THE DEVELOPMENT OF A FIBREGLASS CABLE BOLT

By

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ABSTRACT

The development of a fibreglass cable bolt (FCB) as an alternative to steel cable bolts has been presented. The primary objective of the investigation was to develop a working FCB prototype that was cuttable and easily installed in hard rock mines. The FCB was required to be cuttable by a continuous road-header without adverse affects to equipment, personnel or processing circuits. POLYSTAL, an advanced composite with a circular profile, has been used to develop the working prototype. The methods of investigation, included: over seventy-five (75) laboratory and in situ pull-tests, five (5) preliminary laboratory shear tests, two (2) trial in situ installations and three (3) preliminary flotation tests. Conclusions have been drawn regarding the selection of a cuttable material, failure modes and mechanisms, axial and shear load/displacement behaviours, immediate and potential applications, design guidelines, mineral processing effects, installation costs and future research directions. In general, it has been proven that the FCB exists as a viable alternative to steel for cable bolt reinforcement. However, the FCB does not currently exist as an optimized, or only, composite support alternative to steel. These aspects remain outstanding to the further development of composites for use as cable bolt reinforcement. Control of the composite manufacturing process is crucial to achieve a more economical product in the future.
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1. INTRODUCTION

1.1 Continuous Hard Rock Methods and Equipment

In mining, continuous excavating machines have traditionally been restricted to soft rock conditions found predominantly in coal, salt and potash. Continuous excavator technology advances have expanded potential mining applications to hard rock. The increase in shape control and decrease in wall damage of a continuously mined excavation can significantly reduce support requirements over conventional drill and blast methods (McIlwain, 1988). Research has been conducted to develop a continuous hard rock mining method with positive results (Smith et al, 1992). Earlier attempts at developing continuous hard rock mining methods were also deemed successful. For example, American Borate adapted two road-headers to the cut and fill stoping of a borate ore deposit where rock strengths varied from 48 MPa to 138 MPa (Sparks, 1980). To quote, "...we at American Borate are satisfied with the result of this rather unorthodox mining system (Sparks, 1980)." The mining cycle consisted of three cycles: breasting, filling and an overhand pass (Figure 1). The road-headers evaluated were the: Super Roc-Miner 330 and Dosco TB 600. A typical boom-type miner, or road-header, is illustrated in Figure 2 (Schenck, 1982). Both road-headers exhibited excellent selectivity and ability to cut high compressive strength rock at reasonable production rates and costs.
Figure 1. Continuous CAF Mining (Sparks, 1980)

Figure 2. A Typical Road-Header (Schenck, 1982)
Not only have there been significant advancements in single and double-pass continuous hard rock methods and equipment, there have also been successful developments in ground support. One of the most promising break-throughs was the development of a "cuttable" support system. Glass fibre reinforced plastic (polyester resin) rock bolts manufactured by WEIDMANN of Switzerland were marketed in 1987 and successfully used in numerous civil and mining projects throughout the UK and West Germany. One such project was a double-pass highway tunnel (Meechan, 1989). An initial twin-tube pilot tunnel was driven with a full-face tunnelling machine and supported with 2 m WEIDMANN bolts. The pilot tunnel was subsequently enlarged to the required profile with a roadheader. The WEIDMANN bolts were mined without problems or damage to the cutter head. Further advantages of the WEIDMANN bolt included: improved safety since steel bolts did not have to be cut, improved cycle times (cutting steel bolts was very time consuming), and reduced damage or interruptions to the mucking system.

The support requirements for a multiple-pass continuous mining method demand new, innovative developments. Some of the support techniques currently used in hard and soft rock mining conditions have been used as a basis for the development of the FCB.

1.2 Existing Support Measures

1.2.1 Underground Hard Rock Mining Support Methods

One of the oldest methods of support in hard rock mining consists of leaving ore behind as pillars to support the back and walls. Economic demands have led to the development of less expensive support techniques which can be categorised as: external and internal. External support prevents movement and failure of the exposed rock mass surface and may take the form of: steel sets, wood cribs, shotcrete or backfill. Internal support consists primarily of rock bolts and cable bolts that limit movement and maintain the cohesion or arching capacity of the excavation walls from within the rock mass. Rock bolts resist load by relying on three main anchoring systems: frictional, mechanical or grouted. The term cable bolt is reserved for "long"
cement grouted support reinforced with high strength steel wire. Steel cable bolts (SCB's) utilize three mechanisms of resistance: adhesion, friction and mechanical interlock (Fuller et al, 1975). A number of steel wire configurations are used: plain (wires separated by spacer), strand, rope (strands twisted around a fibre core), and birdcaged. The most common cable bolt reinforcement used in Canadian hard rock mines is the 16 mm (5/8") prestressing or high tensile strength strand which consists of six steel wires wrapped around one king wire. This strand can be in conventional, birdcaged or nutcase form (Figure 3).

Figure 3. Examples of Conventional, Nutcase and Birdcaged SCB's (Bawden et al, 1992)
The Australian method of separating the seven wires of a conventional strand and then recombining them in such a way as to form a series of nodes and antinodes from the memory of the plastically deformed steel wires (approximately 178 mm periods) is called "birdcaging" (Goris 1990). Birdcaging effectively increases the surface area of wire exposed to the grout and changes the mechanisms of resistance. As a result, birdcaged SCB's demonstrate greater pull-out loads than conventional SCB's. This technology has been extended towards the development of a "laced" FCB prototype. In underground mines, cable bolt lengths typically vary from 3 to 20 m and are usually passive.

Grouted steel cable bolts were introduced to the Canadian mining industry during the 1960's. Geco Mine, Noranda was the first underground mine to use tensioned cable bolts and document the results (Bray, 1967). It was discovered during these early installations that pre-tensioning was not required and, in some instances, adversely affected performance. SCB have been used to support pillars, drawpoints, hanging/foot walls and ore. SCB's have also allowed the transition from cut and fill mining to more economical open stoping methods. A summary of various cable bolt practices and their design parameters is found in Table 1 (Pakalnis 1989). The following descriptives have been abbreviated in Table 1: breather tube (BT) and grout tube (GT).

