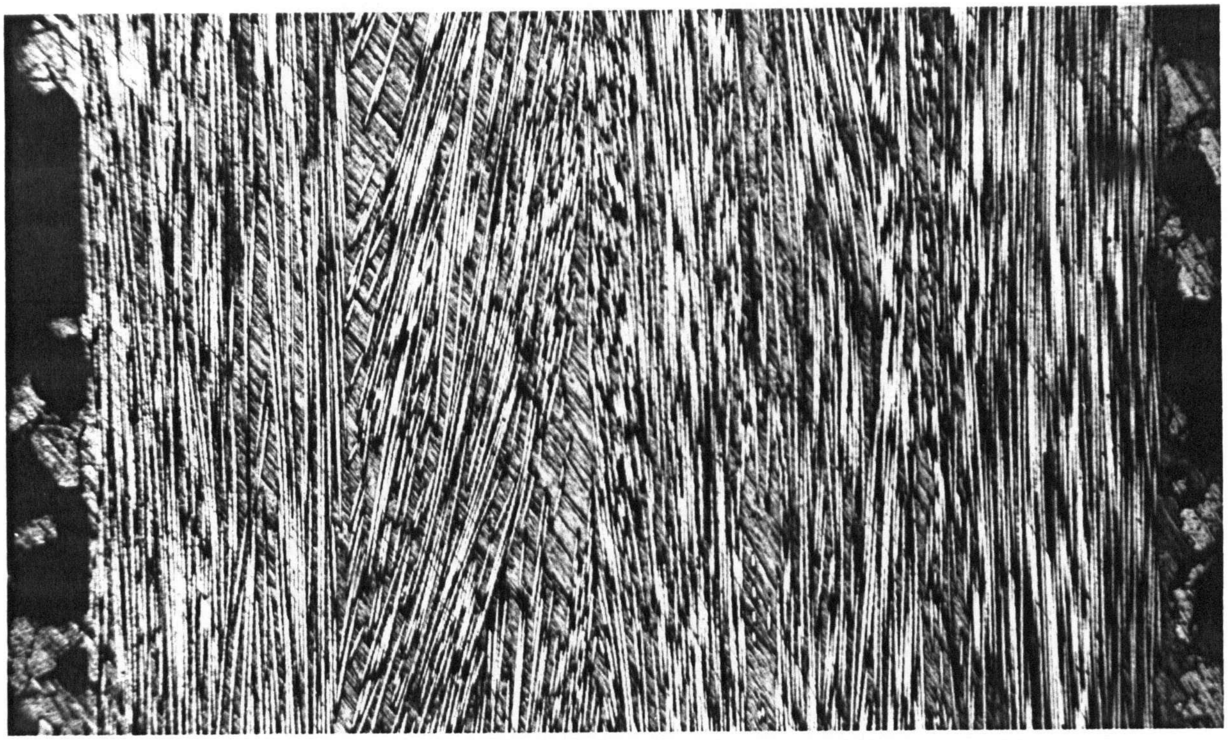
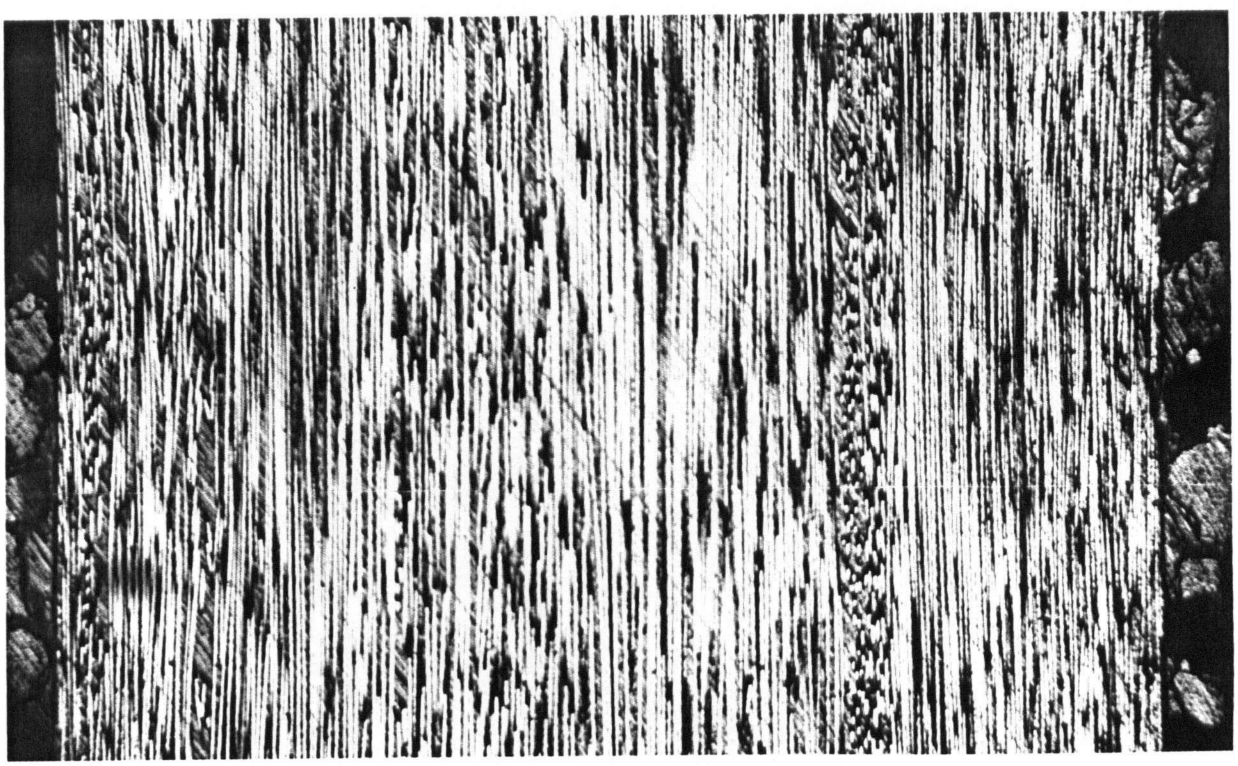


Figure 86. Pullout Curves Displaying Two Types of Failure

6.1.4 Quality Control of DAPPAM

During phase 3, emphasis was placed on improving the quality of the pultruded rod to the largest degree possible without any undue expenses or loss of production. During the months of September and October, 1993, modifications to the pultrusion process were conducted.





UPPER Figure 87. Section From Early Batch, 20x
LOWER: Figure 88. Section From Later Batch After Increasing Back Tension, 20x

A number of samples taken from various batches were examined under the scanning electron microscope at UBC (Delfosse 1993). Figure 87 shows a typical cross section of a glass fibre rod (Pacific Pultrusions). It was observed that in all rods the fibre orientation was generally better along the cable surface, whereas knots and severe misalignment were found in the center of the rod. Rods from a subsequent batch produced after increasing the back tension in order to reduce fibre twisting during the first stage of the pultrusion process has led to a better overall fibre alignment (figure 88).

Throughout the course of phase 3, a series of pull tests have been conducted utilizing the same test parameters, with the exception of grout strength. During these tests, the cable bolts were constructed with material produced at any one of three separate periods during a one year period. Figure 89 display the results. The bars represent the grout compressive strength of the samples while the type of bar represents the pultrusion batch the cable bolts used in the test series originated from. Each dot represents the cable bolts pull out load. As the strength of the grout increases (from left to right) it is expected that the load at which the cable bolt pull out increases proportionately (linear relationship). As shown in figure 89, this does not occur. However, this increasing trend is evident when considering only the test series originating from the same pultrusion batch, i.e., series 3,5,7 as one batch; series 4,9 as the second batch; series 6,8 as the third batch. The deciding factor which dictates the failure load of the cable bolt at the bond lengths tested (15cm) in figure 89 is the surface coating and its bond to the composite rod. Since the linear trend of the failure loads does not exist for all of test series (combined data), it is apparent that the quality between pultruded batches is not equal. If the quality in the application of the surface coating was consistant, a linear trend would have been visible for all pull out tests, regardless of the pultruded batch in which it originated from.

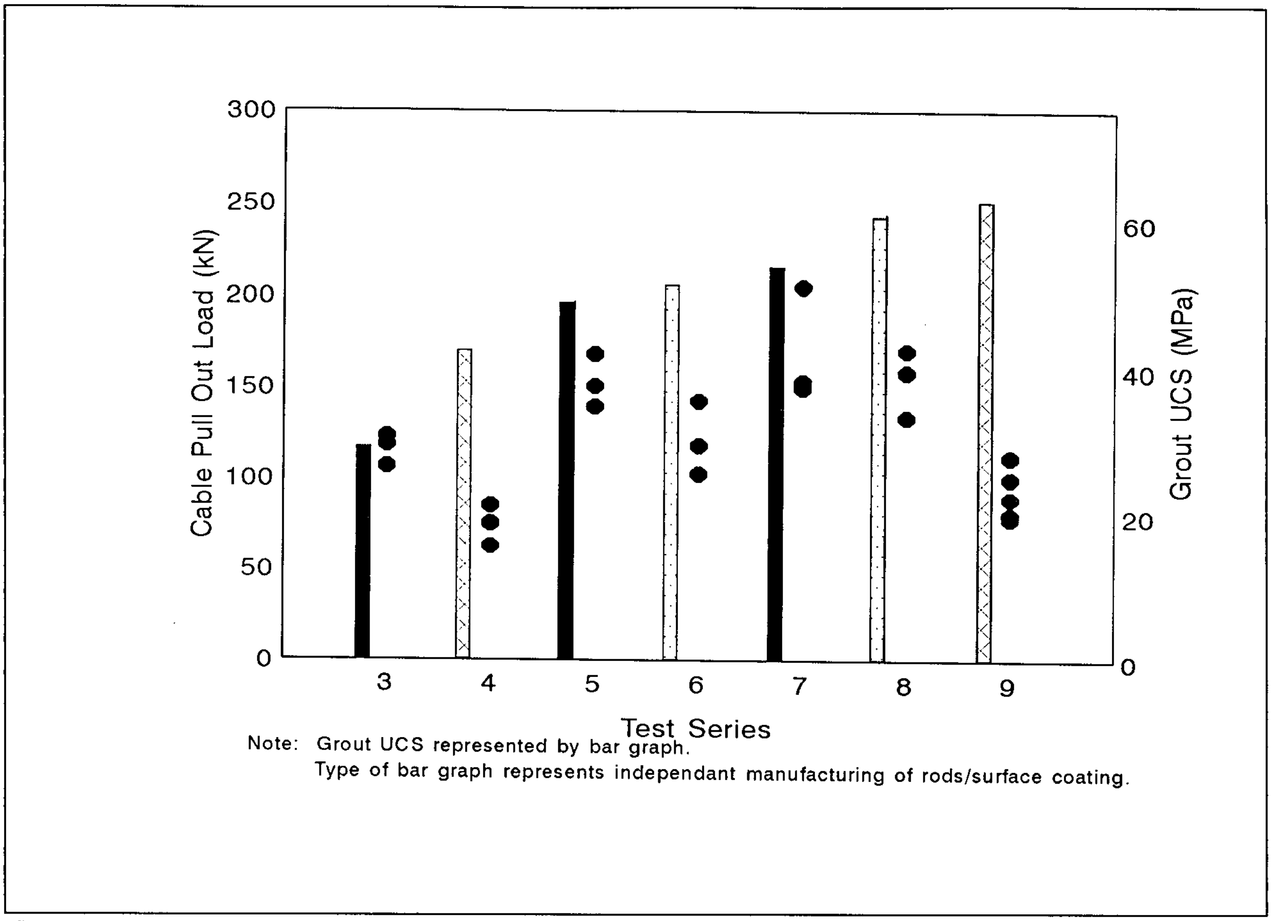


Figure 89. Variance in Quality Control With Surface Coat Applications

6.1.5 GROUT DISTRIBUTION

Grout column tests were completed to determine the grout flow characteristics around the DAPPAM cable bolts (type III, IV and V) and to ensure complete grout coverage of the cable bolt. In addition, tests were completed on single, double and birdcage configurations of steel cable bolts for the purposes of comparison. Large scale tests consisted of PVC pipes (6m in length) hung vertically to represent a drill hole within the rock mass. Two series of tests were completed, one to represent a 4.45cm diameter drill hole and a second to represent a 5.40cm diameter drill hole (figure 90).

Cable bolts (DAPPAM and steel cable bolts utilizing grout tube method of installation) were pushed into the pipes. Portland type 10 cement was mixed to a water:cement ratio of 0.35 and pumped via a Spedel 6000 pump. The samples were

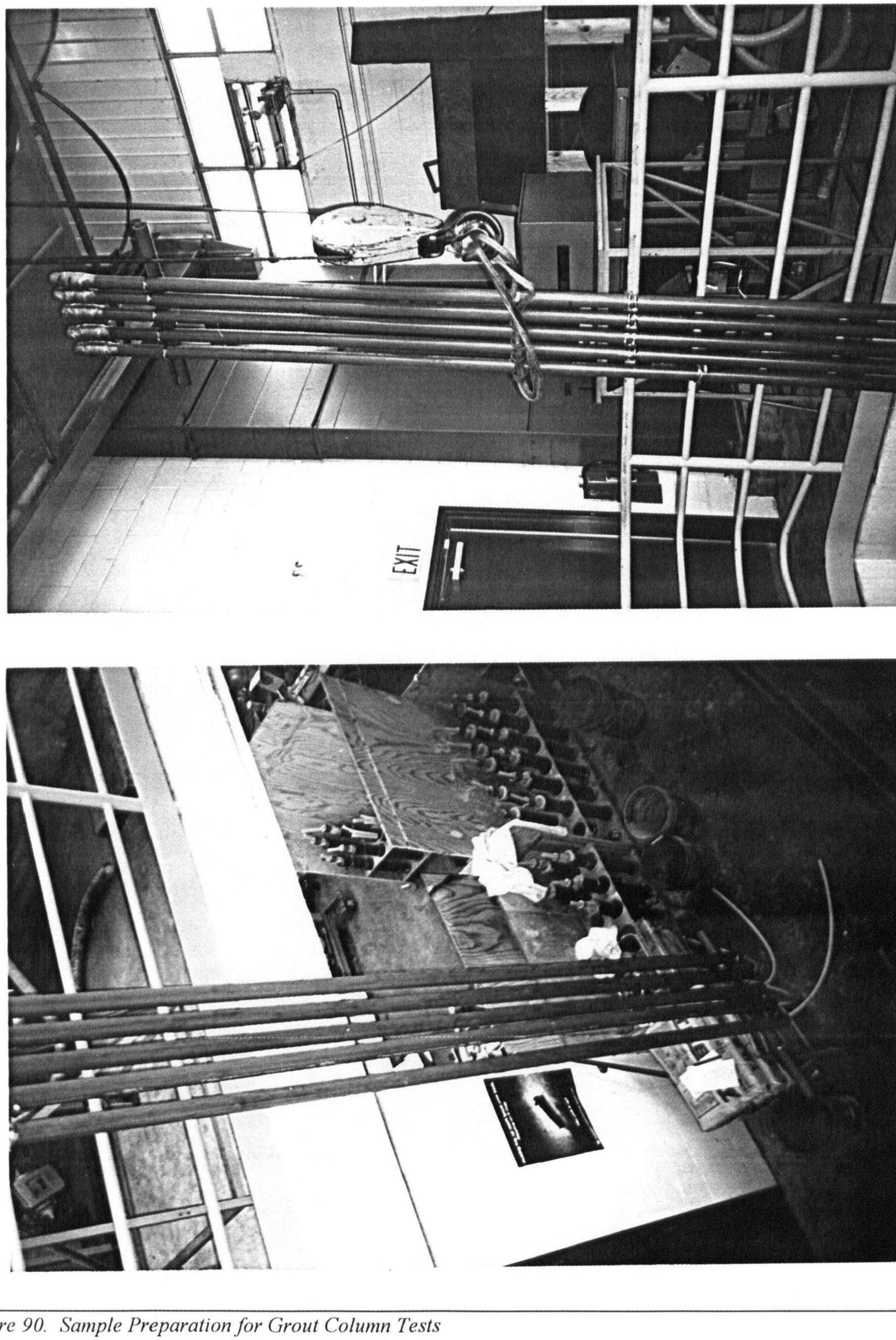
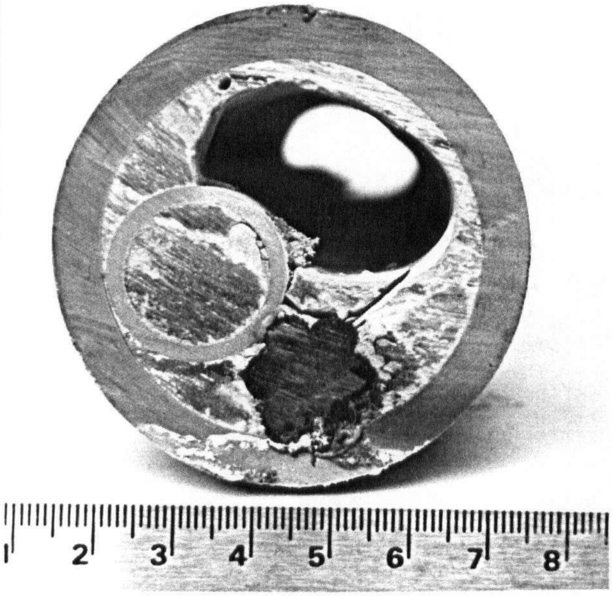
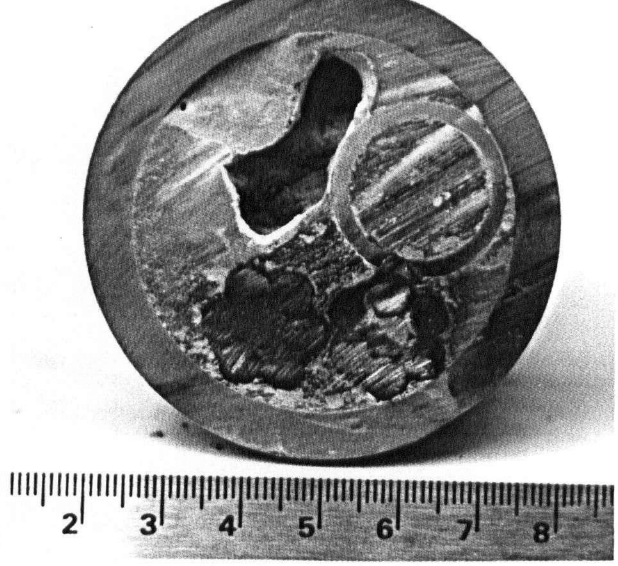


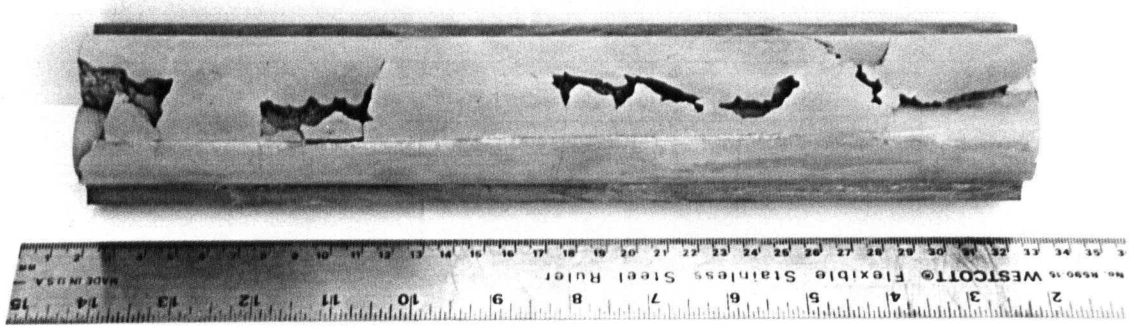
Figure 90. Sample Preparation for Grout Column Tests



"Slumping"
Single Steel Cable Bolt
4m from Collar
Figure 91

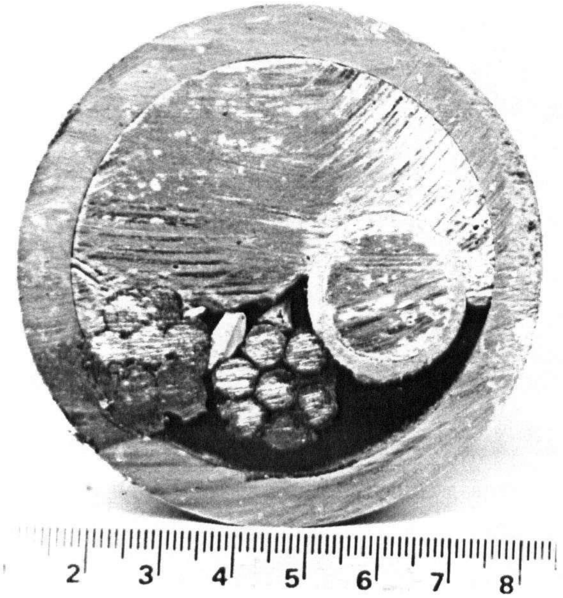


"Worming"
Double Steel Cable Bolt
3m from Collar
Figure 92

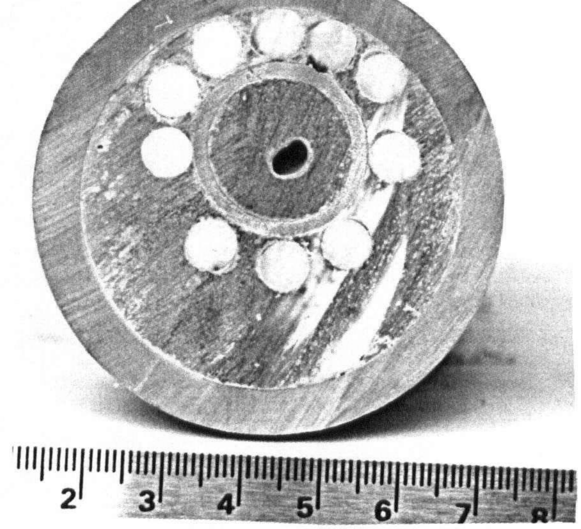


"Worming"
Single Steel Cable Bolt
5.2m from Collar
Figure 93

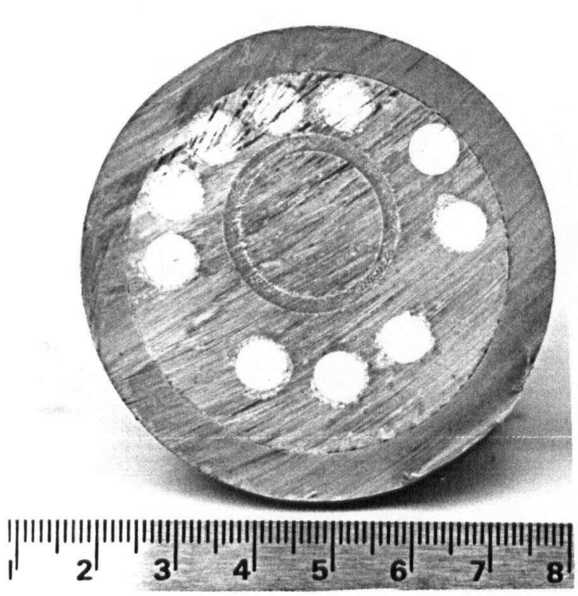
Figure 91, 92 and 93. Sectioned Grout Columns



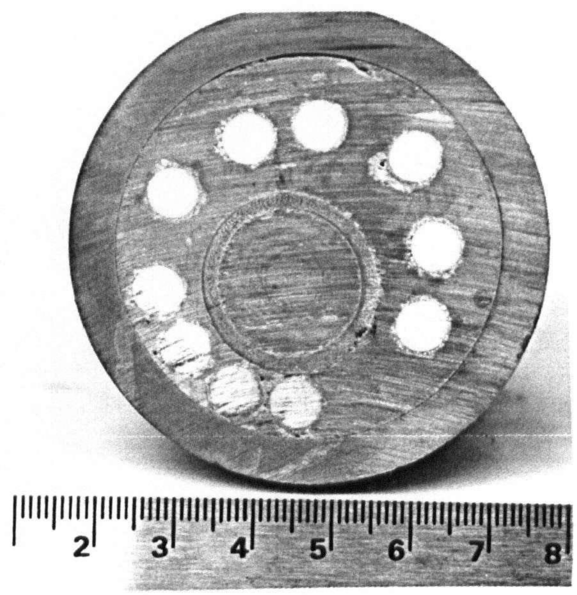
"Walling"
Double Steel Cable Bolt
Figure 94



Type III
DAPPAM
Figure 95



Type IV
DAPPAM
Figure 96



Type V
DAPPAM
Figure 97

Figure 94, 95, 96 & 97. Sectioned Grout Column allowed to cure for several days and then sectioned. Observations revealed that coverage around the cable is less than ideal for single and double steel strand cables when installed by the grout tube method. Voids within the grout column for steel cables are formed by three methods, slumping, worming and walling:

1) The head of the grout flow separates from the body of the grout (slumping) and stops after intersecting the cable and pipe walls, causing it to form a plug. As a result, a void is created between the primary and secondary grout heads (figure 91). This type was especially prevalent in single steel cable bolts.
2) The grout "worms" around the cable, causing to leave voids (figure 92 and 93). Voids of this nature are considerable smaller than voids created by slumping.
3) The cable bolt and grout tube effectively form a "wall" which does not allow grout (the bulk of) to pass through in order to complete fill the drill hole (figure 94). This type of failure is prevalent in double steel cable bolts.

It is recognized that the inside of the PVC pipe does not have similar frictional qualities to that of a borehole within the rock mass. However, it is apparent from the results that full grout coverage of the single and double steel cable bolts is jeopardized, since "worming" and "walling" is not a function of the borehole's wall friction.

Figure 95, 96 and 97 displays the grout flow around the DAPPAM cable in all three configurations of the composite cable bolt. All of the cut sections on DAPPAM (all configurations) displayed excellent grout coverage of the cable bolt. In doing so, the load transferred from the rock to the cable via the grout can be done so in an efficient manner.

6.1.6 CORROSION RESISTANCE

The corrosion resistance of the composite cable bolt DAPPAM is extremely important since the cable is subjected to the basic elements provided by the cement based grout and acidic air/ground water if fractures in the grout occur (caused by ground movement). Mines using steel cable bolts have displayed premature failed cables due to stress corrosion within only six months of installation (Mt. Isa, 1994) (Hudyma, 1993) (figure 98).

Figure 98. New and Rusted Steel Cable Bolts with Barrel & Wedge Assemblies

It is well known that environmental stress corrosion by dilute acids can weaken glass fibres within the composite. As a result, the fibres fracture at a much lower strain and stress than they normally would (up to only 20% of normal strains and stresses). In order for the fibres to be affected, micro cracks or liquid diffusion must exist in the surface coating and matrix of the composite (Delfosse, 1993).

The worst conditions for stress corrosion exist when the composite is exposed to more than 0.3% strain in an environment with a pH below 3 or above 10 (Collins 1978). For DAPPAM, 0.3% strain will usually be exceeded and the cable is generally embedded within the grout which has a pH of approximately 10. The results of pre stressed glass fibre composites exposed to the extremely acidic or basic environments vary considerably

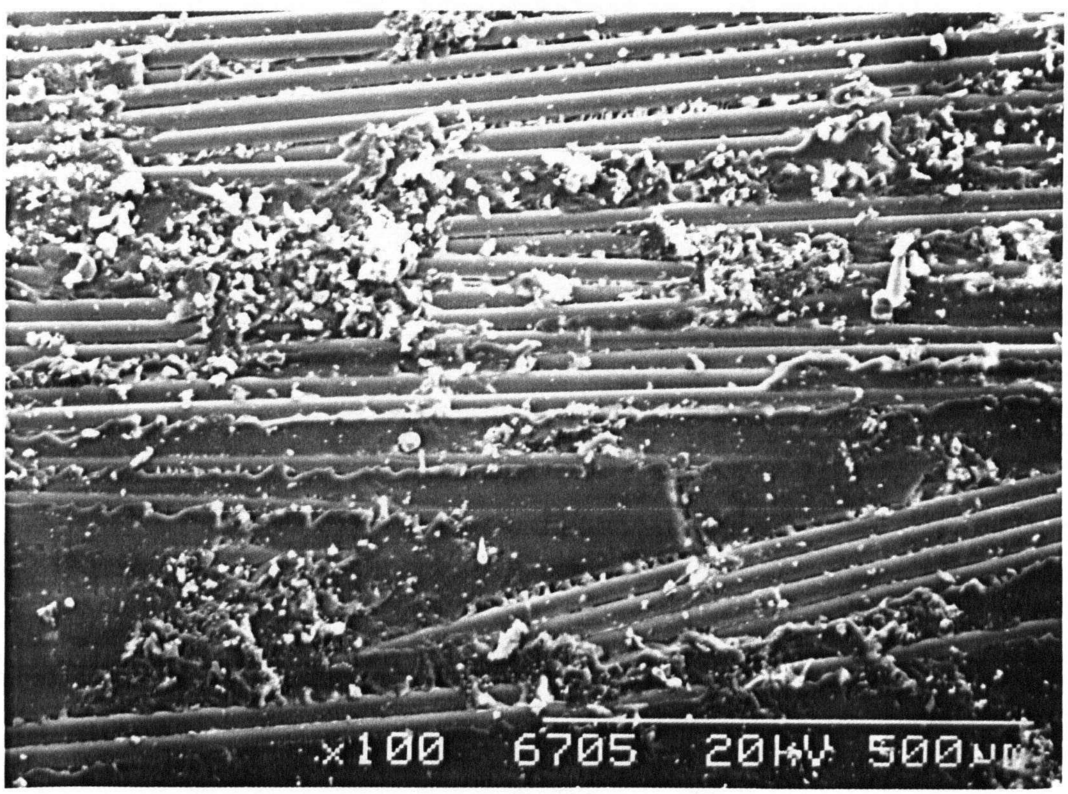
It is hypothesized that even at an adverse pH level, a long time-to-failure can be expected in the absence of matrix micro cracks. For DAPPAM, the degradation process will be slowed considerably by the protective epoxy surface coating. However, the glass fibres within the rod could be exposed to the basic grout and/or corrosive environment if either of the following occurs:

- application of the surface coating does not fully cover the glass fibre rod
- micro cracks develop in the surface coating as a result of an applied load on the cable bolt
- part of the surface coating is knocked off during transportation/installation

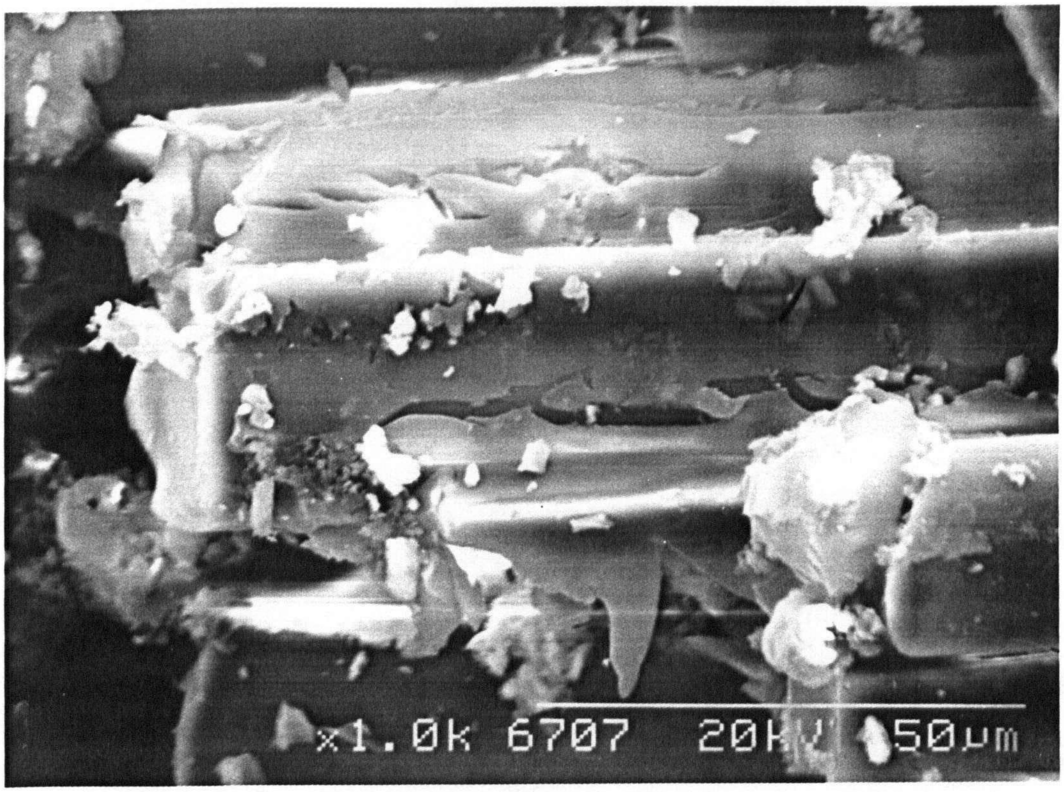
In view of life expectancy of two years or more, accelerated stress corrosion tests should be performed (Delfosse 1993).

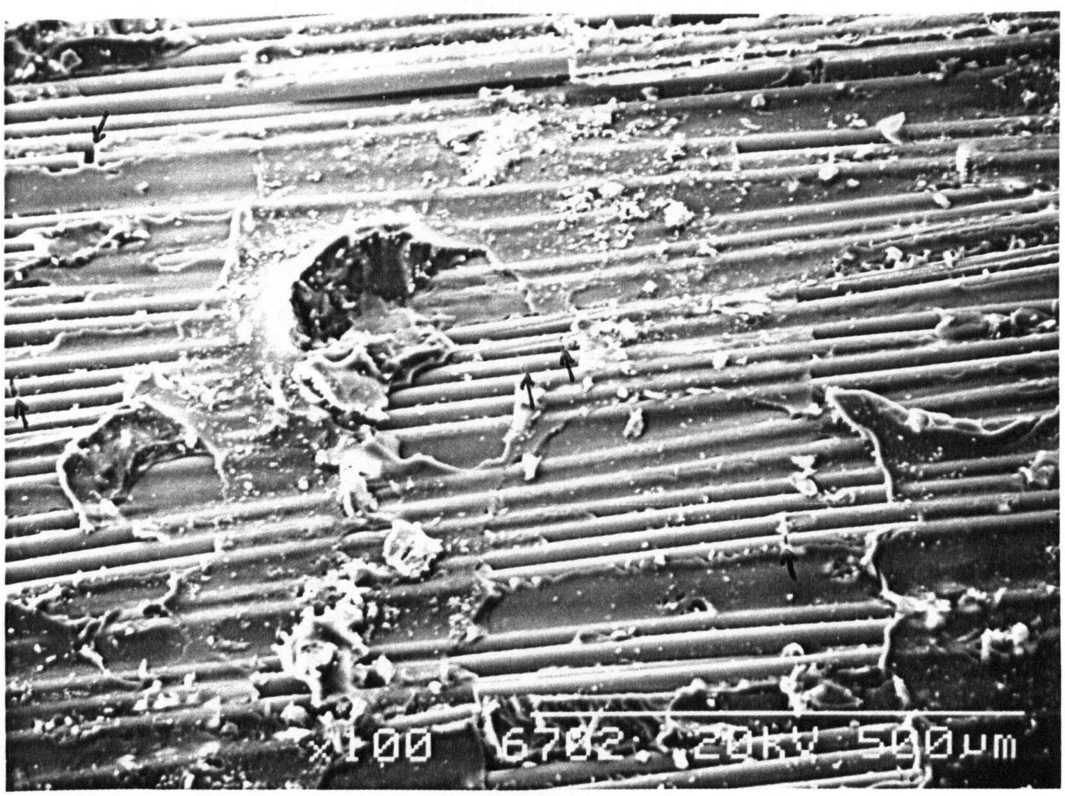
6.1.7 FAILURE OBSERVATIONS UTILIZING SEM (SCANNING ELECTRON MICROSCOPE)

Glass fibre rods taken from cable bolt samples which were pull tested to tensile failure were viewed under the scanning electron microscope to confirm the nature of failure. Failure of the rods usually occur within 2.5cm in length of the rod. Figures 99, 100 and 101 are of a failed tendon while figures 102, 103 and 104 are of a tendon that did not visibly fail during pull testing.