1.2.2 Underground Soft Rock Support Methods

Underground soft rock support methods are basically identical to hard rock internal support systems with the exception of low modulus wooden or bamboo grouted dowels. Hydraulic jacks are used primarily as external support for areas where a mechanical excavator passes. Shotcrete has also been used in soft rock applications. The development of the FCB was based on hard rock internal support techniques and has the potential to transcend the barrier between hard and soft rock internal support applications.
<table>
<thead>
<tr>
<th>MINE</th>
<th>METHOD</th>
<th>BOLT LENGTH (m)</th>
<th>PATTERN (m x m)</th>
<th>HOLE SIZE (mm)</th>
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<td>INCO, Thompson</td>
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<td>6.1, 12.2</td>
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<tr>
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<td>2 x 2</td>
<td>57</td>
</tr>
<tr>
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<td>open stope cut &amp; fill</td>
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<td>3 x 3</td>
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<td>open stope H/W support</td>
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Table 1. (continued)

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<td></td>
<td>12.5 mm GT</td>
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</table>

1.3 Objectives and Scope

Hard Rock Mining Research Limited (HDRK) and the University of British Columbia (UBC) have conducted a research program to produce a cuttable, regional support system as part of a larger venture in developing a hard rock continuous mining method. The cuttable support project directed, by Doug Milne of the Noranda Research Centre and members of HDRK, was
divided into two areas of study:

- A literature search into cuttable support alternatives conducted at McGill University under the direction of Dr. Ferri Hassani.
- The development of a cuttable cable bolt prototype as an alternative to steel. This portion of the program was conducted at the University of British Columbia, Vancouver under the direction of Dr. Rimas Pakalnis and was initiated to gain practical experience with composite materials as cable bolts. As a result, a FCB prototype was developed and tested in the laboratory prior to \textit{in situ} trials.

It was decided to focus this research on developing regional, internal 'stope' support since cuttable, local internal support already existed such as fibreglass rock bolts (e.g. WEIDMANN rock bolts), shotcrete and injection grouts.

SCB's are most frequently and economically used in conventional mining environments and this work looks at a replacement to steel. Two cable bolt applications in conventional drill and blast operations were used as test-sites to compare FCB's to SCB's. Continuous mining test-sites and control of the composite manufacturing method were not available for this study.

1.4 Areas of Investigation

The following areas were investigated:

- raw material selection
- composite types
- costs
- manufacturing methods
- pull-test behaviour (laboratory and in situ)
Each of these areas have been explored to varying degrees in the development of an FCB. Two investigative environments were studied: laboratory and in situ. The research combined existing grouted reinforcement technology and applied it to a cuttable material. A brief literature search was conducted to determine the most suitable reinforcement. Next, laboratory and in situ pull-tests and laboratory shear tests were conducted on the FCB. The pull-tests proved the FCB supplied similar pull-out resistances to steel. As a result, enough confidence was generated to attempt trial installations and assess the FCB over time on a larger scale. Finally, the effect of the FCB on mineral processing circuits was assessed with a number preliminary flotation tests.

2. SELECTION OF A CUTTABLE REINFORCING MATERIAL

2.1 Introduction

Even though polymer composites with high fibre content possess equivalent to improved mechanical and physical properties as compared to steel, little mining research has been initiated in this area. Perhaps in the past, the relative high cost of composites and their low demand from industry has deterred interest. As problems associated with conventional SCB's such as their poor corrosive resistance (Kaiser et al, 1990), low bond strength and high density have been
documented, an increasing need for alternate materials and configurations has become apparent. Recent developments in the manufacturing and application of "advanced" composites has resulted in reduced costs and improved properties. Fibreglass and aramid fibre reinforced polymer composites have found use in many civil applications such as rock anchors or concrete reinforcement (Preis, 1986). Some of the main advantages of advanced composite reinforcement relative to steel are:

- Easily taylorable mechanical and physical properties.
- Easily taylorable shapes and surface profiles.
- Low density (high strength to weight ratios).
- Corrosion resistance.
- Directional control of properties through fibre orientation.

The selection of which composite to use was not straight forward since most composites available on the market have not been developed for the mining industry. To truly evaluate the potential for composites in the mining industry, one must have control of the manufacturing process. As already mentioned, this was not available at the time of this study so alternate sources of composite materials were sought.

There were other factors that affected the selection of a composite for this study such as availability. The availability of advanced composites in Canada is limited. The majority of the higher strength, advanced tendons are manufactured in Europe, the United States and Japan. Thus, a fair portion of current advanced composite material costs in Canada can be attributed to import and freight charges. Advanced composites also tend to be developed for low volume, specialty markets and as a result are higher priced. Less advanced composites, termed "low-tech" for the purposes of this investigation, are readily available in Canadian and world markets, but generally lack quality control measures to ensure their properties. This has precluded their recommendation for evaluation at this stage, but it does not mean that acceptable quality control
methods and support capacities cannot be developed for them. In fact, low-tech composites are generally available at a fraction of the cost of advanced composites with moderate mechanical properties. This investigation has concentrated on the evaluation of advanced composites to improve safety during trial installations.

2.1.1 Polymer Matrix Classification

A composite material can be defined as a macroscopic combination of two or more distinct materials with recognizable interfaces (Reinhart et al, 1988). Structurally speaking, the definition of composites can be restricted to include only those materials that contain a reinforcement medium protected and supported by a binder material called the matrix. The matrix material transfers load to the reinforcement through interfacial shear. Composite mechanical properties depend on the matrix, fibre and interfacial properties.

Many structural composite matrix materials exist such as metal or ceramic, but not all are currently applicable to mining. This section is restricted to those which are easily cut, low cost, versatile, low to medium temperature resistant and low density, namely polymers. The polymer matrix in a composite has five distinct functions:

- maintain shape
- hold fibres together
- introduce load to the fibres through interfacial shear
- protect the fibres from the environment
- provide support for fibres in compression

All polymers consist of carbon chains with repetitive combinations of either H, O, Cl, F, S or N. They are divided into 3 categories:
- Elastomers
- Thermoplastics
- Thermosets

**Elastomers** are either natural or synthetic linear polymers that exhibit large elastic strain. Typical tensile strengths range between 2.1 MPa and 28 MPa while elongation to failure can be as high as 2000%. Their low tensile strength and extremely high elongation to failure suggest poor suitability for mine support.

**Thermoplastic** polymers are formed and reformed at elevated temperatures without changing the structure or properties of the polymer. They have separate carbon chains without chemical bonding between them. They are reformable (can be recycled) by applying temperature and pressure. Thermoplastics offer the advantages of high performance and the absence of reaction kinetic problems experienced with thermosets. The cure cycle involves continuous thermo-forming through progressive heating, compaction and cooling. A decrease in processing time as compared to thermoset resins is often observed. Other advantages include:

- improved toughness
- greater impact strength
- unlimited shelf-life of prepreg
- faster processing cycle

A disadvantage of a thermoplastic system is its' high resin cost ranging from $10/kg to $100/kg. Resin cost becomes particularly important to price sensitive applications. For example, since the material cost of pultrusion generally accounts for the majority of the overall fabrication costs, thermoplastic resins are less attractive for the pultrusion of a competitive mining support alternative to steel if less expensive, adequate performance thermosets are available.

**Thermosetting** resins are typically formed in two stages:
- Stage I  -long, linear carbon chain formation
- Stage II -chain cross-linking to produce rigid 3-D networks

Original and cross-linked chains often involve either addition or condensation polymerisation. Thermosets cannot be reprocessed (recycled) after cross-linking. To initiate cross-linking, an exothermic process, a two part resin mixing system and/or temperature/pressure addition are used. The advantages of thermoset matrices are:

- good performance
- low cost ($1/kg to $40/kg)
- controlled processing
- environmental stability

The disadvantages of thermosets when compared to thermoplastics include:

- low impact strength and toughness
- limited shelf-life
- cure process is exothermic therefore the heat added must be balanced with the heat given off to prevent burning of the part

The resin industry has been dominated by thermosets in the past because of their low material costs, large range of properties and simple processing characteristics. They account for approximately 92% of advanced composite matrices (Poursartip, 1990). Polyester resins are one of the least expensive thermosetting resins, but are restricted to low temperature uses.