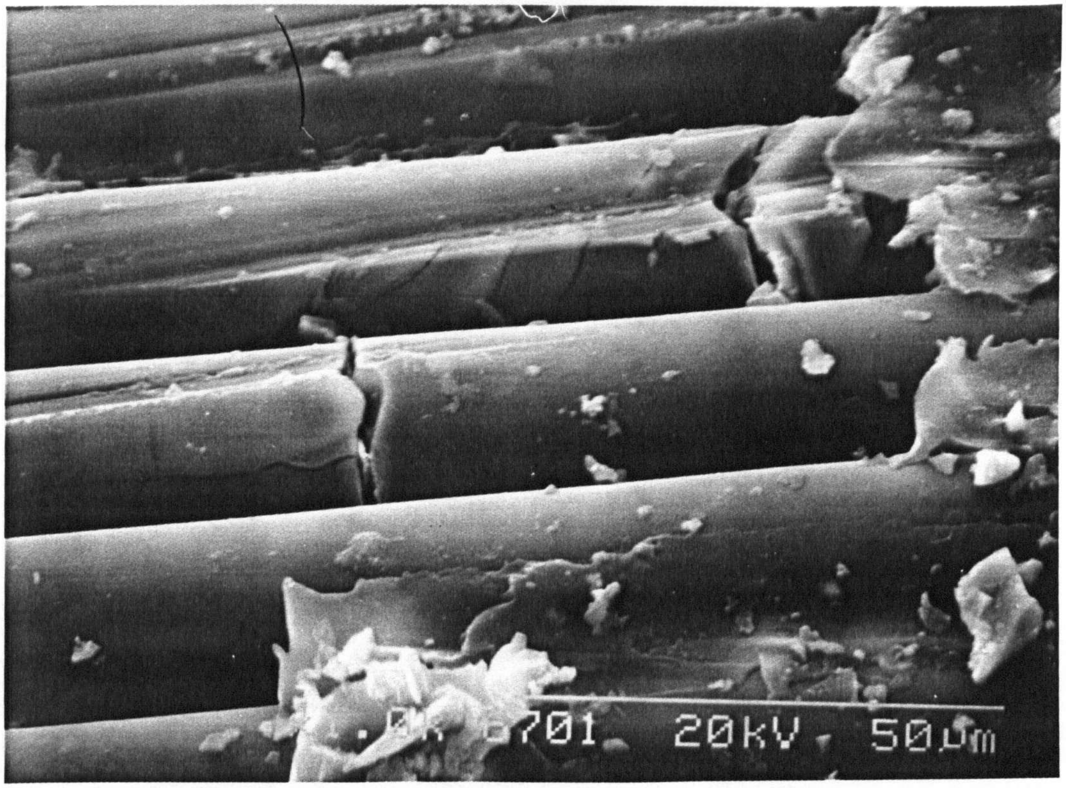


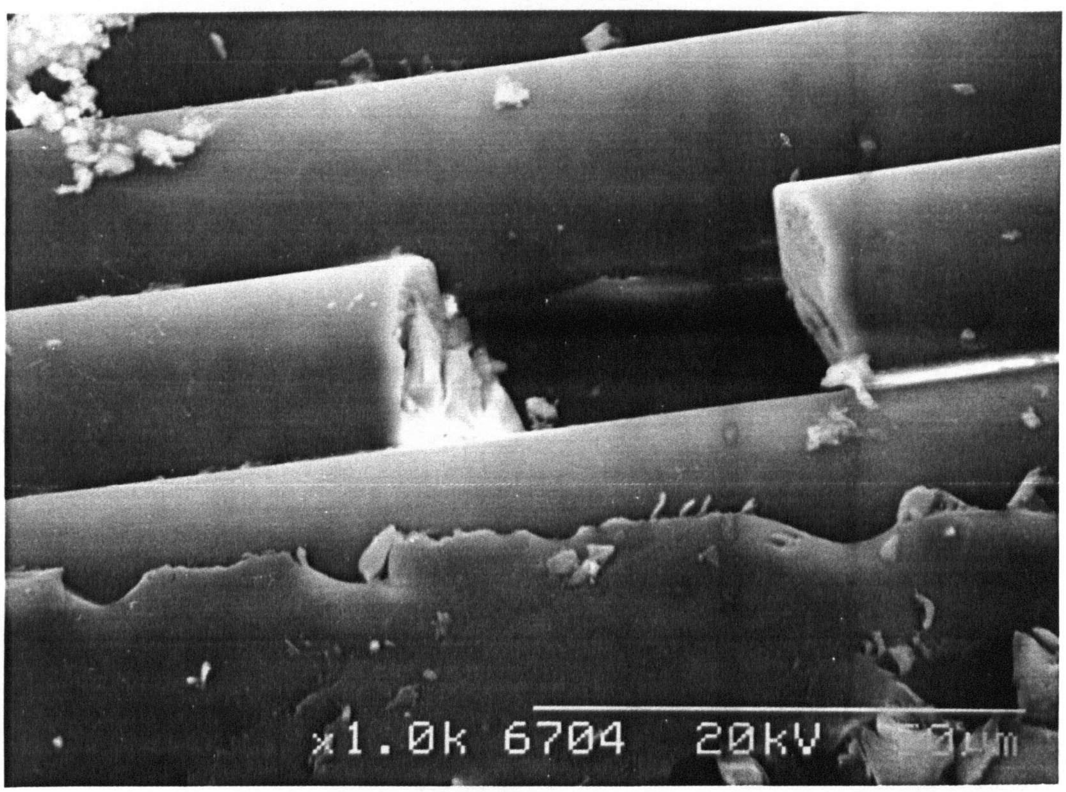
UPPER: Figure 99. Failed Fibres Within a Failed Tendon, 100x
LOWER: Figure 100. One Inch From Fracture Zone, 100x





UPPER: Figure 101. Longitudinal Splitting of FIbre, 1000x
LOWER: Figure 102. Fibre Failures Along Axis of Unfailed Tendon, 100x





UPPER: Figure 103. Fibre Failure in Unfailed Tendon, 1000x
LOWER: Figure 104. Fibre Failure in Unfailed Tendon, 1000x

Figure 99 shows the fibres breaking in a pure tensile mode, while figure 100 is taken approximately one inch from the failure zone, showing no failed fibres. A higher magnification level used in figure 101 shows some longitudinal splitting of the fractured fibres, though this failure mode has only been found in very few places and is not representative for the bulk of fibre failure.

Though figures 102, 103 and 104 are from a tendon which did not experience failure, a number of individual broken fibres can easily be detected along the surface of the tendon. Though these tendons did not fail, it is evident that they were achieving loads close to failure. Figure 102 shows initial failure of the fibres occur at different locations along the tendon, leading eventually to a failure zone which extends over a certain length as observed. Figures 103 and 104 show some of the fibre failures at a higher magnification, again, a pure tensile mode is evident (Delfosse 1993).

6.1.8 SECONDARY SHEAR TESTING

Preliminary shear testing was conducted at an earlier date at UBC using a test machine built in house specifically for shear testing the composite cable bolt. Additional shear testing of steel cable bolts was not feasible due to the load limitations of the test machine.

During 1993, the USBM commissioned a shear test machine which had high load capabilities in addition to taking into consideration joint strength. Six additional (secondary) shear tests were performed at the USBM under the direction of John Goris on DAPPAM and steel cable bolts for the purpose of comparison and to confirm the earlier preliminary shear tests.

Figures 105 and 106 show the sample preparation and testing apparatus while figure 107 displays a schematic of the test apparatus. As shown, a modeled joint is built within the sample, approximately 90° to the cable bolt. During testing, an axial load of 258kN was applied to the sample while the shearing load was increased. The axial load,

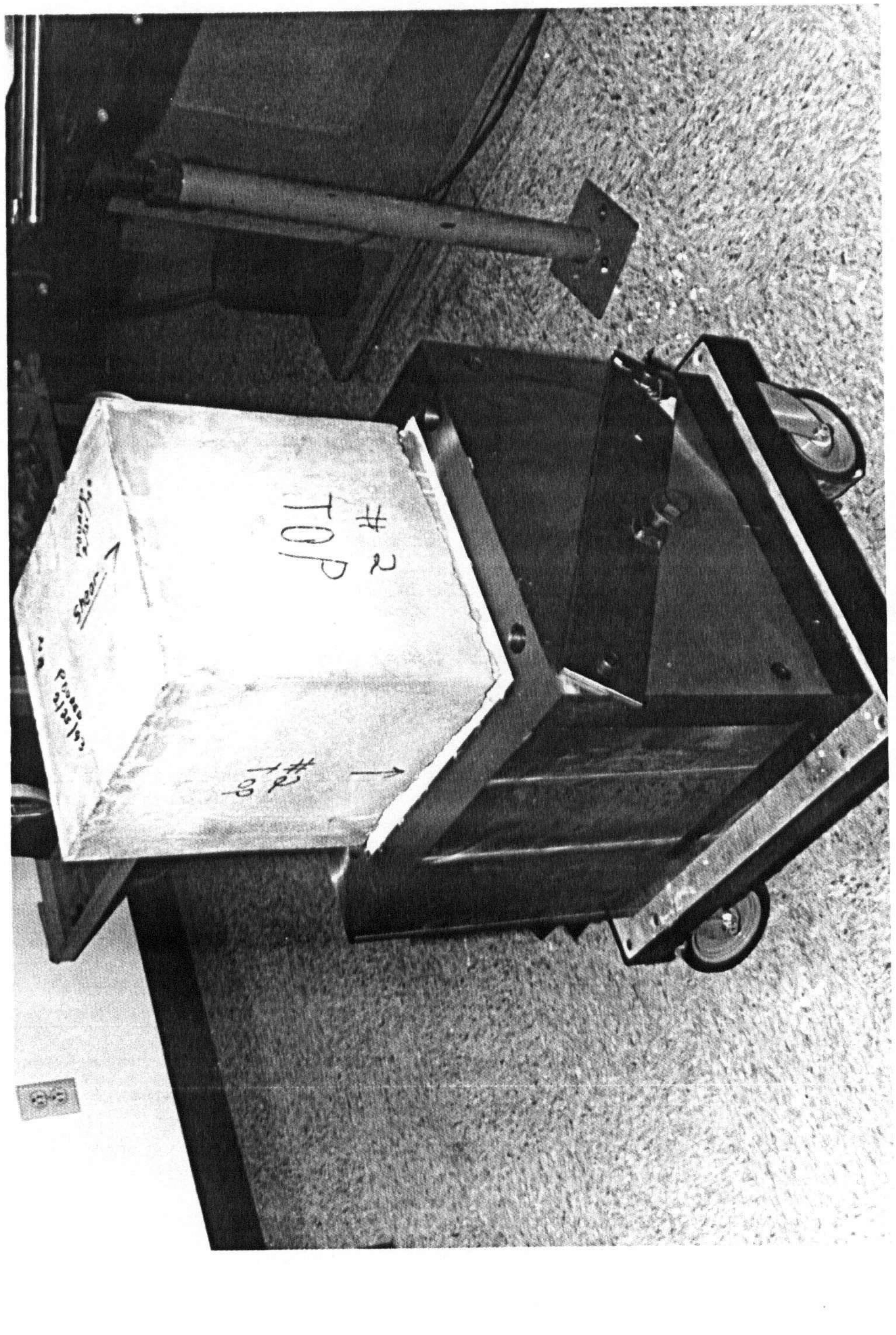


Figure 105. Shear Sample Consisting of Two Shear Blocks (USBM)

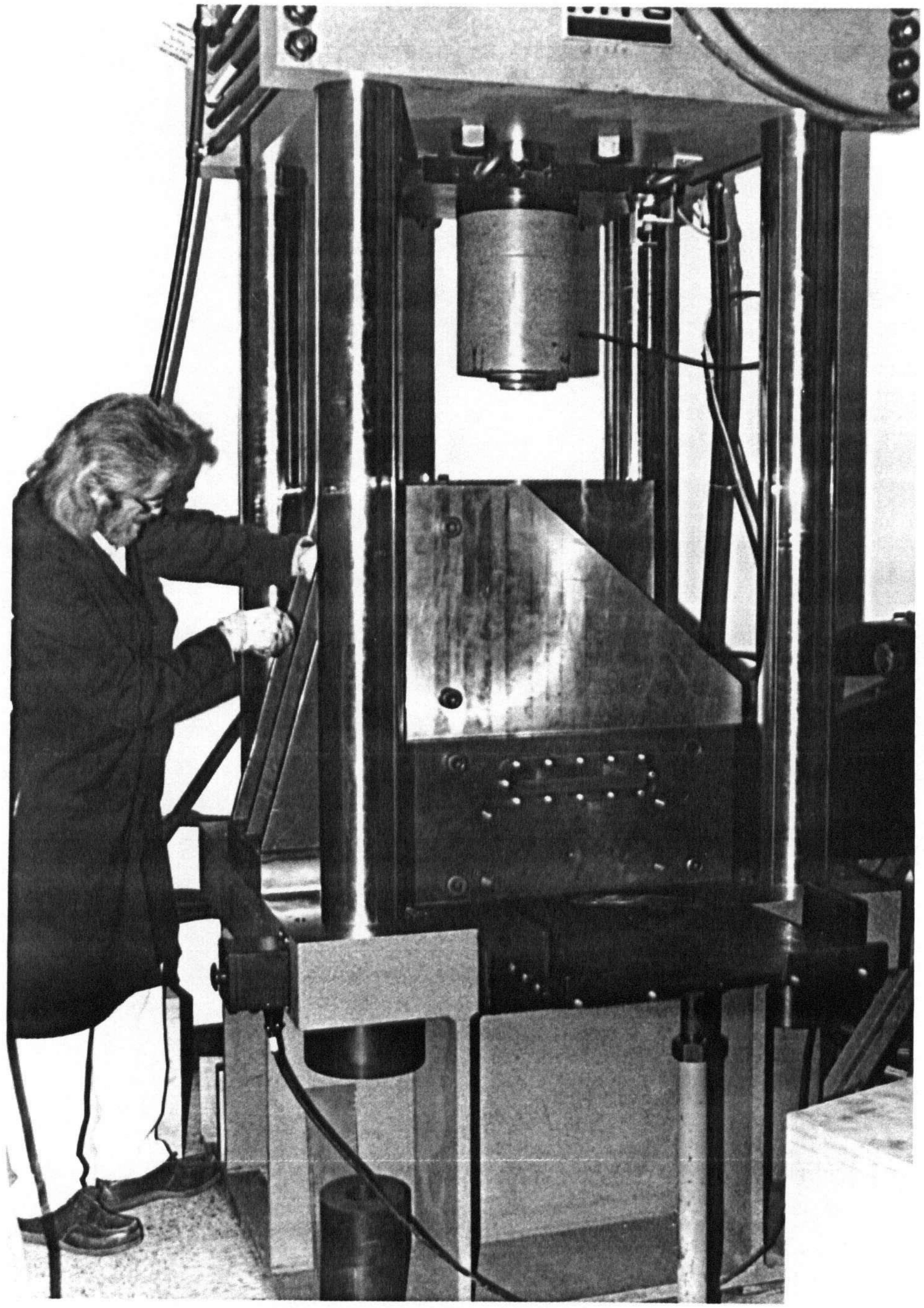


Figure 106. Preparation of Shear Sample In Test Machine (USBM)

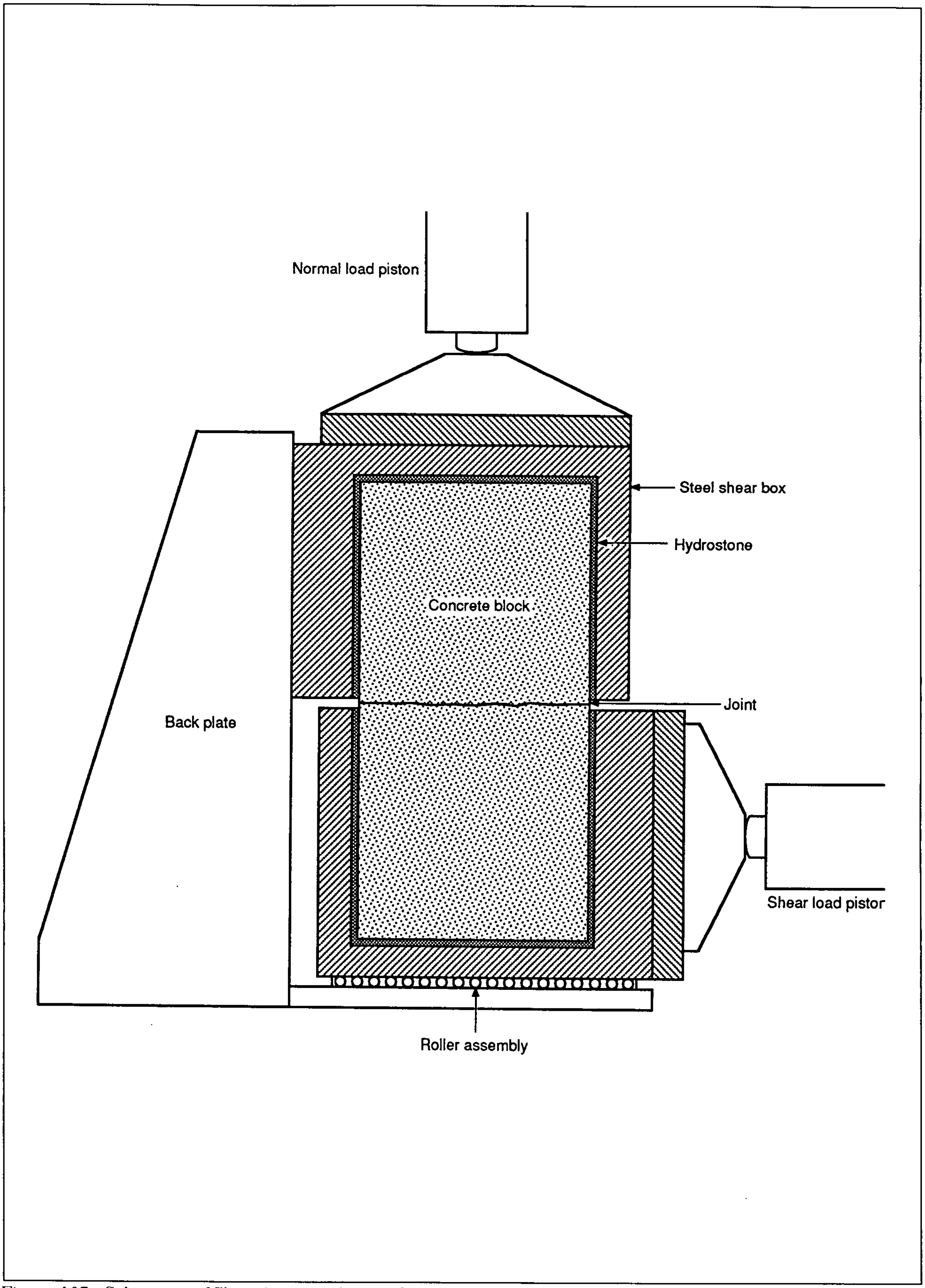


Figure 107. Schematic of Shear Test Machine (USBM)

shear load and shear displacement was constantly monitored during testing. Three samples were tested with no cable bolt included within the test specimen in order to determine the peak joint strength. Figure 108 displays one of two molded joint surfaces of the test specimen.

Figure 109 shows three of the nine samples tested, reflecting the pull out curves for DAPPAM, steel cable bolt and no cable bolt. The average shear strength developed by DAPPAM is 109kN, slightly higher than the 98.7kN obtained by the preliminary shear tests. The difference in shear strength is attributed to the method of testing. It is important to note that the resistance to shear loading for DAPPAM is very similar to steel cable bolts up to approximately 1cm of shear displacement. At this point, the composite shear cable fails and provides little to no resistance upon increased shear displacement while the steel cable bolt has the ability to elongate past 3.8cm. The shear strength of the cable bolt was determined from the peak shear load minus the residual joint strength. Table 12 presents shear strength for various types of support. It is important to note that the method of shear testing on DAPPAM, Polystal and the remaining types of support differ. However, the values are presented for approximate comparison purposes only.