Generally, as temperature stability goes up, resin and resin curing costs increase. A general guide to thermoset selection is outlined in Table 2.
Table 2. A Relative Guide for Thermoset Resin Selections

<table>
<thead>
<tr>
<th>THERMOSET RESIN</th>
<th>TEMPERATURE</th>
<th>COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>polyester</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>epoxy</td>
<td>medium</td>
<td>medium</td>
</tr>
<tr>
<td>bismaleimide</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>polyimide</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.1.2 Composite Classification

Reinforced polymers can be divided into three categories:

- discontinuous fibre (chopped fibres)
- continuous fibre (fibre length comparable to composite length)
- laminates (layered composites, two dimensions >> third)

In terms of rock support, continuous fibre reinforced composites are recommended since they possess the potential mechanical properties and adaptability for mining. Intuitively, the bond length and therefore strength between fibre and matrix for discontinuous, or short fibre, composites is lower than continuous composites. As a result, the overall axial load carrying capacity and stiffness of discontinuous composites is reduced. They tend to fail by matrix shear rather than fibre breakage. The fibre surface area is often too low to develop a sufficient bond to take advantage of peak fibre strengths. Fibre orientation is also more difficult. Conversely, continuous fibre composites have high mechanical properties.

In addition to lower mechanical properties, short fibre composites are not recommended for rock support since the tendon diameter required to provide adequate support would increase drilling costs which typically comprise 65% of the overall support cost. Conversely, it is conceivable that drill hole size and cost may be reduced by using smaller diameter higher strength...
composites provided the surface area and profile characteristics of the tendon remain adequate for a desired critical bond strength. This is one consideration for optimization.

Laminates are a combination of single layers, lamina, consisting of a fibre orientation scheme. A unidirectional composite belonging to the continuous or laminate reinforcement family is coded [0]. An infinite possibility of fibre orientations exist, but four major categories are commonly used for discussion:

- **Unidirectional** - All fibres lie in one direction (e.g. [0], [90]).
- **Bidirectional** - The fibres lie at 90° to each other. For example, this can be achieved using woven fabric or unidirectional layers (e.g. [0/90], [±45], [±60]).
- **Multidirectional** - The fibres have more than two orientations. Each layer has unidirectional characteristics (e.g. [0/90/+45/-45/90/0] = [0/90/±45]_9)
- **Random** - Fibres are randomly distributed in one plane.
The most likely orientations to succeed in mining are the unidirectional and bidirectional formats (Figure 4).

2.1.3 Figure 4. Comparison of [0] and [±45] Composites

Unidirectional Composite [0]
Fabrication Technique - Pultrusion
Mining Application - Tension = Dominant Driving Force

Bi-directional Composite [±45]
Fabrication Technique - Not fully developed
Best Fibre Orientation Combination for Shear Resistance

(a) (b)

2.1.3 Fibre Reinforcement Classification

This classification refers to continuous and laminate reinforcement prior to composite manufacturing. The terms and reinforcement forms are in many ways analogous to the textile industry. Both continuous rovings and roving fabrics are applicable to the manufacture of a
Fibres are manufactured into mono-filaments which are gathered together to form the following continuous reinforcements:

- **Strands** - Normally an untwisted bundle or assemble of continuous filaments used as a basic unit for yarns or tows.
- **Yarns** - An assemblage of twisted natural or synthetic filaments, fibre, or strands to form a continuous length that is suitable for use in weaving or interweaving into textile materials.
- **Tows** - An untwisted bundle of continuous filaments. A tow designated 140K has 140,000 filaments.
- **Rovings** - A number of strands yarns or tows collected into a parallel bundle with little or no twist.

Strands are usually combined to form unidirectional fibre yarns (twisted bundles) or tows (untwisted bundles) which are then combined to form rovings. In the past, fibre manufacturers have supplied standard 6-12 km fibre tow creels weighing approximately 1 kg. As the demand for higher capacities rose to compete with industries such as steel, desired creel sizes rose to 40 km or larger to alleviate start-up losses.

Woven rovings also show potential for mining. Fibre producers are capable of supplying woven fabrics in a number of forms applicable to mining:

- weaves
- braids
- knits
- Prepreg

All of these formats have potential for ground support. Continuous rovings are the most suitable format for unidirectional tendons manufactured by pultrusion-like processes. In
principle, rovings, weaves, braids and knits can be used to achieve various fibre orientations with either pultrusion, filament winding or braiding. For example, weaves, braids and knits are well suited for high capacity pultruded [±45] products since they tend to maintain fibre orientation under tension. To achieve a [±45] composite with longitudinal rovings, more time consuming and expensive methods such as filament winding or braiding are required.

Prepreg, which can be used in a number of composite manufacturing processes, is an acronym for "fibre PRE-impregnated with resin." The impregnating resin can be a thermoset or thermoplastic. A thermoset cures at a defined rate and has a limited shelf-life. A thermoplastic requires heat and pressure to initiate cure and has an unlimited shelf-life. The prepreg fabrication process eliminates wet-out, alignment and preforming problems associated with wet resin techniques. Problems associated with using prepreg include: increased cost, preheating, compaction and debulking of B-staged (partially cured) resin.

2.1.4 Fibre Type

As previously mentioned, from a continuous mining perspective, steel cable bolting is not a practical solution and the necessity of a cuttable support system is obvious. The fibreglass rock bolt is an alternative that has been tested without adverse affects to continuous mining machines (Meechan, 1989) and has proven local support capacity. They therefore represent proven composite technology as an alternative to steel. Five types of glass fibre are commonly used to manufacture rods:

- E-glass - electrical grade glass, least expensive.
- S-glass - stronger stiffer.
- R-glass - Civil engineering version of S-glass used for structural applications.
- C-glass - used where chemical resistance is required, especially in acidic environments.
- Cemfil - resistant to the alkali in Portland cement.
Versatility and economy are two advantages of glass that are beneficial to future mining product developments. Poor corrosion resistance, poor handling resistance and moderate mechanical properties are their disadvantages as compared to other fibres. C-glass could reinforce a polymer matrix of similar chemical resistance to produce a rock or cable bolt for highly aggressive chemical environments. Cemfil might be another alternative for such environments where a drill hole could be filled with fibre to provide reinforcement and Portland cement Type 20 or 50 (sulphate resistant cement). The chemical composition for glass fibres varies between manufacturer and for this reason ranges for E, S, C-glass are presented in Table 3. However, these variations do not cause significant fluctuations in the mechanical or physical properties within a given glass type.

**Table 3. Compositional Ranges for E, S, C-glass**
(Reinhart et al., 1988)

<table>
<thead>
<tr>
<th>OXIDE</th>
<th>E-GLASS RANGE (%)</th>
<th>S-GLASS RANGE (%)</th>
<th>C-GLASS RANGE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>52-56</td>
<td>65</td>
<td>64-68</td>
</tr>
<tr>
<td>Aluminum</td>
<td>12-16</td>
<td>25</td>
<td>3-5</td>
</tr>
<tr>
<td>Boric</td>
<td>5-10</td>
<td>--</td>
<td>4-6</td>
</tr>
<tr>
<td>Sodium and Potassium</td>
<td>0-2</td>
<td>--</td>
<td>7-10</td>
</tr>
<tr>
<td>Magnesium</td>
<td>0-5</td>
<td>10</td>
<td>2-4</td>
</tr>
<tr>
<td>Calcium</td>
<td>16-25</td>
<td>--</td>
<td>11-15</td>
</tr>
<tr>
<td>Barium</td>
<td>--</td>
<td>--</td>
<td>0-1</td>
</tr>
<tr>
<td>Zinc</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Titanium</td>
<td>0-1.5</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Zirconium</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Iron</td>
<td>0-0.8</td>
<td>--</td>
<td>0-0.8</td>
</tr>
<tr>
<td>Iron (not oxide)</td>
<td>0-1</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Other fibres with potential as ground support members include aramid and carbon. Aramid fibres are recommended for tensile applications only. Aramid fibres tend to form defects called "kink bands" under high strain compressive and flexural loads rendering the reinforcement ineffective (Phillips, 1989). A comparison of the mechanical properties for various fibres
currently available has been listed in Table 4. Glass has been selected primarily based on cost.

Table 4. Mechanical Property Comparison for Various Fibres
(Phillips, 1989 and Reinhart et al, 1988)

<table>
<thead>
<tr>
<th>FIBRE</th>
<th>S.G. (g/cm³)</th>
<th>UTS (MPa)</th>
<th>Tensile (GPa)</th>
<th>Strain at Failure (%)</th>
<th>CREEP (%)</th>
<th>COST ($US/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E-glass</td>
<td>2.62</td>
<td>3445</td>
<td>81.3</td>
<td>4.88</td>
<td>2-3</td>
<td>1-5</td>
</tr>
<tr>
<td>S-glass</td>
<td>2.50</td>
<td>4585</td>
<td>88.9</td>
<td>5.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-glass</td>
<td>2.56</td>
<td>3310</td>
<td>--</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon mesopitch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG-LM</td>
<td>1.9</td>
<td>1400</td>
<td>160</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG-HM</td>
<td>2.0</td>
<td>1700</td>
<td>380</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG-VHM</td>
<td>2.15</td>
<td>2200</td>
<td>725</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NG-LM</td>
<td>2.05</td>
<td>3100</td>
<td>225</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NG-HM</td>
<td>2.15</td>
<td>3100</td>
<td>380</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon PAN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt;1</td>
<td>10-1000</td>
</tr>
<tr>
<td>SG-LM</td>
<td>1.76</td>
<td>3300</td>
<td>230</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG-HM</td>
<td>1.9</td>
<td>2400</td>
<td>390</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NG-LM</td>
<td>1.8</td>
<td>4500</td>
<td>230</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NG-IM</td>
<td>1.8</td>
<td>5300-6800</td>
<td>270</td>
<td>2.0-2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NG-HM</td>
<td>1.8</td>
<td>5500</td>
<td>320</td>
<td>1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon isotopic pitch</td>
<td>1.6</td>
<td>700</td>
<td>55</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon rayon</td>
<td>1.6</td>
<td>1000</td>
<td>41</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-Aramid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10-15</td>
</tr>
<tr>
<td>Kevlar 29</td>
<td>1.44</td>
<td>3600</td>
<td>83</td>
<td>4.0</td>
<td></td>
<td>10-100</td>
</tr>
<tr>
<td>Kevlar 49</td>
<td>1.44</td>
<td>3600-4100</td>
<td>131</td>
<td>2.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kevlar 149</td>
<td>1.47</td>
<td>3400</td>
<td>186</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twaron</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technora</td>
<td>1.39</td>
<td>3000</td>
<td>70</td>
<td>4.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HM-50</td>
<td>1.39</td>
<td>3100</td>
<td>81</td>
<td>4.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyethylene</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5-10</td>
</tr>
<tr>
<td>Spectra 900</td>
<td>0.97</td>
<td>2600</td>
<td>117</td>
<td>3.5</td>
<td></td>
<td>48-62</td>
</tr>
<tr>
<td>Spectra 1000</td>
<td>0.97</td>
<td>2900-3300</td>
<td>172</td>
<td>0.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.1.5 Range of Composites

A summary of the important factors affecting continuous fibre reinforced composite properties are fibre type, volume fraction ($V_f$) of fibres, fibre orientation, and matrix type. A typical range of raw material combinations are listed in Table 5. A wide range of profile shapes are available. From a bond capacity perspective, circular profiles offer the largest bond surface area and a uniformly distributed interfacial shear. Circular profile, tendon, rod, and strand have been used interchangeably.

<table>
<thead>
<tr>
<th>FIBRE TYPE</th>
<th>ORIENTATION AND $V_f$</th>
<th>MATRIX</th>
<th>BEST MATCH FOR ADHESION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>UD (50-70%)</td>
<td>polyester</td>
<td>glass/polyest.</td>
</tr>
<tr>
<td>Aramid</td>
<td>BD (30-55%)</td>
<td>vinylester</td>
<td>glass/epoxy</td>
</tr>
<tr>
<td>Carbon</td>
<td>Random (15-35%)</td>
<td>epoxy</td>
<td>aramid/epoxy</td>
</tr>
<tr>
<td>Polyethylene</td>
<td></td>
<td>polyimide</td>
<td>carbon/epoxy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>bismaleimide</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>phenolic</td>
<td></td>
</tr>
</tbody>
</table>

Discussions regarding fibre type have been restricted to glass, aramid and carbon since these three dominate the composites industry and have the greatest potential for mining applications. The mechanical properties of the fibre are important during selection of a composite for an application since the majority of the load is carried by the fibre. For example, a unidirectional glass/polyester composite with approximately 70% fibre by volume will typically transfer 98.5% of its ultimate load carrying capacity to the fibres. The physical properties of the fibre are less important than the physical properties of the matrix since the matrix (resin) acts as a protector. This is generally true except for cases where stress has cracked the matrix exposing the fibre to the environment. To prevent stress corrosion and matrix cracking, the ultimate strain of the fibre and matrix must be matched.
2.1.6 Volume Fraction

The volume fraction of fibres in a composite is dependent on the fibre orientation, diameter and shape, and the manufacturing process. Unidirectional composites have high fibre contents while random composites have low contents. Considering the range of mechanical properties possible through fibre directionality, composites have the potential for developing ground support products with various combinations of tensile, shear and flexural strengths. The relationships between ultimate tensile strength or modulus and fibre orientation are not linear.