Table 12. Shear Strengths of Various Rock Support

Type of Support	Ultimate Shear Strength
DAPPAM Cable Bolt[1]	109kN
Polystal Cable Bolt[2]	62.3kN
Steel Single Strand Cable Bolt[3]	267kN
Resined Massive Steel Bolts[4] 6mm (0.24") diameter 8mm (0.32") diameter 12mm (0.47") diameter	 10.4kN 19.5kN 45.2kN
Spit Set[4]	85.0kN
Swellex[4]	90.7kN

1 Tested by USBM
2 after Peterson *et al*, 1993
3 theoretical value
4 after Ludvig, 1983

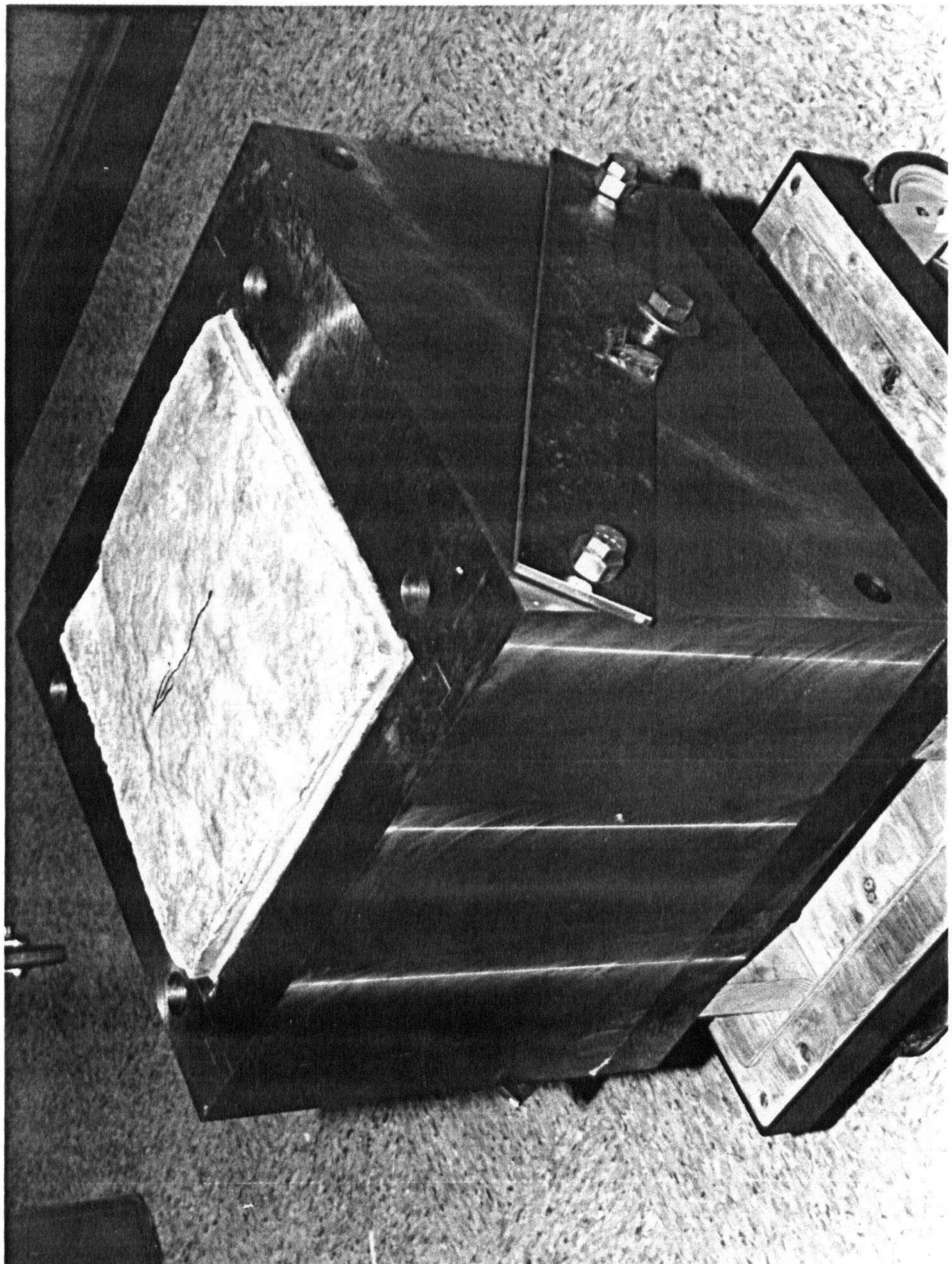


Figure 108. One of Two Molded Joint Surfaces in Shear Test Specimen

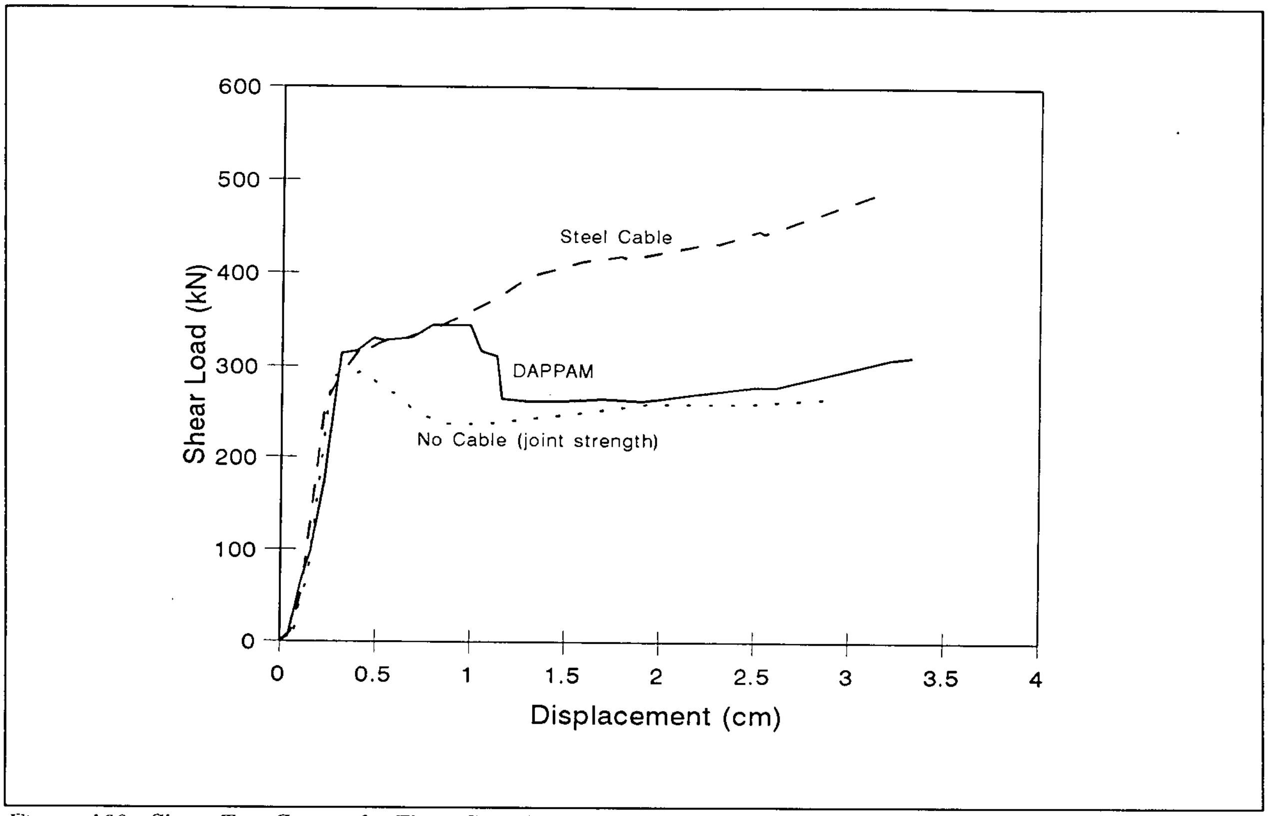


Figure 109. Shear Test Curves for Three Sample Types

6.1.9 PHYSICAL PROPERTIES OF THE DAPPAM CABLE BOLT

The DAPPAM cable bolt consists of ten (10) individual 0.64cm diameter glass fibre rods enveloping a 2.2cm O.D. high density polyvinyl grout tube. During cable bolt installation, the grout is pumped through the annulus of the grout tube thereby filling the hole from toe to collar. The grout tube has an inside diameter of 1.9cm and is rated at a pressure of 1.7 MPa. The glass fibre rods are constructed with 21μm ECR glass and isophthalic polyester resin. A surface coating consisting of a fine sand grit and a modified epoxy is applied to each rod. It is recommended that a 4.4cm diameter drill hole be the smallest the cable is inserted into. The physical properties of the DAPPAM composite can be found in table 13, while the performance of the DAPPAM cable bolt is in table 14.

Table 13. Properties of DAPPAM vs Pre stressed Steel

	DAPPAM (1)	Single Steel Cable Bolt
Tensile Strength (per area) (MPa)	1,212	1,670 (2)
Tensile Strength (of cable bolt) (kN)	409	269 (2)
Shear Strength (kN)	109	269 (3)
Ultimate Strain (%)	2.9	4.4 (2)
Specific Gravity	2.1	7.85

(1) as tested
(2) as rated
(3) theoretical value

Table 14. Performance of the DAPPAM Cable Bolt

Bond Strength or BS (kN) (grout ucs=51.4 MPa) *BS=10.82(bond length)-37.8*	Maximum Load (kN)	Displacement at Maximum Load (cm)	Safety Factor
Ultimate Shear Strength	109 kN	1.0 cm	n/a
Ultimate Tensile Strength	409 kN	2.2 cm	n/a
Designed Shear Load	89 kN	n/a	1.2
Designed Tensile Strength	289 kN	$\approx$ 0.75 cm	1.4
Critical Bond Length (grout ucs = 51.4 MPa)	41 cm (estimated)	n/a	n/a

(1) tested for bond lengths between 10.2 cm to 22.9cm with correlation coefficient equal to 0.977

Chapter 7

TRIAL INSTALLATIONS

The following chapter presents the results from the trial installations of all glass fibre cable bolt prototypes completed for evaluation purposes during Phase II and III of the research program. One trial installation of Polystal during the early part of Phase II and three installations of DAPPAM during Phase III were completed and are discussed.

7.1 Trial Installations

The primary reasons for completing trial installations on the composite cable bolts were three fold:

1) evaluate the prototype qualitatively
2) evaluate the prototype quantitatively (where applicable)
3) introduce the use of composite cable bolts to mine personnel and the industry in general

During the test program (figure 110), testing during steps 3-5 were interative. As a result, prototypes other than DAPPAM (configuration III) were used in the earlier trial installations.

7.1.1 WESTMIN INSTALLATION #1

The primary objective of the installation was to support the hanging wall of an open stope. A shear zone approximately 1m in thickness was located approximately 1.5m to 10m above the hanging wall (figure 111).

Thirty (30) twelve metre long uncoated Polystal cable bolts constructed by Con-Tech were to be installed in down holes within the N-394 BP3 stope beside a nest of 28 double steel cable bolts. The polystal cable bolts had a designed tensile strength of 222 kN using four (4) 7.7mm diameter rods combined in a node-antinode fashion with a

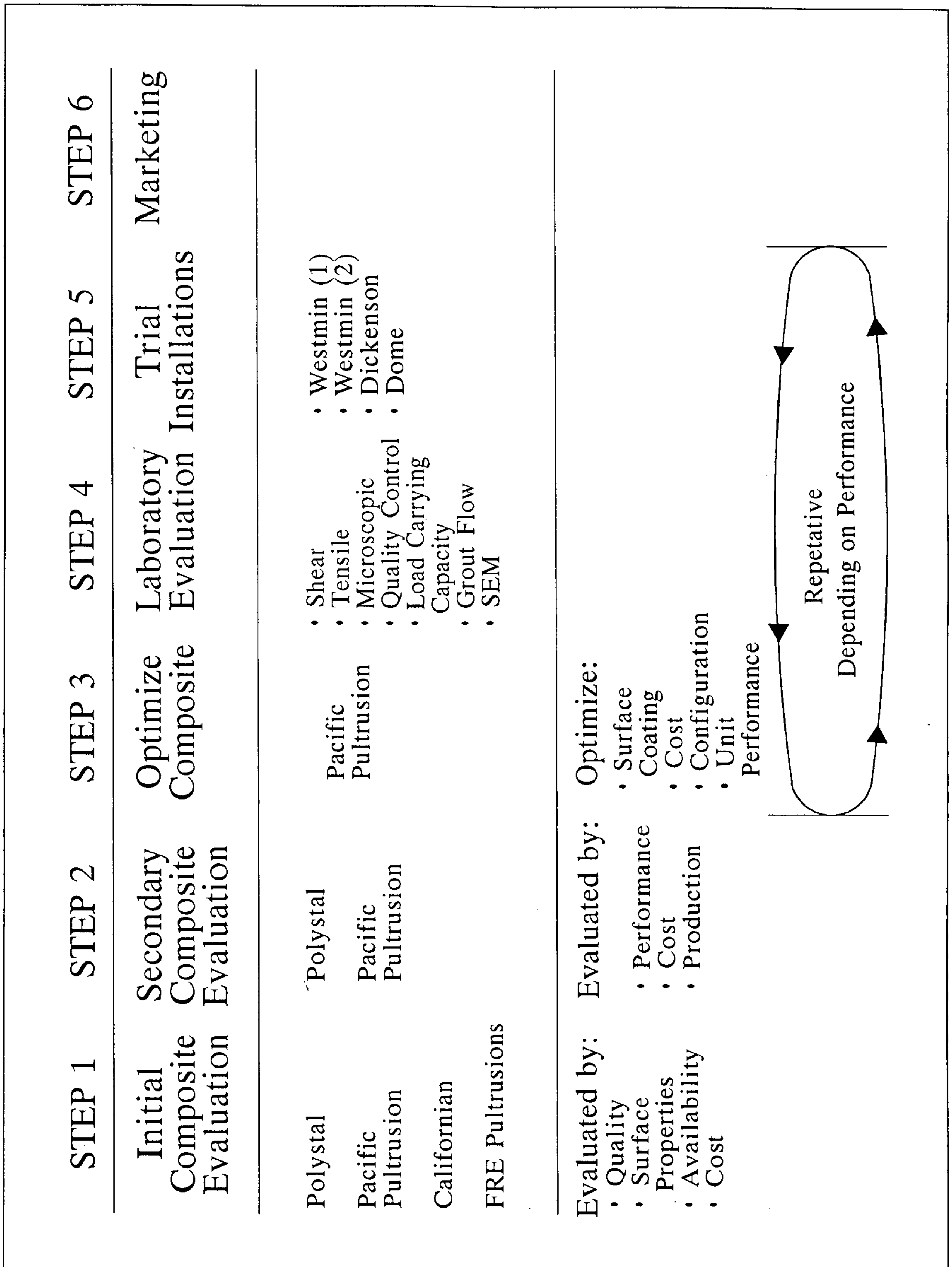


Figure 110. Research Flowchart - Step 5, Trial Installations

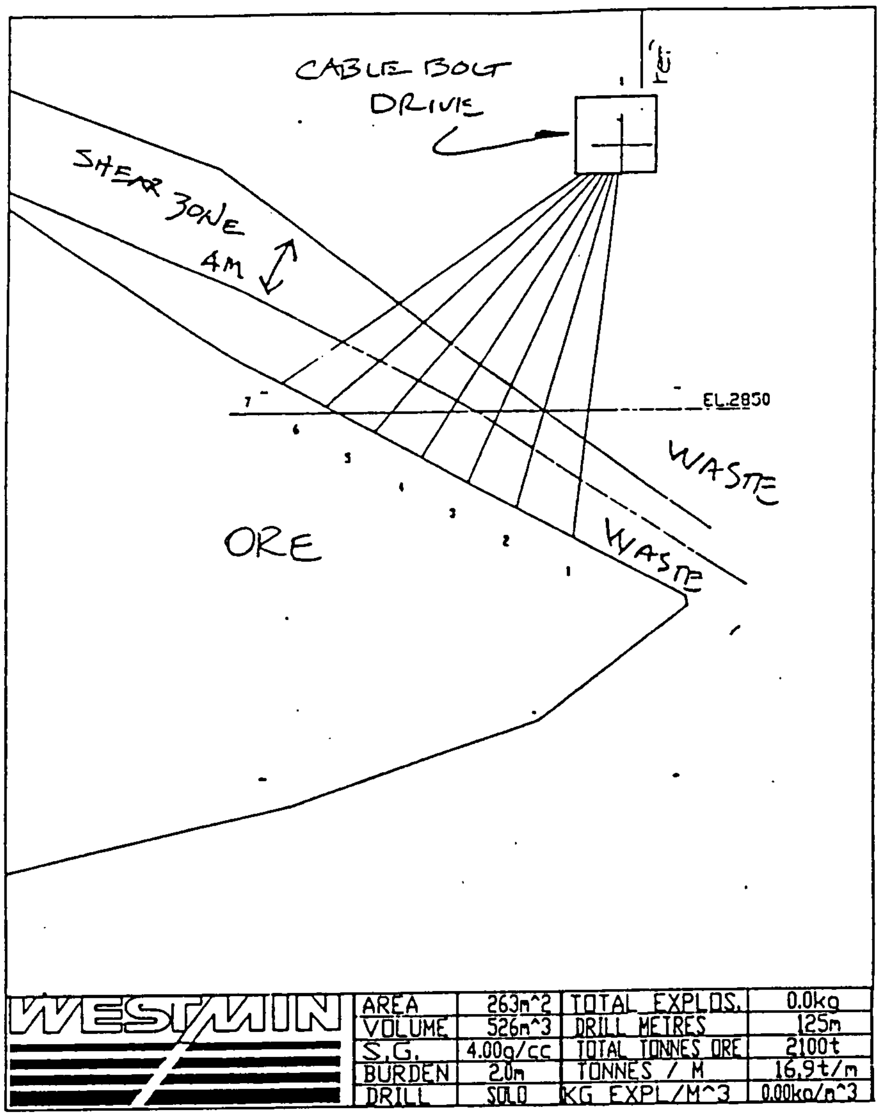


Figure 111. Section of Area Supported During Polystal Trial Installation #1

10.2cm spacing between nodes. Two multiwire extensometers were to be installed to measure rock movement within the hanging wall.

During January 1992, thirteen (13) Polystal cable bolts were installed along with one extensometer (figure 112). Also installed were 45 double steel cables. The stope was mined during the month of May (1992) and a visual evaluation of the stope was conducted June 3, 1992.