2.1.8 Composite Surface Treatment

Composite surface treatments act as protection against mechanical damage, impact, corrosion, abrasion and weathering. Surface treatments increase the service life and application range of a composite. They can be altered to give a desired surface roughness or can be selected to reduce die abrasion and drag in manufacturing processes such as pultrusion. Three types of resin rich veils are common:

- polyethylene
- nylon (polyamide)
- polypropylene

Additives and reinforcement can be added to the veil to achieve desired properties such as flame retardancy and increased strength or frictional characteristics.

2.1.9 Composite Market Classifications

Reinforced polymer composites have been classified according to their technology (Table 6):
Table 6. Composite Market Classifications

<table>
<thead>
<tr>
<th>COMPOSITE CLASSIFICATION</th>
<th>RESIN</th>
<th>REINFORCEMENT</th>
<th>FIBRE CONTENT</th>
<th>QC</th>
</tr>
</thead>
<tbody>
<tr>
<td>reinforced plastics</td>
<td>thermoset</td>
<td>discontinuous particulate</td>
<td>very low</td>
<td>low</td>
</tr>
<tr>
<td>low-tech</td>
<td>thermoset</td>
<td>continuous laminate</td>
<td>moderate</td>
<td>moderate</td>
</tr>
<tr>
<td>advanced</td>
<td>both</td>
<td>continuous laminate</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>(high-tech)</td>
<td>both</td>
<td>continuous laminate</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>thermoplastic</td>
<td>thermoplastic</td>
<td>continuous laminate</td>
<td>high</td>
<td>high</td>
</tr>
</tbody>
</table>

Note: 
QC = Quality Control

Reinforced plastics have been rejected because of their low mechanical properties while thermoplastics were rejected because of their extremely high cost. Low-tech and advanced composites exhibit excellent mining potential. Very few advanced polymer composites exist in tendon form. The majority of the market is flooded with lower fibre content rods which are manufactured with limited quality control measures or technical input. It must be stressed again that quality control is vital to ensure proper safety standards for composite manufacturing and their use in ground control. Attempts to use low-tech composites for ground support are discouraged unless acceptable verification of the composite properties has been made. This does not rule out the possibility that relatively inexpensive existing quality control measures could promote confidence in low-tech composite properties. Documentation on quality control and testing is abundant (Phillips, 1989). It is unlikely low-tech composites would be able to develop tensile strengths greater than two-thirds of advanced composites without significant improvements to manufacturing. This could be overcome by increasing the number of low-tech rods used for cable bolt reinforcement provided drilling costs remained competitive. Emphasis has been placed on the application of advanced composites for cable bolt reinforcement and will
be referred to as composites for the remainder of this investigation.

2.2 Selection Criteria

The manufacturing processes currently used to produce composites are far from optimised and property data is limited. For these reasons, a more flexible approach to material selection has been presented. As mentioned, glass, aramid and carbon fibres are the most common plastic reinforcement. Since the majority of an applied load is carried by the fibres, they have the greatest influence on the mechanical properties and behaviour of a composite. Physical properties such as the maximum working temperature and corrosion resistance in unstressed situations are primarily determined by the matrix composition. An understanding of the constituent material properties and their joint influence on the overall composite properties is essential to selection. Constituent material properties are most valuable when considering the design and manufacture of composites. The benefits and limitations of each composite and constituent material are presented as they relate to mining. Certain properties have been omitted according to their relevance. It must be emphasised that composite material properties are vastly different than constituent material properties. The reader is advised to be careful in this respect and to ensure that similar test conditions exist between comparisons.

The composite selected to replace steel as a reinforcing agent for cable bolts in continuous or drill and blast mining operations must be comparable in overall cost, performance and handling. The ideal support requirements for mining are:

1. Low flexural stiffness to facilitate coiling (< 2 m diameter)
2. Rigid enough to insert in hole
3. Low density to promote handling
4. High corrosion resistance
5. High bond strength to grout
6. Low creep of grout bond under static load
7. Low creep of reinforcement.
8. Safe handling (body contact and respiratory)
9. Flame retardant
10. Low coefficient of thermal expansion to prevent shrinkage or expansion of reinforcement with respect to grout and stability at low temperatures.
11. Electrically non-conductive
12. High vibrational and dynamic resistance (rock burst or blast induced) and fatigue.
13. High toughness
14. High shear strength
15. Mineral processing "friendly"

In terms of the installation, quality control and handling of cable bolts, a relatively low flexural stiffness and density are preferred to uncoil and insert the cable in the hole. Unidirectional composites are easier to uncoil than SCB's. The flexural stiffness of composites is a function of the matrix modulus, fibre modulus and fibre orientation. Lower modulus resins and fibres result in a more flexible tendon. Resins can be selected improve composite flexibility. Fibre orientations off-axis tend to supply bending and torsional rigidity. SCB's store more energy when coiled and as a result are more dangerous to uncoil and maintain a clean cable underground. Grease and dirt are known to decrease the pull-out load by as much as 50% (Goris, 1990). Composites are easier to handle due to their low density which is approximately one quarter that of steel.

High corrosion resistance is desired for long-term or aggressive environment cable bolt applications. A composite must therefore be resistant to a number of environments such as the alkaline conditions created by the Portland cement, acids generated by oxidation of sulphide minerals in the presence of water or humidity. Composite corrosion can also include solvent dissolution, moisture absorption or chemical attack.
The rate at which chemical corrosion occurs for composites is dependent upon factors such as the matrix type, fibre type, the corrosive solution, temperature, oxygen content in atmosphere or water, area of exposed surface, time, etc. The chemical resistance of a composite relies heavily upon the matrix resistance to chemicals and cracking.

A general ordering of the increasing corrosional resistance for various selected resins is as follows:

- orthophthalic polyester  (least resistant)
- isophthalic polyester
- vinylester
- biphenol
- epoxy  (most resistant)

However, there are exceptions to the above ordering. The resin manufacturer's advice should be sought when determining corrosion resistances of a matrix.

Under stressed conditions, the ability for the matrix to resist cracking is vital. Since one of the functions of the matrix is to protect the relatively sensitive fibres from harmful environments it is important to match the ultimate strain characteristics of the fibre and matrix. As a consequence, the matrix becomes the limiting factor for chemical resistance under low strains. Polymer matrices have different chemical resistances as do fibres and should be chosen according to the service environment. Invariably, matrix cracking occurs as the applied stress approaches the ultimate strength of the composite. In such cases, the chemical resistance of the fibre becomes important to the overall corrosion resistance of the composite. Table 7 is a relative comparison of typical fibre corrosion resistances.
Table 7. General Guide to Fibre Corrosion Resistance
(Phillips, 1989)

<table>
<thead>
<tr>
<th>FIBRE TYPE</th>
<th>BASES</th>
<th>ACIDS</th>
<th>WATER</th>
<th>OTHER SOLVENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>STRONG</td>
<td>WEAK</td>
<td>STRONG</td>
<td>WEAK</td>
</tr>
<tr>
<td>Carbon</td>
<td>H</td>
<td>H</td>
<td>--</td>
<td>H</td>
</tr>
<tr>
<td>Technora</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Kevlar 49</td>
<td>L</td>
<td>G</td>
<td>L</td>
<td>G</td>
</tr>
<tr>
<td>E-glass</td>
<td>VL</td>
<td>L</td>
<td>VL</td>
<td>L</td>
</tr>
</tbody>
</table>

Note:
H = high
G = good
L = low
VL = very low

E-glass is highly resistant to most chemicals, but it is susceptible to acids and alkalis at low concentrations. Corrosion resistant fibres such ECR-glass and R-glass are available.