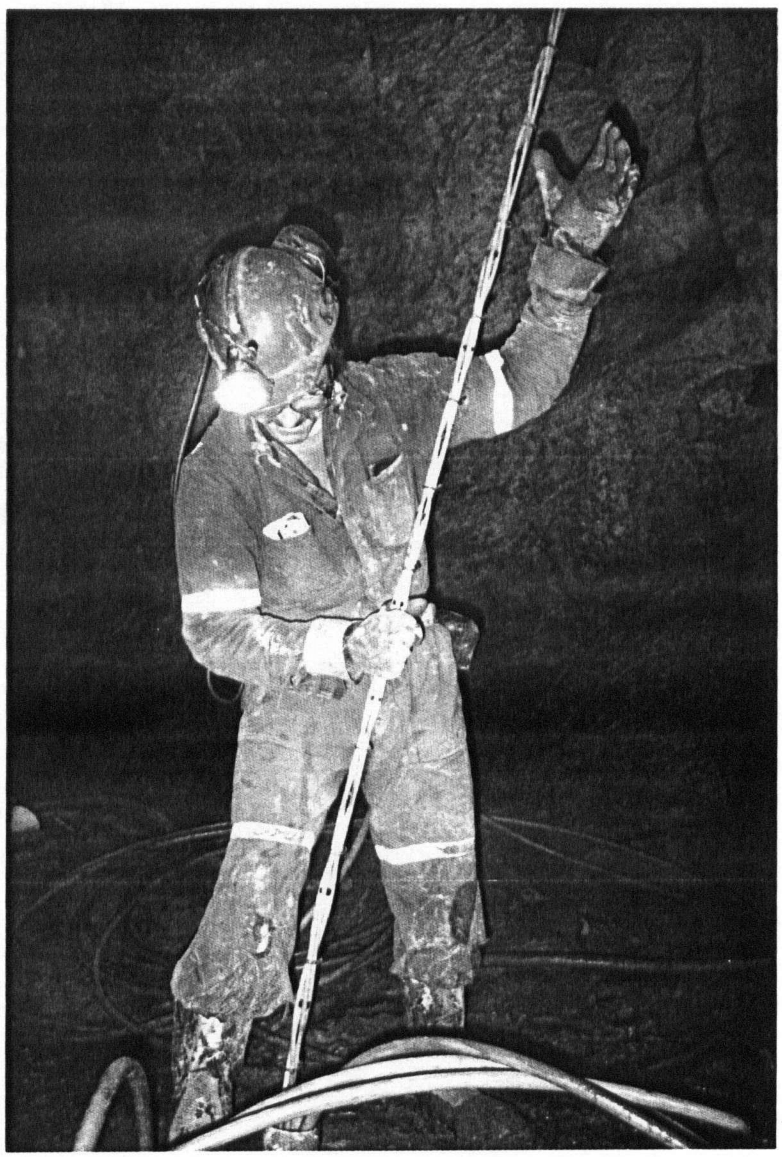


Figure 112. Installation of Polystal Cable Bolt at Westmin

Complications were encountered in the installation of the Polystal cable bolts. The complications were contributed by the wire wrap used to tie the rods together at the nodes, and by the gout tube. The wire wrap rubbed on the side of the drill hole, breaking apart several of the wires. Corrosion was observed on the wire wrap used to tie the rods together at the nodes. In addition, the 22.2mm diameter grout tube and the Polystal cable bolts were installed as a unit into a 54mm diameter drill hole. The amount of clearance between the cable bolt/grout tube and the drill hole was minimal, causing the unit to fit tightly into the hole. As a result, it was very difficult to push the cable bolt/grout tube unit into the drill hole. The size of the grout tube and drill hole are standard within the industry, suggesting that the cable size (overall diameter) must be decreased as to promote easy installation.

Only one of two extensometers was installed. This is due to the hole into which it was to be installed was drilled short in length. The hole was unable to be deepened due to scheduling commitments of the drill and its crew. Most of the monitoring stations on the installed extensometer were rendered useless as a result of the blast and overbreak.

Once the stope was blasted, a visual inspection was conducted to qualitatively observe the Polystal and steel cable bolts. It appeared that the glass fibre cables supported the rock mass better than the twin steel cable bolts. The mode of failure of the twin strand cable bolts was a grout/cable failure. Up to 4m of rock slipped off of the steel cable bolts. This indicated that the load created by the rock was greater than the cable/grout bond strength. No steel cables were broken. The mode of failure for the glass fibre cables were grout/cable failure and cable failure. Three of the thirteen glass fibre cables failed by having up to 1.5m of rock slip off the cable bolt. The cables which broke indicated that the bond between the cable and grout was greater than the strength of the cable. It is unknown how much load the Polystal cable bolts took before breaking. If the load was strictly tensile, laboratory tests indicated that the cable bolts were fail at approximately 222kN. If the load was directed perpendicular to the cable bolt, the cable would break at approximately 49kN. Observations from the site inspection indicated that considerable ground movement occurred in the immediate area. This would imply that the loading of the cables would be a combination of tensile and shear forces, lowering the cable's overall breaking strength.

Comments originating from personnel within the management, engineering and production departments were pleased with the performance of the composite cable bolts and were optimistic about their future use within the industry.

As a result of the installation, future prototypes would need to incorporate the grout tube within the design of the cable bolt and must fit adequately within a 4.45cm diameter drill hole.

7.2.2 WESTMIN INSTALLATION #2

A trial installation of DAPPAM at Westmin's Myra Falls was undertaken January 4, 1993. Fifteen DAPPAM cables (type IV), each 6m in length, were installed in up holes to support the hangingwall in an open stope (figure 113 and 114). Figure 115 shows the uncoiling of DAPPAM. Figure 116 shows the manual installation of DAPPAM, as featured on the January 1994 CIM bulletin cover. The workers and shift boss were very enthusiastic in how effortless and fast DAPPAM was uncoiled and pushed into the drill hole. A time study during the installation revealed that each DAPPAM bolt took 0.054 (3.24 minutes) man hours to uncoil and push. Conventional cable bolts within the area took, 0.417 (25 minutes) man hours per cable.

The installation was monitored with two remote ground movement monitors. Each monitor is connected to a transmitter which relays its readings to a data logger via a receiver (figure 117 and 118). The purpose of the instruments was to monitor the movement of the rock immediately above the opening. The DAPPAM bolts were installed to support a shear zone approximately 1 metre in thickness (figure 114).

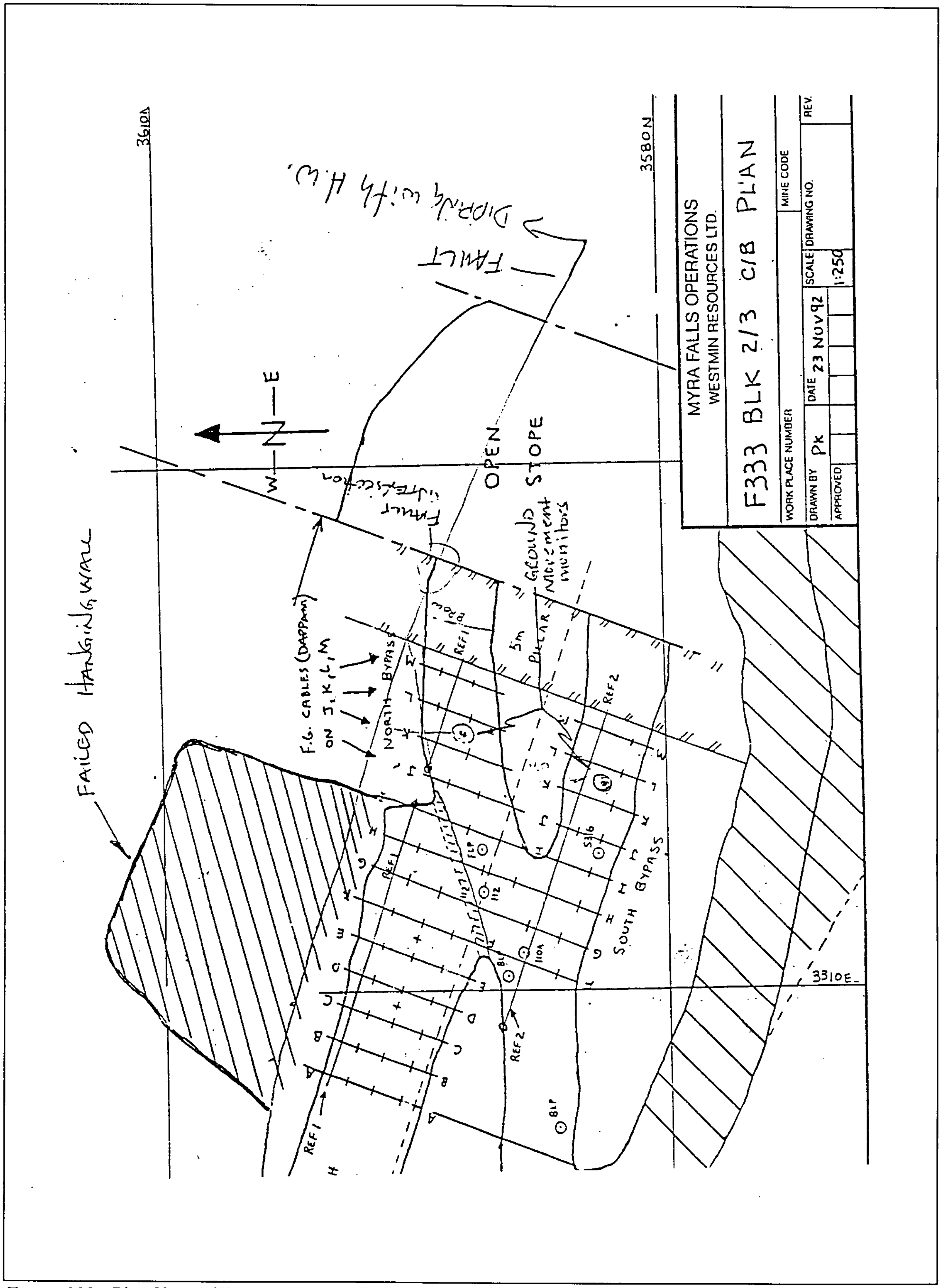


Figure 113. Plan View of Westmin #2 Installation

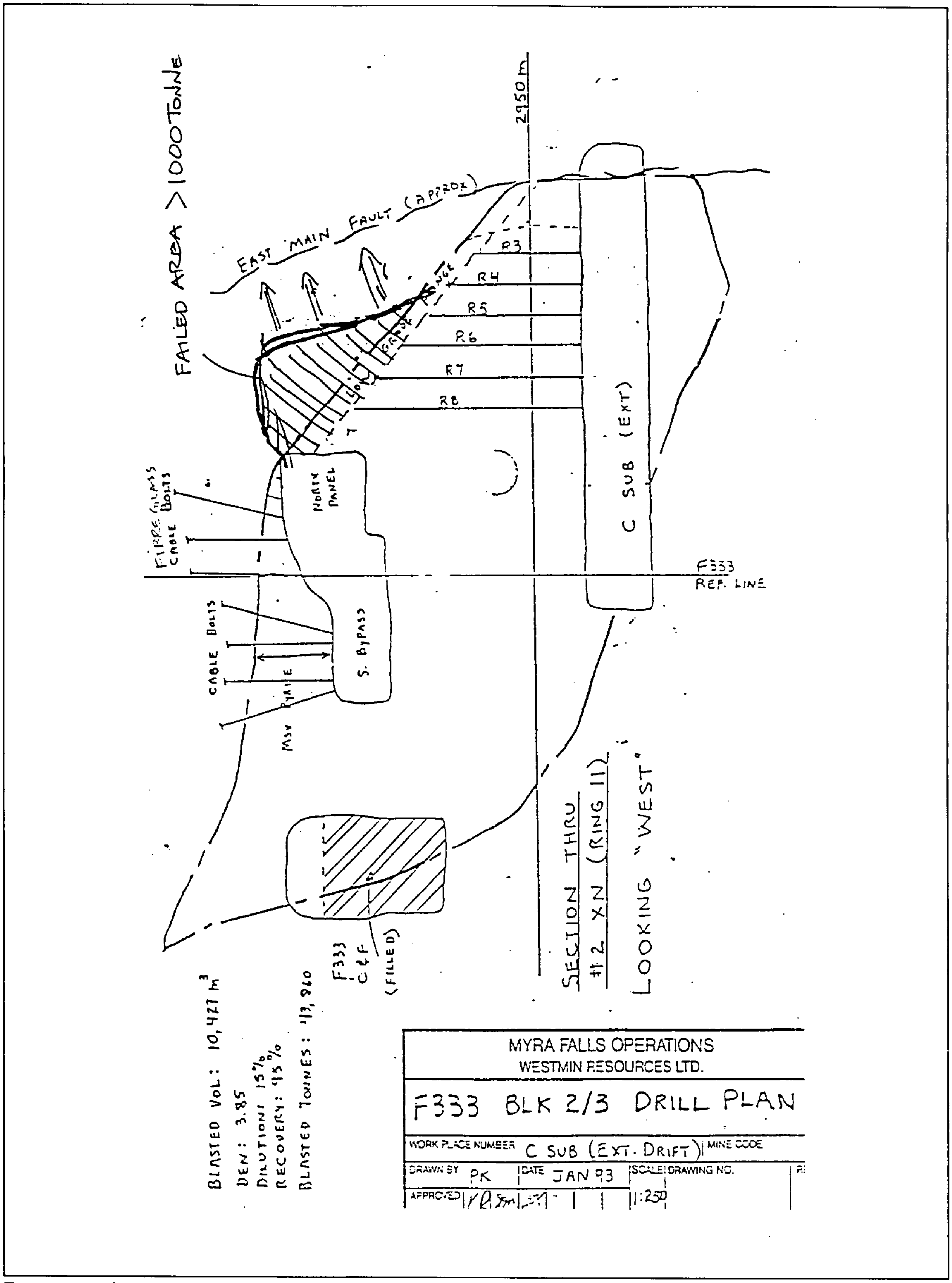


Figure 114. Section of Westmin #2 Installation

Figure 115. Uncoiling DAPPAM at Westmin #2 Installation

During the month of April (1993), the stope was blasted in three stages, resulting in a failure of the stope's hangingwall in excess of 1000 tonnes of rock. The location of the glass fibre cables with respect to the failed zone can be seen in figures 113 and 114. The first blast consisted of developing a slot raise, which was located directly underneath the glass fibre cables and ground movement monitor (GMM) #2. The GMM did not survive the blast and was rendered useless. The second blast consisted of opening the stope full height for one third of the strike span. This included delayed blasting of the pillars in the upper drill drive. This blast rendered GMM #1 unusable. At this stage, the stope was stable. The third and final blast defined the stope's full length along strike. Immediately following the blast, in excess of 10,000 tonnes of rock (ore and waste) fell from the hangingwall into the stope (figures 113 and 114). As a result, the mine decided not to remove approximately two thirds of the muck from the final blast due to dilution

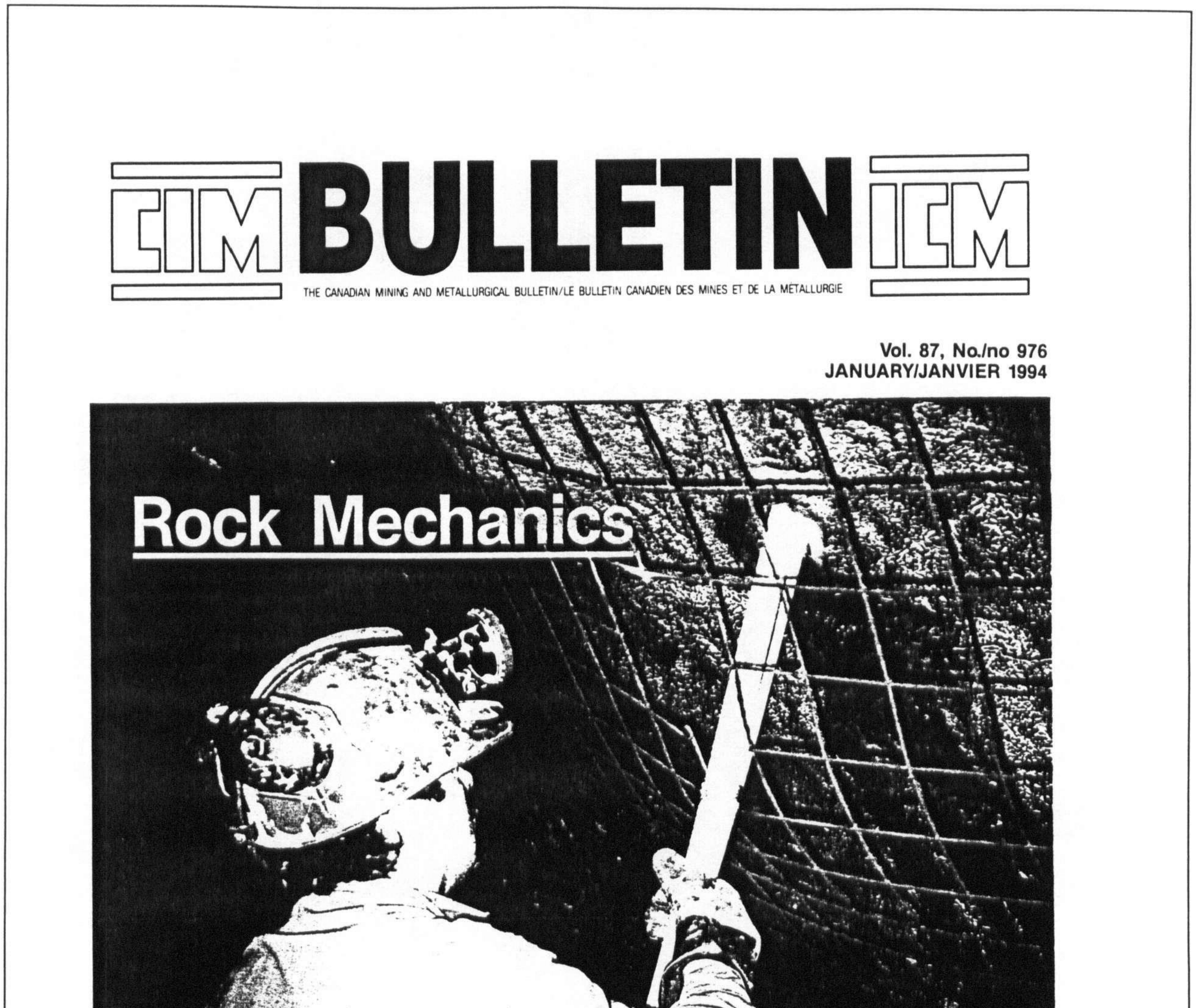


Figure 116. Installing DAPPAM at Westmin #2 Installation (CIM, 1994)

UPPER: Figure 117. Remote Transmitter & GMM
LOWER: Figure 118. Receiver & Datalogger

and mucking problems caused by the fall of ground. Approximately 1.1 million dollars in revenue was lost.

Qualitative results from the stope inspection conducted in April indicate that the DAPPAM cables performed well. Unfortunately, no quantitative results were collected due to the destruction of the GMM's transmitters during the blasts. No instability where the DAPPAM cables was evident.

7.2.3 DICKENSON MINE INSTALLATION #1

Fifteen (15) DAPPAM cable bolts (type III) were installed in down holes within the 26-976 stope at Dickenson Mine in order to support the hanging wall of a stope.

The 26-976 stope has been mined previously by cut and fill methods. The stope is mining a sill pillar, which separates 26-976 stope from 25-986 cut and fill stope (figure 119). The remaining 20m (along dip) will be mined by long hole mining in order to alleviate problems derived from high stress. Separate lenses or pods from the main orebody exist at various locations. It is the S.E. pod (26-976 S.E. pod) which the DAPPAM cable bolts are being used as pre-support.

At this location, 26-976 stope consists of two pods, (N.W. and S.E. pods), separated by approximately 18m of waste. The N.W. pod has been developed, supported and mined (by longhole), while the S.E. pod's overcut and undercut still must be completed (slashed) and cable support completed prior to being mined.

Six (6) of the planned fifteen (15) DAPPAM cable bolts were installed during the sight visit. The cable bolts were inserted into down holes, resulting in the grout being pumped to the toe of the hole via DAPPAM's grout tube, allowing the hole to fill from toe to collar. The water:cement ratio used was approximately 0.40. No problems with the cable bolt installation were encountered.

Since the number of DAPPAM cable bolts installed were small and the installation was not carried out by the regular cable bolt crew, the installation time for the cables can not be compared to previous steel cable bolt installations. From initiation of uncoiling the cables to the completion of grouting, the time to install the six cable (three batches of grout) took an approximate 95 minutes. No problems were encountered in mining the 26-976 stope.