Aramid fibres can be categorised into two main groups according to their chemical resistance:

- Low resistance (e.g. Kevlar 49) - high modulus
- High resistance (e.g. Technora) - low modulus

Kevlar 49 is sensitive to strong acids and bases and is resistant to most other solvents and chemicals (Pigliacampi, 1988). Technora, manufactured by Teijin of Japan, exhibits high strength retention in both acids and alkalis (Phillips, 1989). Carbon fibres are not affected by moisture, atmosphere, solvents, bases and weak acids at room temperature (Diefendorf, 1988).

Composites comprised of fibres with low corrosion resistances can be protected by a surface coating. In conclusion, ECR-glass, Technora and carbon fibres are highly resistant to chemical corrosion.

The most common cable bolt failure occurs at the cable/grout interface. In these instances, the pull-out bond strength of a cable bolt can be thought of as the sum of adhesion and frictional
resistance between tendon and grout (Jeremic et al, 1983). Adhesion is a function of the chemical attraction between the tendon and grout. The friction is determined by the tendon surface profile, tendon configuration and confinement. It increases with normal stress. Laced FCB's have an adhesive resistance, but more significant forms of frictional resistance and mechanical interlock contribute to their overall resistance.

In general, the higher the bond strength, the lower the creep of that bond strength under static load conditions. The bond strength of a conventional SCB is less than ideal. Nevertheless, SCB's are used extensively in mining where high bond strengths are not required. Birdcaged SCB's have excellent bond strength characteristics, but are not widely used in North America (Vancouver, 1991). Perhaps in the past the drill hole size necessary for the installation of birdcaged SCB's, higher material cost or the lack of familiarity with birdcaged SCB's has discouraged their use. Current trends have revealed that birdcaged SCB's are gaining acceptance in Canadian underground mines (Vancouver, 1991). Ground control engineers are realising the importance of a high bond strength to the effectiveness of cable bolts, in blocky ground. Under long-term static loading (62 months) prestressed cable anchors will experience a loss in load of 8.2% (Benmokrane et al, 1991). Load losses of up to 10% have been tolerated for anchors prestressed to 75% of their rupture limit load (Littlejohn and Bruce, 1979).

Composites creep rates and characteristics vary with the orientation of the fibres with respect to a load and temperature. When subjected to a tensile load in the direction of the fibres, composites exhibit linear elastic creep rates. Figure 5 compares creep data for various composites and steel under these conditions. In general, carbon composites possess the greatest creep resistance. Their creep rates are slightly less than low relaxation steel. E-glass composites have the next lowest creep rates followed by standard steel and the distant, aramid composite family.
For a composite with an off-axis static load, the matrix properties become more significant to creep. This results in a reduction in the creep resistance and elastic recovery of the composite. This is due to the fact that polymers creep visco-elastically, which means they exhibit both a linear elastic and non-linear viscous response to external forces. Furthermore, as temperature increases so does the amount and rate of creep in composites. Thus, the heat deflection temperature (HDT) is an effective measure of the creep resistance of a polymer or composite. A high HDT indicates high creep resistance. Typical HDT's for polyester resins range from 80-
140°C. In general, epoxies and thermoplastics have greater HDT's.

A coating is recommended for a composite intended for cable bolting. The coating enhances the bond strength, safer handling, abrasion resistance and toughness.

Generally, fibre reinforced polymers have low coefficients of thermal expansion similar to Portland cement. In Canada, mining service temperatures typically range between -60°C and 40°C depending on the geographic location. The mechanical properties of composites degrade as temperature increases. Large decreases occur as the temperature approaches the glass transition temperature, Tg, of the matrix or fibre. The temperatures associated with mining lie well below the Tg for virtually all fibres and polymer matrices of interest. Low temperature resins tend to degrade at much lower temperatures than fibres in the order of 300°C and, hence, are the limiting component for elevated temperature applications. During low temperature service, composite stiffness and strength are unaffected or slightly enhanced (Phillips, 1989).

Glass and aramid fibres are electrical insulators. Carbon fibres on the other hand will conduct electricity. To quote from R. J. Diefendorf (Reinhart et al, 1988), "Carbon fibre conductivity varies with precursor type and heat treatment temperature and is 1/50 or less that of copper for commercial 230 GPa fibres."

In general, composites have a higher vibrational damping capacity when compared to steel and are more likely to withstand rockburst or blast induced vibrations. The tendency for seismic shock to propagate through steel cables can reduce the strength of the grout bond for peak particle velocities greater than 500 mm/sec (Stillborg 1984). Phillips (1989) quotes, "Metals and ceramics have particularly low internal losses and hence have poor damping characteristics. Polymer composites, on the other hand, and particularly CFRP (carbon fibre reinforced plastics) and ARP (aramid fibre reinforced plastics), have very good damping performance, which can be used to reduce vibration resonance."

Composites do not exhibit a definite fatigue limit at two million cycles. Fatigue is defined as the gradual deterioration of a material through cyclical loading. In general, low modulus composite reinforcement causes excess matrix cracking under cyclical loads. This results in early
fatigue. The applied stress can be tension-tension, compression-compression or tension-compression. Such loading conditions can be induced to support systems by blasts, rockbursts or gradual changes in the mining induced stress field. The fatigue resistance of a composite is a function of the matrix as well as the fibre orientation, content and type. For example, unidirectional carbon fibre composites loaded in the direction of the fibres exhibit excellent fatigue resistance. The matrix plays a more dominant role in [±45] composites stressed transverse to the fibre direction. This results in reduced fatigue resistances. Fatigue resistance also decreases with decreasing fibre content. A general ordering of fatigue resistances for unidirectional composites under longitudinal load cycles can be summarised as follows:

- Carbon
- Aramid
- Glass

Carbon fibre composites show a two to four fold increase in fatigue strength over steel. The ratio, after cycling, of tensile strength to short-term ultimate tensile strength for carbon fibre reinforced epoxy composite after $10^7$ tension cycles is in the range of 53-58%. This applies to [0], [±45], [90] and quasi-isotropic configurations and compares favourably with 2024 T3 aluminum at 28% and 4130 steel at 44% (Phillips, 1989). Glass composites have greater flexural fatigue resistance than aramids for large numbers of cycles and have lower fatigue strengths than steel. Carbon fibre composites maintain their superiority over other composites for all fibre orientations and are relatively insensitive to fatigue when unidirectional, longitudinally loads are considered.

Note that the potential disadvantages of SCB's have been their failure to meet ideal support requirements (1), (3), (4), (11) and (12) as outlined in Section 2.2.

The potential disadvantages of the FCB are the ideal support requirements (8), (14) and (15). Filament winding and pultrusion are continuous composite fabrication techniques capable of
various off-axis fibre orientations which increase the shear strength of a tendon. Pultrusion is well suited for both cable and rock bolts. When compared to filament winding, pultrusion is usually favoured due to its' simplicity and production rate. The drawback with pultrusion is lower shear strengths. Pultruded composite shear strength can be improved by using braided, woven or knitted rovings as opposed to standard roving feeds, but these composites will never achieve shear strengths as great as those with equivalent cross-sectional areas produced from filament winding.

Filament winding has slightly slower production rates than pultrusion, but improved fibre orientation, and thus, high shear strengths are possible with this technique. The drawback when increasing shear strength is sacrificed tensile strength. Larger cross-sectional areas to achieve a desired tensile strength and lower tendon flexibilities are the result of increasing shear strength.

The effects of the fibres on the working environment and processing circuits were briefly explored. Results on these aspects are documented in Section 8.0 and 9.0.

2.3 Manufacturing Techniques

A number of composite manufacturing techniques were briefly studied to evaluate their versatility, commercial potential, advantages and disadvantages. Four continuous fabrication techniques have potential for the commercial production of cable bolts:

- Filament Winding
- Braiding
- Pultrusion (e.g. CELTITE, POLYGLAS, etc.)
- Patented Methods (e.g. POLYSTAL and ARAPREE)

Each method has been briefly presented. It was found continuous production methods were basically limited by the maximum length of roving available on a spool and the mechanics of the
equipment to handle these lengths. In general, the roving feed size and their number of spools can be selected to best suit the production requirements in order to achieve a virtually "continuous" production of tendons. In each method, production ideally continues until the spools of rovings are used, at which time the system must be shut-down and new spools loaded.

The manufacturing potential of each process was ranked according to the driving forces described in Section 4 (Table 8).

Table 8. The Potential of Various Composite Manufacturing Processes for the Production of Cable and/or Rock Bolts

<table>
<thead>
<tr>
<th>MANUFACTURING METHOD</th>
<th>BOLT TYPE</th>
<th>MOST FAVOURED DRIVING FORCE CASE$^b$</th>
<th>RELATIVE PRODUCTION RATE RANKING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filament Winding</td>
<td>RB$^a$,CB</td>
<td>(2)</td>
<td>slow</td>
</tr>
<tr>
<td>Patented</td>
<td>RB,CB</td>
<td>(1)</td>
<td>medium</td>
</tr>
<tr>
<td>Pultrusion</td>
<td>RB,CB</td>
<td>(1)</td>
<td>fast</td>
</tr>
</tbody>
</table>

Notes:

- anchor device requires development (resin, cement, mechanical, etc.).
- all fabrication methods have potential to manufacture tendons for applications with Case (1), (2) & (3) driving forces, but each is most suited to a particular Case. RB Represents rock bolt. CB Represents cable bolt.

Each method can potentially manufacture cable bolts or rock bolts. Filament winding is most suited to manufacture reliable composites for shear applications, however, the pultrusion and patented methods also have potential in this respect. Control of a manufacturing method would be necessary to evaluate these options.

Braiding is a fibre format manufacturing method, but it can be combined with resin impregnating stages to manufacture composites. Braided composites are used extensively in the fishing, skiing and golfing industries.

Although each method was characterised by different capabilities and production potentials,
all have similar production concerns as summarized below:

- Most efficient if operated on a 24 hour basis.
- A significant investment is required to stock raw materials and equipment.
- The raw materials represent the majority of the production costs.
- Raw material availability can determine plant location.
- Fibres are supplied on standard creel sizes limiting the continuous process.
- The manufacturer usually has limited technical support and often draws on the knowledge of the raw material supplier.
- Continuous consistent resin supply is required.
- Manufacturers are unfamiliar with advanced composite problems such as void content, compaction, degree of cure and fibre volume determinations.
- Start-ups should be minimized.

2.3.1 Filament Winding

Filament winding involves a continuous feed of fibre bundles (tows, rovings or yarns) through a resin bath onto a rotating mandrel (Figure 6). It is most suited for complex shapes requiring multi-fibre directions. The component is partially or fully cured before removal. The process is cyclical and less suited for long component manufacturing. Advantages include precise fibre orientations and excellent fibre content control. The major disadvantage of filament winding is its' slow production rate. This fabrication method has potential for short shear resistant bolt construction, but its relatively high cycle time is a severe hindrance. One way of improving the production rate has been to combine filament winding or braiding with pultrusion technology. In this manner, acceptable production rates and mechanical properties can be achieved.
2.3.2 Braiding

Braiding is a continuous process capable of biaxial, triaxial and multiaxial fibre orientations (Figure 7). Fibre bundle spools are rotated on a track to form two dimensional tapes or three dimensional tubes. Resin impregnation can occur during the manufacture or service of the braid. Braiding has excellent potential for the manufacture of high shear strength rock or cable bolts. New Port Composites Inc., Fountain Valley, California supplies glass, aramid and carbon fibre braided composite tubes varying in diameter from 1 cm to 15 cm. Braided tubes have the
potential to act both as the grout tube and the reinforcement in a cable bolt. If braided tubes were used for this purpose, the bond surface area would be reduced to that of the tube's outer diameter. Adhesion between the tube's inner diameter and the grout would not contribute to the bond strength of the cable bolt as a whole. Assuming an outer diameter of 40 mm, the bond surface area for a unit length of tube would be equal to 126 mm². Since bond surface area is a crucial factor to achieve high pull-out loads, this system has not recommended on its' own.

Alternatively on a microscopic level, it has been well established by the fibre reinforced composites industry that reducing fibre diameter to less than approximately 20 microns substantially increases their mechanical properties (Poursartip, 1990). This technology can be directly applied on a macroscopic level to the development of a fibre reinforced composite cable bolt using braids. For example, many 1 cm diameter braids would have a high bond surface area, and as a result would have higher pull-out load, than one large tube of equivalent mechanical properties (cross-sectional area). Combinations using braided and UD composites also have potential for cable bolting.
2.3.3 Pultrusion

Pultrusion is a continuous fabrication technique most suited for shapes with constant cross sectional areas (Figure 8). The advantages of pultrusion are: low capital start-up costs, low cycle times and simplicity of operation. It is the most well suited fabrication technique for commercially produced rock or cable bolts. Off-axis fibre orientation can be achieved by pultruding braids, weaves or knits. A complete list of the benefits associated with pultrusion are listed below:

- can use thermoset or thermoplastic
- low capital cost
- low direct labour costs
- decreased quality control costs
- low tooling cost
- longer tool life
- easily automated
- high continuous output compared to other fabrication processes
- limited operator influence on properties
- lack of secondary finish required
- multiple die capacity

Figure 8. Pultrusion (Poursartip, 1990)
The curing of fibres under tension is a disadvantage of this method. This can result in lower strain capacities and fibre relaxation causing debonding.