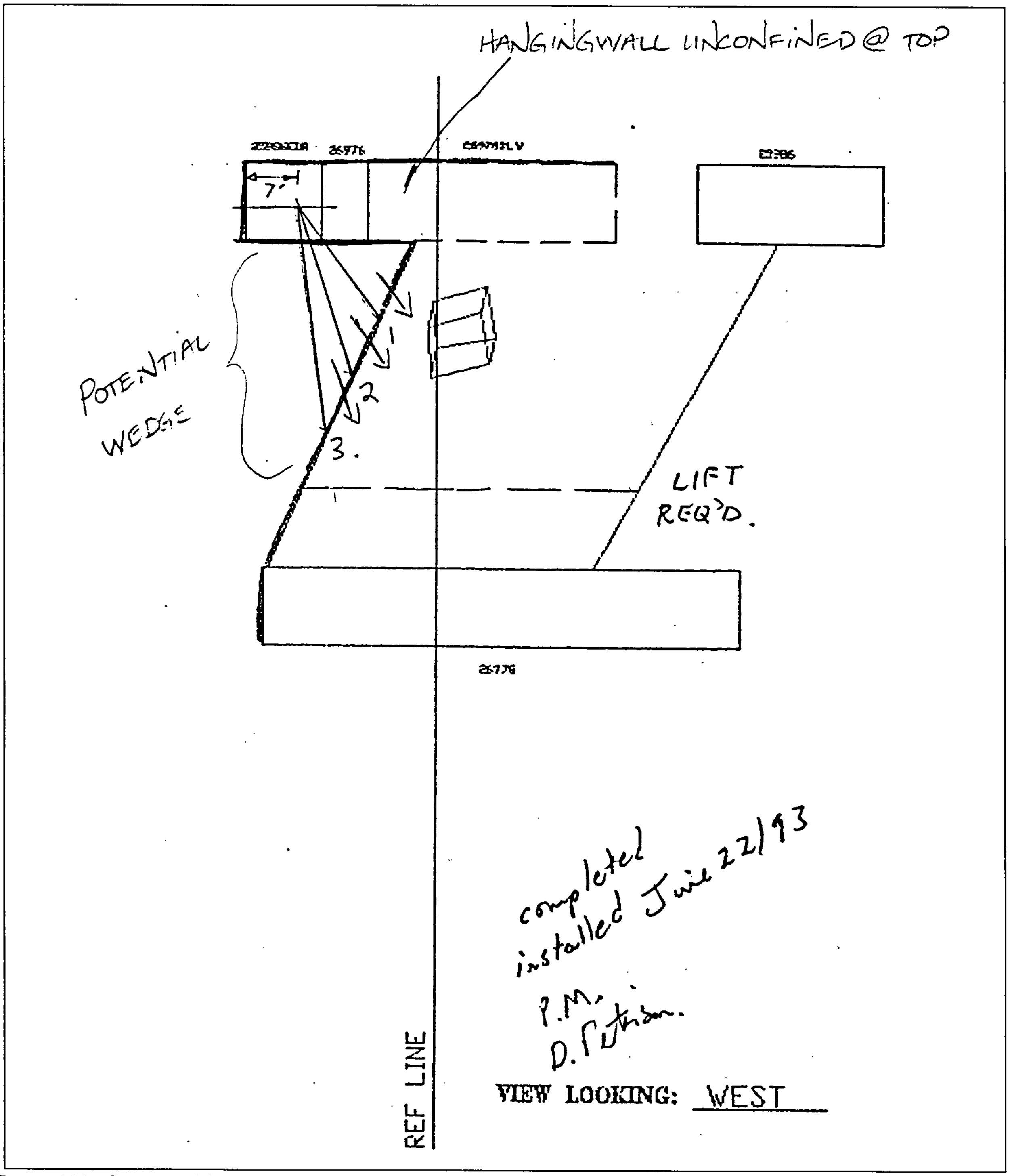


Figure 119. Section of the Dickenson Installation

7.2.4 DOME MINE INSTALLATION #1

An installation of DAPPAM was conducted during the month of October (1993) at the Dome Mine, located in Timmins, Ontario. The mine used 100 DAPPAM bolts, each 14m in length to support a sill pillar in a location where mining has been completed. The cable bolts were installed in down holes and have been used as long term support. The mine chose to use the composite cable bolts since the drill holes used for installation had previously contained explosives.

Figures 120, 121 and 122 display the location and orientation of the installation. The installation was successful, with the glass fibre cables taking approximately 32 man hours less to install than convention cable bolts. The workers commented that the grout tube should be counter-sunk within the confinements of the composite rods on the cable bolt end which enters the drill hole first. This would eliminate plugging of the grout tube during the pushing of the cable bolts.

The only criticism made by the engineering department was the high price paid for the DAPPAM cable bolts. The mine purchased the DAPPAM cable bolts for \$7.55/m (\$2.30/ft) while regular cable bolts are purchased for \$2.30/m (\$0.70/ft). The engineer responsible for the installation commented that DAPPAM would be economically attractive to them at a price no higher than \$4.00/m (\$1.22/ft).

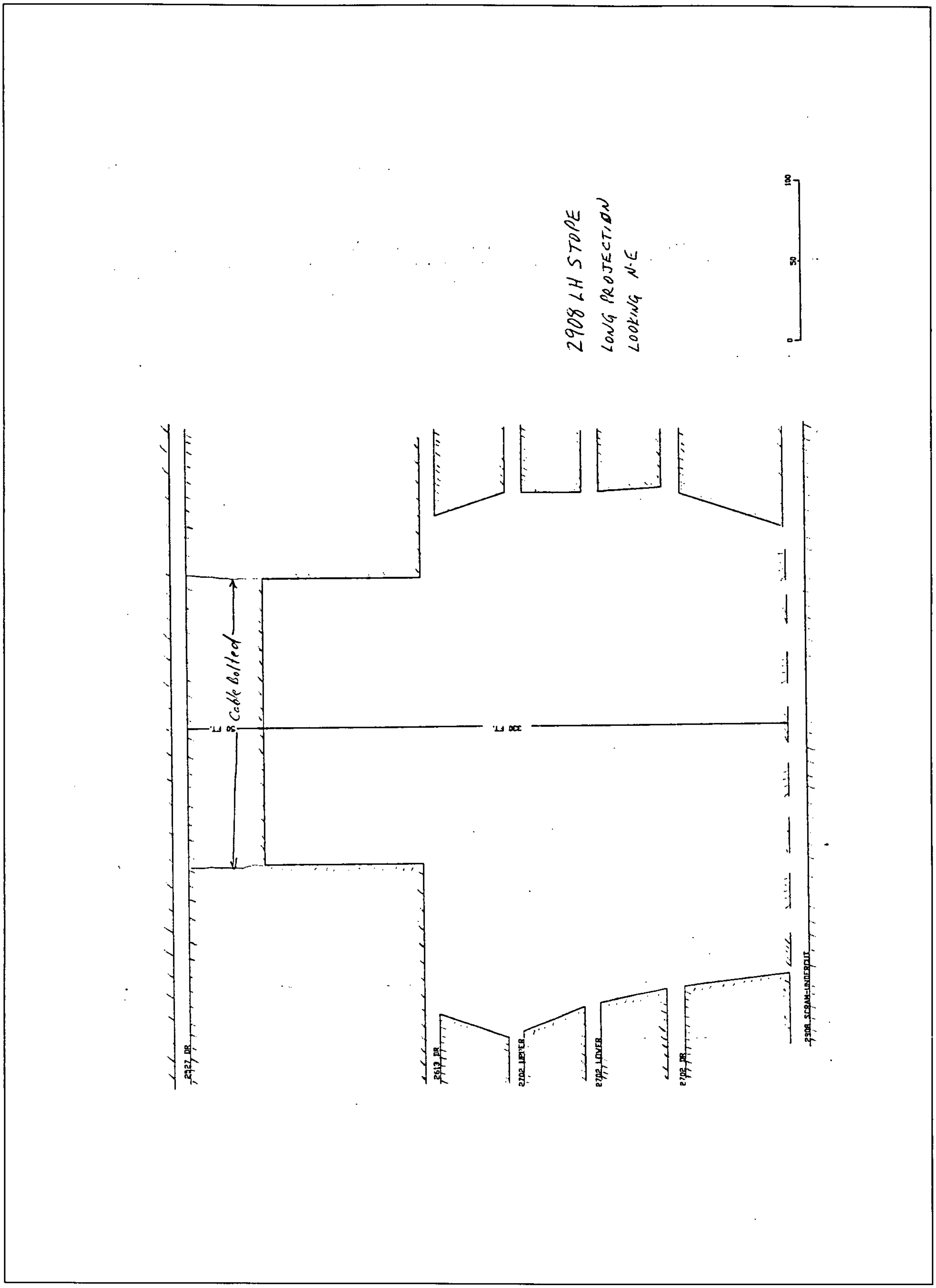


Figure 120. Longitudinal Section of Dome Mine Installation

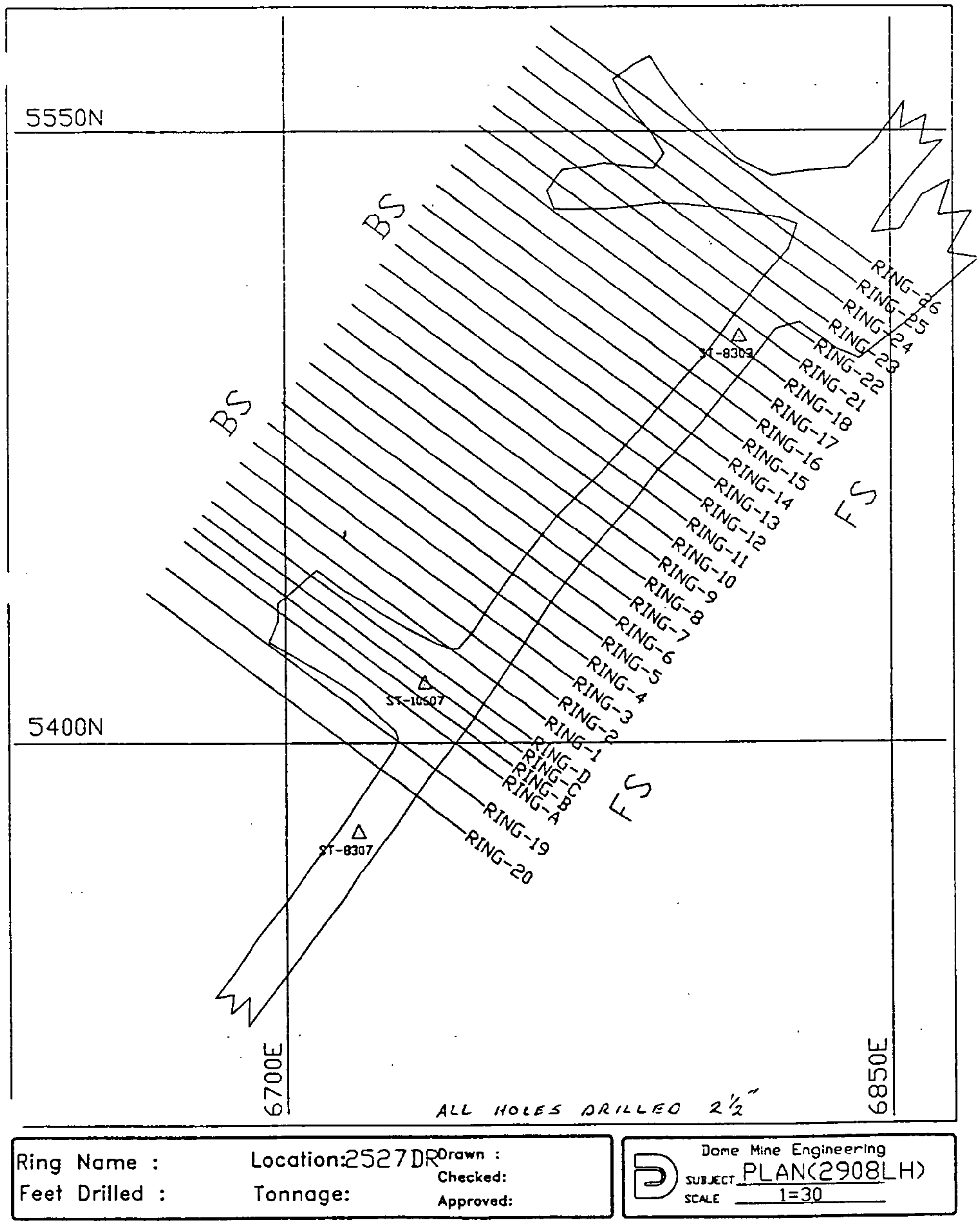
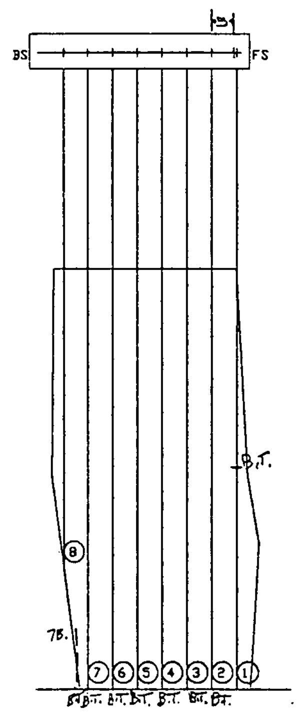


Figure 121. Plan View of Dome Mine Installation

Hole	Dip	Length	Offset From Backsight	Drilled Length	Drilled Date	
1.	90	148	50	32\120	MAR-21-93	
`.	90	148	44	45\97	MAR-22-93	
3.	90	148	38	20\128	MAR-23-93	
4.	90	148	32	40\108	MAR-24-93	
5.	90	148	26	148	✓	
6.	90	148	20	136	MAR-25-93	REDRILL.
7.	90	148	14	140	MAR-26-93	
8.	90	120	8	120	MAR-30-93	
7A	90			116\32	MAR-30-93	B.T.

3" DRILLING



·g Name : RING-D	Location: 2527DR	Drawn:
Feet Drilled : 1156	Tonnage:1402	Checked:
		Approved:

Dome Mine Engineering
SUBJECT 2908SCR
SCALE 1=30

Figure 122. Cross Section of Dome Mine Installation

Chapter 8

COMMERCIAL APPLICATIONS of DAPPAM

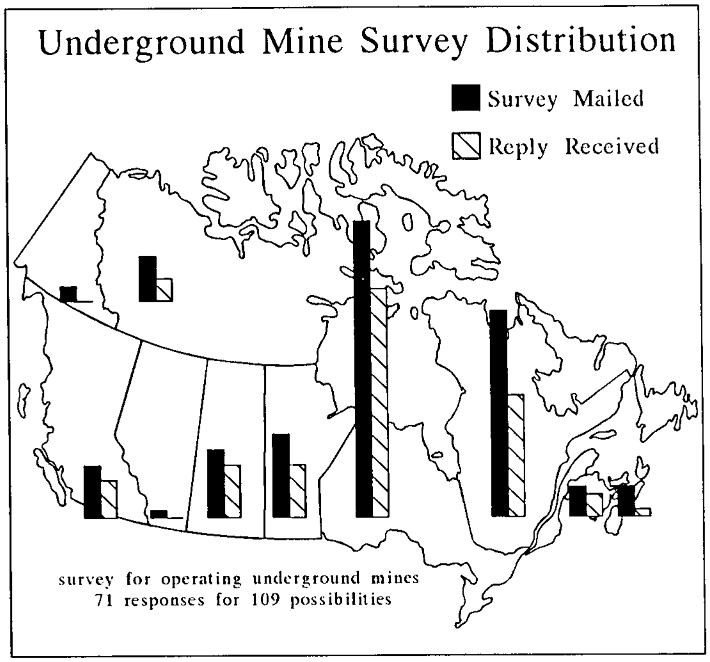
The following chapter presents the results from a market survey of all underground mines in Canada concerning the use of ground support, including cable bolts. Recorded and estimated usage of steel cable bolts are discussed. Marketing of the DAPPAM cable bolt is also introduced.

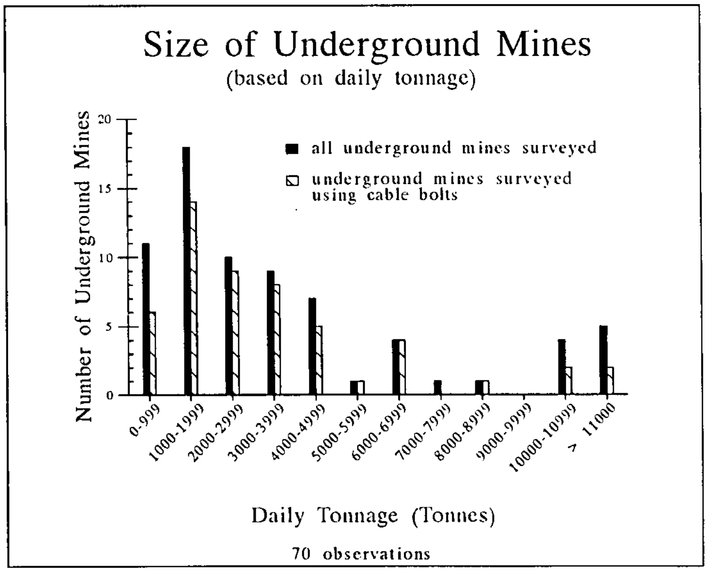
8.1 Market Analysis of Cable Bolt Usage in Canada

A market survey was completed in the Spring of 1992 (Kalynchuk, 1993) to quantify the existing market for cable bolts in Canadian underground mines. Of the 109 mines to which the questionnaire was mailed, 71 replies were received, representing a return of 65%. The relative distribution of the questionnaire is shown in figure 123 and table 15.

Table 15. Questionnaire Distribution

Province	Questionnaires Mailed	Replies Received	Percentage Received
British Columbia	7	5	71.4%
Yukon	2	0	0%
Alberta	1	0	0%
Saskatchewan	9	7	77.8%
Manitoba	11	7	63.6%
Ontario	38	29	76.3%
North West Ter.	6	3	50.0%
Quebec	27	16	59.3%
New Brunswick	4	3	75.0%
Prince Edward Isd.	0	0	-
Nova Scotia	4	1	25.0%
Newfoundland	0	0	-
Totals	109	71	65.1%



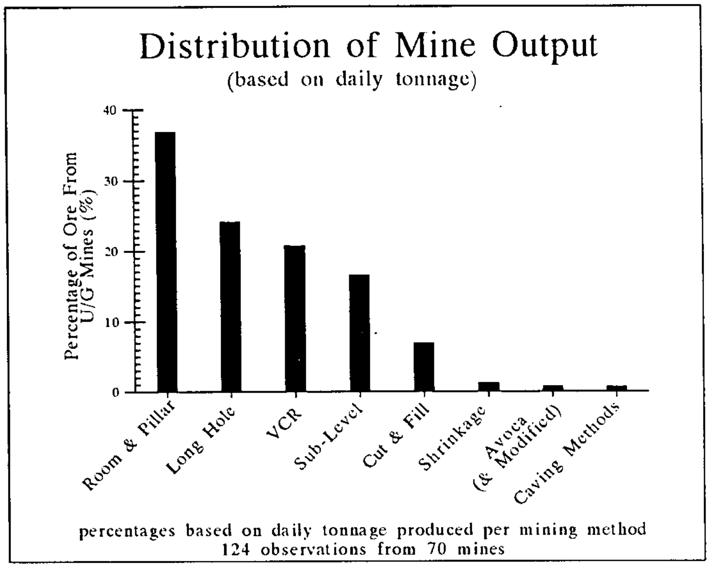


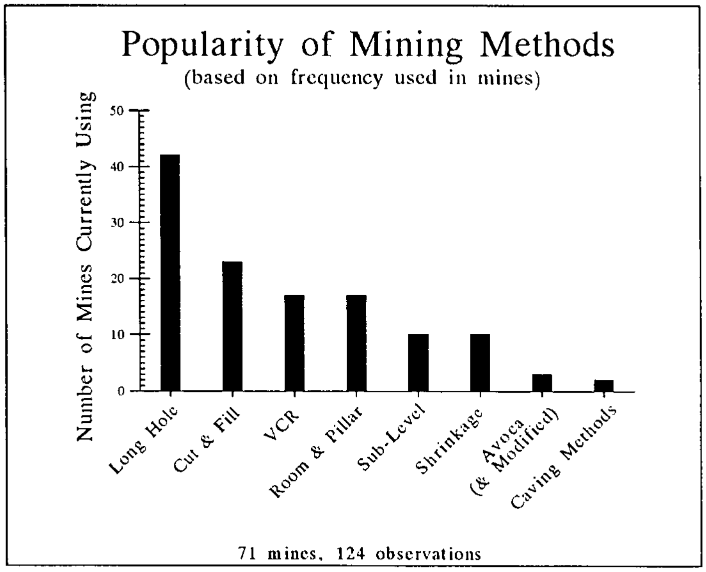
UPPER: Figure 123. Survey Distribution
LOWER: Figure 124. Size of Underground Mines

An analysis on the size of underground mines was performed based on daily tonnage output. As shown in figure 124, most of the reporting mines have a daily output of less than 5000 tonnes/day. Seventy of the seventy one mines reported their daily output. The distribution of tonnage per mining method is shown in figure 125. The method producing the largest tonnage was room and pillar. This is primarily due to the large potash mines in Saskatchewan which accounts for 32% of the total production in Canadian underground mines (based on reported tonnage). Open stope mining methods account for an additional 61% of the total production. Open stoping is sub-divided into long hole, vertical crater retreat and sub-level mining methods. It is these bulk methods which can utilize large spans within the stopes and frequently require cable bolt support. Figure 126 displays the number of mines utilizing the various methods of mining. As shown, long hole mining is utilized in 42 of the reporting 71 mines.

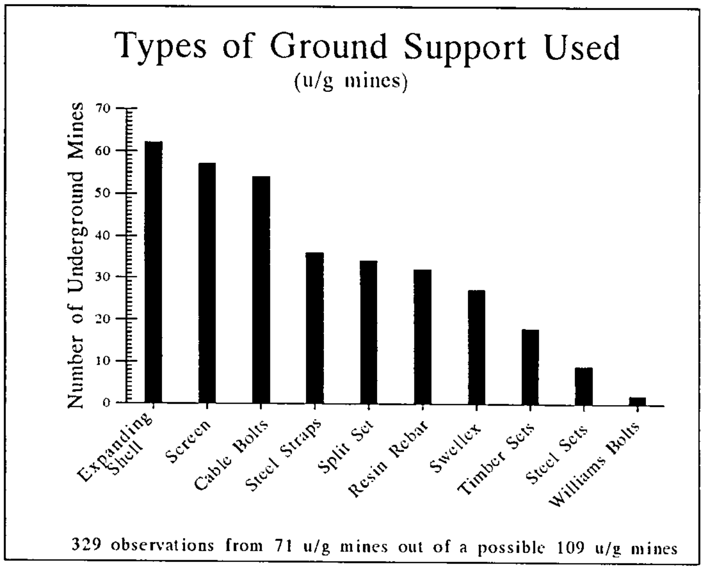
The types of ground support used within mines varies considerably with respect to rock properties, size of supported spans, economics and installation preference. Figure 127 shows the ground support used by the number of reporting mines. The most common type, expanding shell rock bolts, is utilized by 62 mines out of a possible 71. The second most common type of internal rock support is cable bolting. This is warranted by the number of mines utilizing bulk mining methods as displayed in figures 125 and 126.

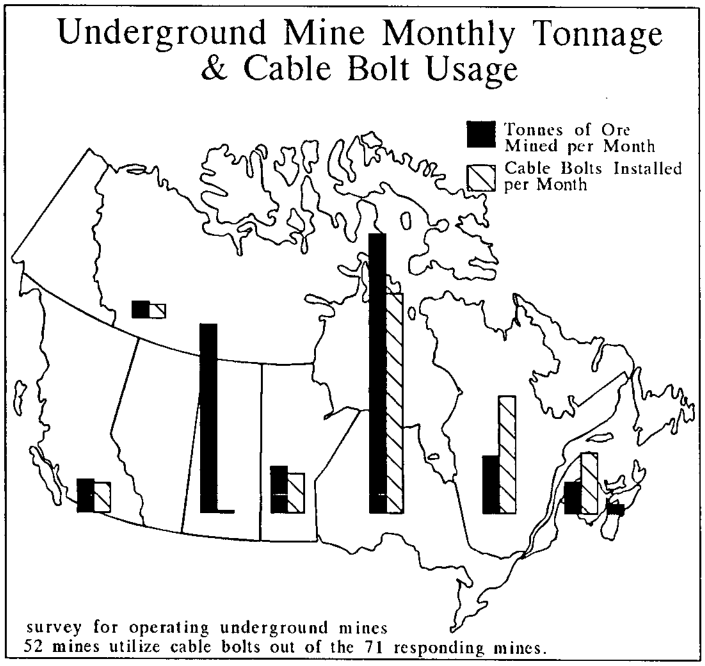
Out of the 71 mines that responded, 52 mines utilize cable bolts as a form of ground support. During the course of one year, approximately 740 000 metres of cable bolt are installed. In considering the 38 mines which did not answer the survey, a projected annual consumption for all underground mines (109) is 870 000 metres of cable bolts. Projection of cable bolt usage for the 38 mines was based on the mine's tonnage and mining method. In addition, the projected values were compared to actual cable bolt usage reported by the 71 mines. Figure 128 displays the spatial distribution of cable bolt usage from the reporting mines. As shown, over 70% of all cable bolt consumption is from mines within Ontario and Quebec while only 17.4% of consumption is in western Canada (Manitoba, Saskatchewan, Alberta, British Columbia, North West Territories and the Yukon). In comparison, over 44% of total tonnage from underground mines in Canada comes from the western provinces/territories. As shown in figure 128, this is





UPPER: Figure 125. Distribution of Mine Output
LOWER: Figure 126. Popularity of Mining Methods





UPPER: Figure 127. Types of Ground Support Used
LOWER: Figure 128. Tonnage vs Cable Bolt Usage

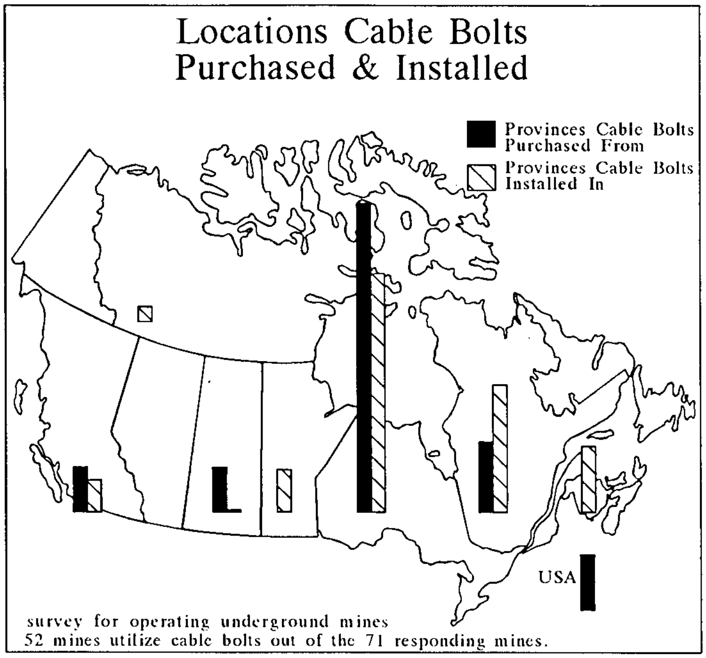
Table 16. Cable Bolt Consumption

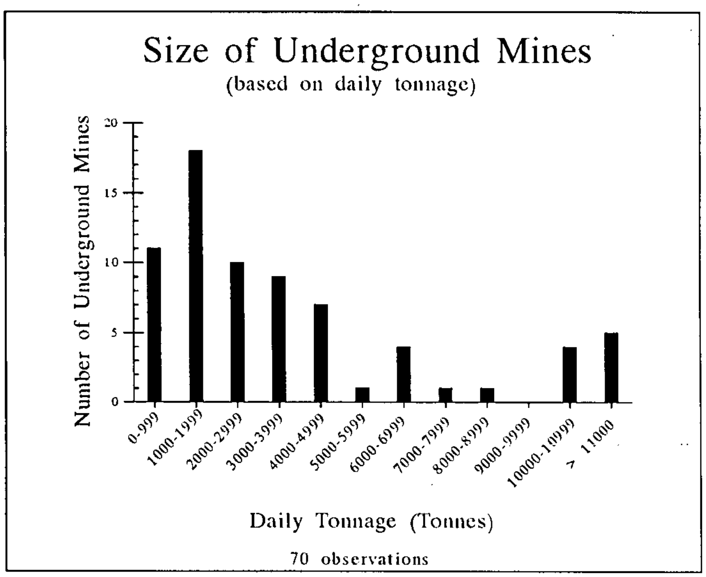
Province	Monthly Tonnage (*1000) (surveyed)	Cable Bolt Consumption (meters/month) (surveyed)	(projected)
British Columbia	420	3750	3750
Yukon	0	0	250
Alberta	0	0	0
Saskatchewan	2,426	250	250
Manitoba	595	5,000	5,000
Ontario	3,203	28,210	32,460
North West Ter.	215	1,750	3,250
Quebec	733	15,000	19,650
New Brunswick	402	7,750	7,750
Prince Edward Island	0	0	0
Nova Scotia	121	0	0
Newfoundland	0	0	0
Totals	8,115	61,710	72,360

primarily due to the high tonnage potash mines located in Saskatchewan. No correlation exists between daily tonnage and cable bolt usage. Table 16 displays cable bolt consumption from the reporting mines and the projected cable bolt consumption of all underground mines in Canada.

The spatial distribution of cable bolt usage vs location of cable bolt purchase is shown in figure 129. The majority of cable bolts are purchased from distributors in Ontario (59%) with only 10 500 metres/month purchased in western Canada. It is evident that the largest market share is in Ontario (59%) which has less than six distributors for cable bolts. The western provinces/territories sell approximately 17% of all cable bolt sold in Canada.

Figure 130 displays the typical size of mine (reported) which utilizes cable bolts. Most mines which use cable bolts range in size between 1 000 Tpd to 4 000 Tpd. The majority of the mines which do not use cable bolts are either less than 1 000 Tpd or larger than 10 000 Tpd. These are primarily a result of either the small tonnage, manual mining methods or the large tonnage, mechanized soft rock methods.





UPPER: Figure 129. Location of Cable Bolt Purchase & Usage
LOWER: Figure 130. Size of Underground Mines

Of the 51 observations, 60% of the individuals from the surveyed mines rated the cable bolt's overall performance as good while only 2% rated their performance below average. Figure 131 displays the cable bolt's performance of the reported mines. Though the observations are very subjective to the individuals surveyed and does not take into consideration the distinctive parameters of each installation within a mine, it does show the overall trend that cable bolting is considered to be an effective method of ground support.

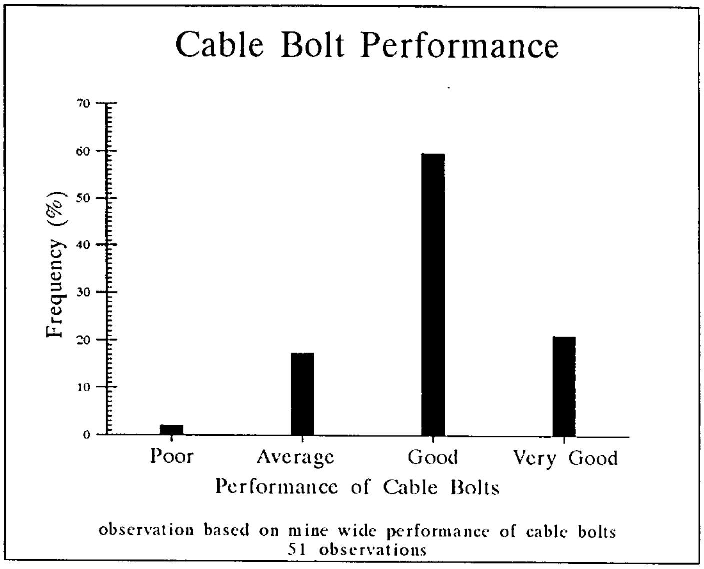
The most common configuration of cable bolt used is the regular steel single strand. Based on cable length installed, 57% of all installations are single strand, while 35% are double steel cable bolts. The remaining 8% of cable bolt installations utilize high bond strength cables such as birdcage or buttoned cables. In considering the amount of cable bolts that are double strand configuration, the actual amount of steel cable installed (reported) is increased to 960,000 metres annually (in 740,000 metres of drill hole). Of the reported 52 mines which utilize cable bolts, 24 mines (46%) install, to some degree, face plates on the cable bolts.

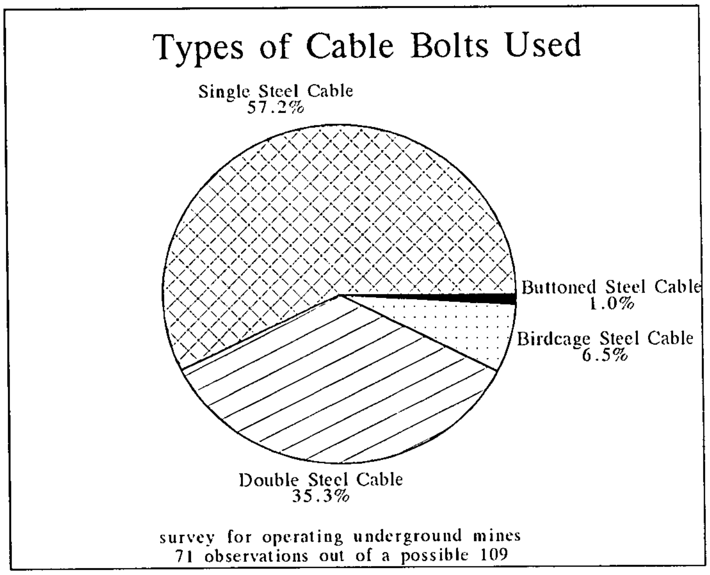
Of the mines surveyed, the most common type of grout pump used is the Spiedel pump from South Africa. However, the recently introduced Minepro/Langford grout pump has achieved over 36% of the market (figure 133). Over 31% of the mines have two types of grout pumps all of which have the Minepro/Langford in addition to another type, usually Spiedel. This is primarily due to the recent introduction/purchase of the Minepro/Langford pumps.

Of the reported mines, 89% have established some form of written procedures for cable bolt installation, while 74% have dedicated crews for cable bolting.

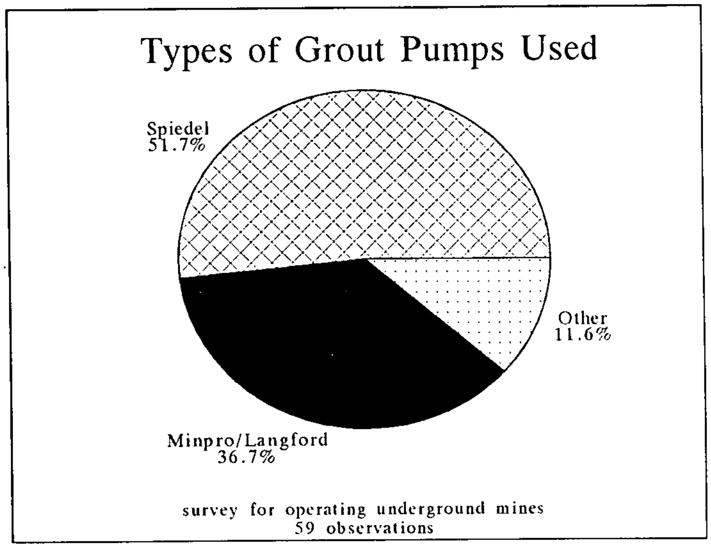
The average time to fully install the cable bolts (less time required for drilling) is 1.6 +/- 1.3 man-hours per 10 meters of cable. The installation times ranged between 0.25 man-hours to 6.0 man-hours for the 35 mines which reported installation times. The reported installation times have a large deviation as a result of unstandardized time studies and are considered to only be estimates.

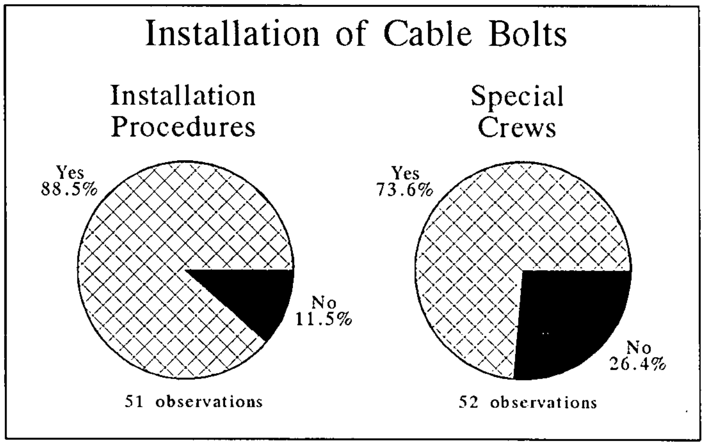
Total cost of installing the cable bolts is reported at $23.00 +/- $6.60 per metre. For the 18 mines which reported, installation costs ranged between $13 and $35 per metre, again, resulting in a high standard deviation due to unstandardized costing procedures. Based on the





UPPER Figure 131. Cable Bolt Performance
LOWER: Figure 132. Types of Cable Bolts Used





UPPER: Figure 133. Types of Grout Pumps Used
LOWER: Figure 134. Installation of Cable Bolts

reported information, the Canadian mining industry installs an estimated 870 000 meters of cable bolts at a cost of over 20 million dollars per year. The cost of transporting the steel cable bolts to the mine site contributes less than 10% of the cable bolt cost for over 56% of the mines (figure 135).

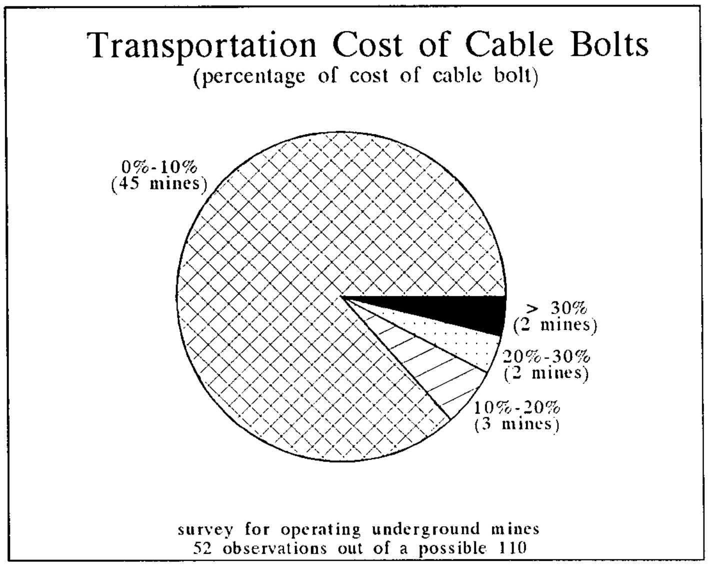


Figure 135. Transportation Cost of Cable Bolts

8.2 Marketing of DAPPAM

Pacific Pultrusions is currently manufacturing DAPPAM and commercially retailing it through Thiessen Team Ltd. (Langley, British Columbia). Figure 136 is a brochure produced by Thiessen Team on DAPPAM.

8.2.1 COST ANALYSIS OF DAPPAM

Figure 137 compares the cost of various types of cable bolts f.o.b. Vancouver. Using the labour costs and installation rates from Westmin mine, a cost comparison of

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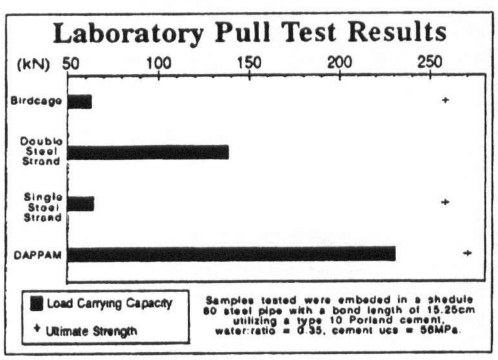
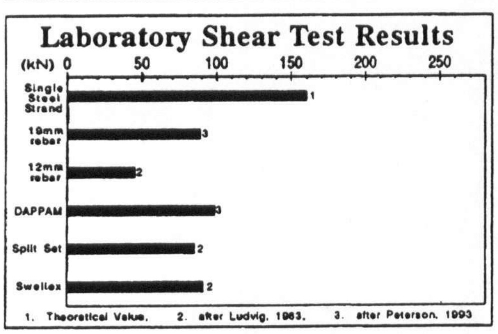
Thiessen Team Glass Fibre Cable Bolts - Through world leading research and development we are proud to introduce the newest member to our line of rock support, the **DAPPAM** Cable Bolt.

The DAPPAM cable bolt provides distinct advantages in applications through improved safety, load carrying capacity, installed cost, corrosion resistance and freedom from bolt contamination.

The DAPPAM cable bolt is assembled using ten straight glass fibre tendons, 6.4mm (0.25in) in diameter. These are bound rounding the central grout tube, in customer specified lengths. Through the application of a special surface coating, the cable provides superior bonding to cement based grouts. The designed ultimate tensile strength of the cable bolt is 275kN (62,000lbf). Due to its ease of cuttability, DAPPAM can be installed in mines which utilize road headers/continuous miners.

Monitored installations of the DAPPAM cable bolt at Myra Falls Mine, Detour Lake Mine, Arthur White Mine and Dome Mine as hangingwall, footwall, back and pillar support have concluded in the following advantages over conventional steel cable bolts.





- Higher bond strengths than any other steel cable bolt. As a result, the DAPPAM cable bolt has a very high load carrying capability in highly fractured ground (small joint spacing).
- Installation costs are lower as a result of the cable bolt weighing 75% less than steel cable bolts. In addition, the grout tube is included within the cable, substantially reducing the installation time. Past installation have realized a 700% reduction in man-hours spent "pushing" cable.
- Mucking out cut and fill stopes is made easier as DAPPAM "brooms" when blasted through, reducing the time consuming methods of having to cut through the steel cable bolts.
- Uncoiling highly energized steel cable bolt coils can be dangerous and time consuming. DAPPAM cable bolts are coiled to 1.1m (3.75ft) diameter coils and are easily unpacked since they are more flexible.
- Mill Processing is made easier with fewer interruptions to clear away tangled cable in conveyors, chutes and magnets. The glass fibre cable bolt does not effect floatation or slurry pumps.
- Resistance to corrosion by acidic mine waters is superior to other materials.

DAPPAM is a joint development of Pacific Pultrusions Inc., UBC Department of Mining & Mineral Process Engineering and Thiessen Team. Technical papers describing the methods of research, testing and development of DAPPAM at UBC and the United States Bureau of Mines have been published in Canada, USA, France and the Netherlands. Copies are available at UBC Mining Department, 519 - 6350 Stores Rd., Vancouver, B.C., V6T 1Z4, Ph. (604) 822-2540, Fax (604) 822-5599

Figure 136. Marketing Brochure for DAPPAM

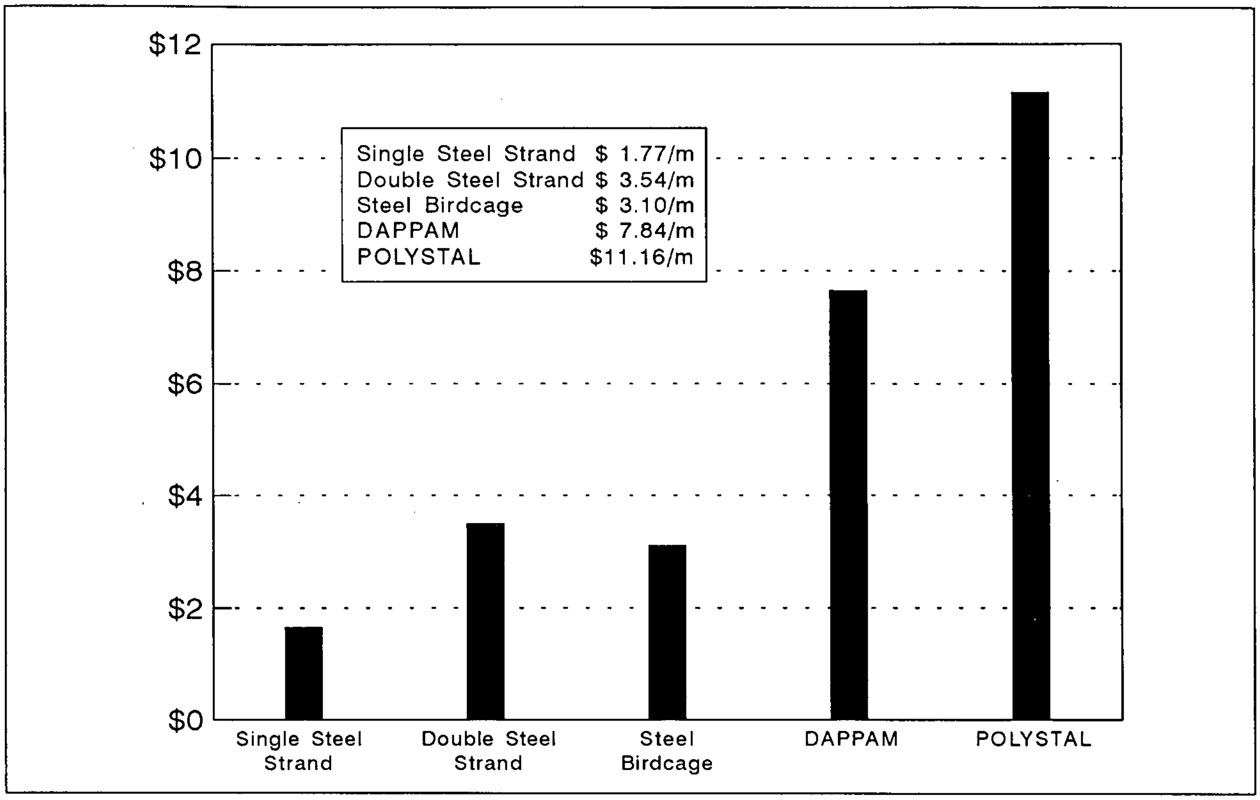


Figure 137. Cost of Cable Bolts f.o.b. Vancouver (not installed)

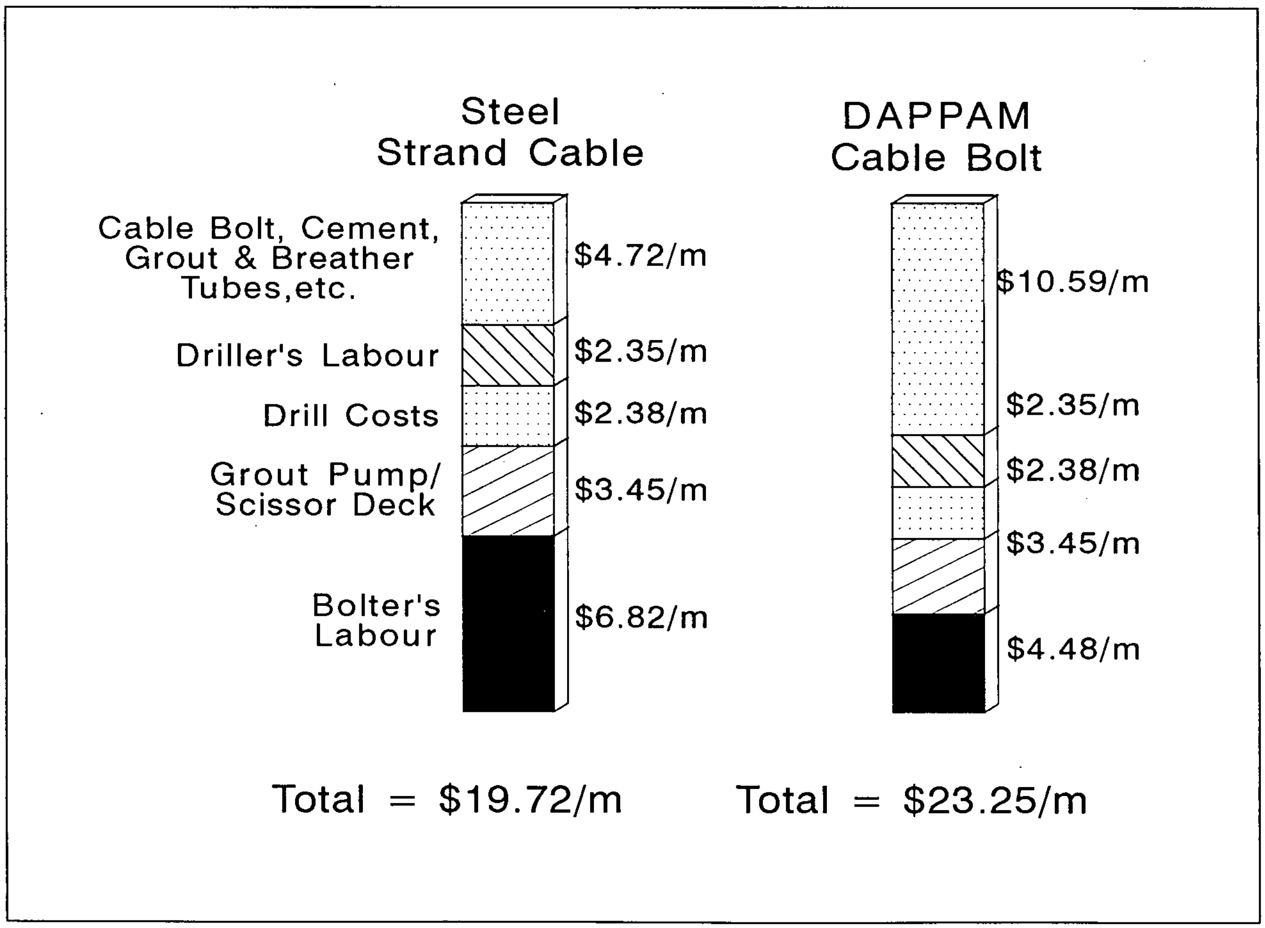


Figure 138. Cost Comparison of Installed Cable Bolts (Westmin #2 Trial Installation)

DAPPAM and single steel conventional cable bolts can be seen in figure 138. It is important to note that approximately 25% of the total installed cost is comprised of the bolters' labour. Due to the light weight of the DAPPAM cable bolts, an increase in installation rate for "pushing" cables (does not include grouting) is reflected in figure 138. The cost reduction in bolters' labour per metre of DAPPAM will vary between installations. With conventional steel cable bolts, the cost of the cable bolt contributes approximately 9% to the total cost of installing a single steel cable bolt.

Chapter 9

CONCLUSIONS

The following chapter presents the conclusions derived from Phase II and Phase III of the research program to develop a commercially available composite cable bolt.

1) A six step program was introduced to design, evaluate and market a commercially competitive glass fibre cable bolt. During the course of the project in excess of 300 laboratory tests were performed at UBC, Department of Mining & Mineral Process Engineering, Metals and Materials Engineering and the United States Bureau of Mines.
2) Primary composite evaluation was conducted on four manufactured products from Canada, Germany and the United States. Bayer's Polystal and Pacific Pultrusions' product was recommended for modifications and secondary evaluations.
3) It was determined that the most effective method of increasing a cable bolt's pull out resistance for short bond lengths is by altering/increasing its surface coating as opposed to lacing/birdcaging.
4) Modifications conducted in the laboratory to the surface coating of Pacific Pultrusions' product yielded acceptable bond strengths, significantly higher than a conventional steel cable bolt.
5) Additional modifications conducted at the manufacturing stage in order to evaluate glass fibre size and binder material were completed. The optimum glass fibre was found to be 21μm diameter ECR glass with a isophthalic polyester resin. Tensile strengths were determined through pull tests.
6) Several prototypes constructed of Polystal were made and tested in order to evaluate the effects of surface area by varying the diameter and number of rods. The highest bond strength in the test program was achieved with in this test series.

7) Preliminary shear tests of Polystal and Pacific Pultrusions resulted in strengths of approximately 98kN and 62kN respectively.

8) Secondary composite evaluations concluded that Pacific Pultrusions' product would be best suited for the use in the construction of a composite cable bolt. The decision was based on availability of the product, cost and past performance.

9) By completing modifications at Pacific Pultrusions during the manufacturing stage, it was determined through laboratory tests that the material which provided the strongest bond between the rod and grit was a modified epoxy. The material which provided the best cable/grout bond was a fine grit silica sand.

10) The most practical cable bolt configuration would consist of ten composite rods, each 6.35mm in diameter with a designed strength of 289kN.

11) Initial testing on five different cable bolt prototypes, each comprised of ten composite rods, were completed. The results reflected that three configurations warranted further testing (type III, IV and V). As a result, one configuration was deemed to be the optimum, type III. This was determined by the ease of manufacturing and the mode of failure in which the sample experienced.

12) The final prototype called DAPPAM (type III) was developed for in-depth laboratory and field evaluations. DAPPAM consisted of ten (10) individual 0.64cm diameter rods enveloping a 2.2cm O.D. high density polyvinyl grout tube. The individual rods were constructed through pultruding 21μm diameter ECR glass fibres within a isophthalic polyester resin. A surface coating consisting of a fine silica grit adhered to the glass fibre rods through the use of a modified epoxy was applied to the individual rods.

13) Tensile testing using the Instron machine in the MMAT department and tensile testing using the pull testing machine in the Mining Department resulted in different tensile strengths of the composite material used in DAPPAM. Tensile testing of the DAPPAM cable bolt at the USBM resulted in even higher strengths, with the cable bolt achieving an average tensile strength of 409kN, 150% greater than a conventional single steel cable bolt.

14) An increase in the quality of pultruded rod was experienced through tensile testing and observed through the use of the scanning electron microscope (SEM). Inconsistency with the quality of the surface coating bond to the composite rod was identified.

15) Observations from the SEM showed that the failure zone within a composite rod is generally confined to 2.5cm (1in) along the rod's axis. The fibres fail in tension, though some longitudinal splitting of the fibres were observed.

16) Since the cable bolts will generally be subjected to high stress and high acid/basic environments, accelerated media testing is needed to quantify the life span of DAPPAM within certain operating environments. Given that the epoxy surface coating in intact, a two year life span is currently recommended in relatively neutral environments until media testing proves otherwise.

17) Secondary shear testing conducted at the USBM resulted in the lower shear strengths than steel cables, and similar strengths as the preliminary shear tests at UBC. The maximum displacement perpendicular to the cable bolt's axis is 1cm. DAPPAM has the same load carrying capabilities as steel cable bolts up to this displacement.

18) The load carrying capacity was determined for DAPPAM for two water:cement ratios and at three bond lengths. A statistical relationship was developed which achieved very good correlation with the data. The relationship is interpolated to the cable bolt's critical bond length.

19) A laboratory evaluation of conventional single steel cable bolts was completed in order to develop the relationship between grout strength, bond length and pull out load. A statistical relationship was developed. The test series was used to compare the laboratory results of DAPPAM.

20) Grout column testing was conducted on three configurations of DAPPAM and three configurations of steel cable bolts. The grout flow around all the DAPPAM cable bolts was suffice, with no voids being created. The grout flow around the double and single steel cable bolts is less than ideal. Three types of voids are identified.

21) Two steel barrel and wedge prototypes were tested. The best design averaged 162kN load prior to failure.

22) The physical properties of the composite material and the DAPPAM cable bolt determined from laboratory testing are:

Maximum Shear Load	109kN
Maximum Shear Displacement	1.0 cm
Ultimate Tensile Load	409 kN
Ultimate Tensile Displacement	2.2 cm
Critical Bond Length (estimated)	39 cm

The designed physical properties of DAPPAM for marketing purposes were determined to be the following.

Property	**Designed Strength**	**Safety Factor**
Tensile Strength	289kN	1.4
Shear Strength	89kN	1.2

23) Trial installations of DAPPAM at Myra Falls Mine, Dickenson Mine and Dome Mine were completed for the purposes of performance evaluation and marketing (market introduction). No serious problems were encountered with the installations.

24) A market analysis of Canadian underground mines for the use of steel cable bolts was concluded. The market locations and cable bolt quantities used were presented.

25) DAPPAM is currently being manufactured by Pacific Pultrusions and marketed in Canada by Thiessen Team. The approximate price of DAPPAM is $7.84/m.

Chapter 10

RECOMMENDATIONS

1) Future research be directed towards increasing the shear strength and decreasing the cost of the cable bolt.
2) Accelerated media testing be completed to quantify the life span of DAPPAM in adverse environments.
3) Testing to determine the amount (if any) creep which exists between the surface coating and composite rod.
4) The quality control of the surface coating be increased and maintained. As a result of low quality, a series of pull tests be completed after the production of each batch of DAPPAM to define and insure sufficient quality control of the product.
5) DAPPAM not be commercially sold until accelerated media testing be completed and quality control testing implemented.
6) Marketing of DAPPAM should focus in eastern Canada, where the bulk of cable bolts are used in the mining industry. An in-depth marketing program should be initiated, consisting of advertising and small trial installations to potentially large clients.
7) Testing be completed to determine the effectiveness of using a modified DAPPAM in soft rock mining (the use of resin as opposed to grout).
8) During the latter part of Phase 3, an increase in the quality of the composite rod (tensile strength) was experienced. Future laboratory tests are recommended in order to define the characteristics of a cable bolt using less than ten 0.635cm diameter rods.

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