The following product size ranges are possible:

- thickness 2 to 76 mm
- width 2 to 1000 mm
- length various

Two major constraints are imposed on pultrusion are the: (1) rate of reaction kinetics for the resin and (2) process mechanics. Constraint (1) dominates thick cross-sectional shapes while constraint (2) dominates thinner shapes. In general, thicker thermoset shapes are subjected to differential stresses during cure resulting in internal exothermic cracking. To solve this problem close control of the resin properties affecting quality and the addition of radio frequency (RF) preheating is required. Typical large cross section production rates range from 0.6-1.2 m/min. Improvements to the reaction kinetics and mechanical workability of resins have led to production rates as high as 4.6 m/min (e.g. RF preheat treatment of solid glass/polyester 12.7 mm diameter rod, Sumerak et al, 1985). To achieve such rates, the effects of the process parameters are often correlated to form empirical relationships used to automate production. Obstacles for capacity growth include low data-bases for advanced composite materials and limited numbers of processors. Pultrusion has excellent potential for continuous, low cost production of rock or cable bolts for tension dominated driving force applications. It also has potential to manufacture bolts with moderate shear strengths.
2.3.4 Patented

Two advanced round bar composites: POLYSTAL and ARAPREE are manufactured under patented processing methods and as a result these methods have not been presented. The advantages of these methods are clearly indicated by their products' superior properties over less advanced composites.

2.4 Composite Tradename Comparisons

Table 9 compares various composites by process, market classification, constituent materials and cost per metre. The composites listed are either glass or aramid fibre reinforced epoxies or polyesters. Other low-tech composites are available on the market, but before using them for cable bolting further product developments such as: manufacturing quality control, fibre content, corrosion resistance, void content control, and bond surface would be necessary. For these reasons it was decided that slightly more expensive advanced composites such as POLYSTAL (construction profile) and ARAPREE should be considered for the development of a cable bolt prototype.

ARAPREE is a Twaron (AKZO tradename for aramid) fibre reinforced epoxy and is considered an advanced composite. Three companies supply aramid fibres worldwide, AKZO of the Netherlands, E. I. du Pont de Nemours & Co. of the United States and Teijin Company of Japan. POLYSTAL is a glass fibre reinforced unsaturated polyester advanced composite manufactured in Germany and distributed in Canada.
Table 9. Unidirectional Composite Comparisons (Khan et al, 1991)

<table>
<thead>
<tr>
<th>TRADENAME</th>
<th>MANUFACTURING PROCESS</th>
<th>MARKET CLASS</th>
<th>FIBRE</th>
<th>RESIN</th>
<th>COST ($/m)$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARAPREE 100</td>
<td>patented</td>
<td>advanced</td>
<td>Twaron (aramid)</td>
<td>epoxy</td>
<td>1.33</td>
</tr>
<tr>
<td>ARAPREE 200</td>
<td>&quot;</td>
<td>advanced</td>
<td>&quot;</td>
<td>&quot;</td>
<td>2.56</td>
</tr>
<tr>
<td>ARAPREE 400</td>
<td>&quot;</td>
<td>advanced</td>
<td>&quot;</td>
<td>&quot;</td>
<td>5.44</td>
</tr>
<tr>
<td>POLYGLAS</td>
<td>pultrusion</td>
<td>low-tech</td>
<td>Glass</td>
<td>unsat'd polyester</td>
<td>1.17</td>
</tr>
<tr>
<td>CELTITE</td>
<td>pultrusion</td>
<td>low-tech</td>
<td>Glass</td>
<td>unsat'd polyester</td>
<td>n/a$^2$</td>
</tr>
<tr>
<td>EXTRENE</td>
<td>pultrusion</td>
<td>low-tech</td>
<td>Glass</td>
<td>polyester vinyl ester</td>
<td>2.39</td>
</tr>
<tr>
<td>POLYSTAL (construction profile)</td>
<td>patented</td>
<td>advanced</td>
<td>Glass</td>
<td>unsat'd polyester</td>
<td>2.56</td>
</tr>
</tbody>
</table>

Notes:
$^1$ = approximate cost per metre of one 7-8 mm diameter rod
$^2$ = 8 mm rods not standard size, but can be manufactured

POLYSTAL and ARAPREE manufacturing processes are both capable of various resin-fibre combinations. Both are imports, but POLYSTAL is commercially sold in Canada whereas ARAPREE is not. Currently, ARAPREE and POLYSTAL have a number of different profiles available, but only ARAPREE 200 and POLYSTAL (Construction Profile) have suitable coiling flexibility for transportation underground. Likely the largest disadvantages of aramid reinforced composites are their expensive raw materials, low availability, relatively lower performance under flexural/shear loading, and relatively high creep rates (Phillips, 1989). Some of the advantages of aramid fibres over glass include impact and chemical resistance. POLYSTAL was chosen based on its' high availability, moderate cost and suitable mechanical properties. However, further investigation into the potential for ARAPREE and other composites as a cable bolt are warranted.
3. POLYSTAL SPECIFICATIONS AND PROPERTIES

3.1 Introduction

This section outlines the properties of POLYSTAL and its' behaviour as a prestressing strand as determined by BAYER. Research by BAYER to develop a continuous, moderate strength and moderate modulus composite for prestressing a road bridge spanning 50 metres began in 1978. The research evaluated glass fibre with polyester and epoxy resins. The bridge was completed on July of 1986 in Duesseldorf, Germany and since then five other bridges have been reinforced with POLYSTAL (Preis, 1986).

To compete with prestressing steel, Bayer had to develop a cost effective, corrosion and abrasion resistant, high performance glass fibre and polyester resin composite. E-glass and unsaturated polyester resin were considered as the most economical constituent materials by BAYER.

POLYSTAL tendons are made by a continuous "pultrusion-like" process and have a UD fibre orientation parallel to the tendon axis. This results in anisotropic mechanical properties, or simply, properties that vary with the angle between the applied load and the fibres. When viewed in cross-section, a uniform distribution of end-on fibres can be seen. POLYSTAL is available with an optional polyamide coating which protects against corrosion and mechanical damage. Coated and uncoated POLYSTAL have potential for long-term (> 1 year) and short-term (< 1 year) excavations respectively. Various diameters and profiles are available.

The majority of the test work presented in this thesis evaluated coated tendon behaviour. Four, 7.5 mm diameter strands, each with a modulus of 1520 MPa, were used to give an ultimate load carrying capacity approximately equivalent to that of steel cables. This allowed for more direct pull-test comparisons between the two.
3.2 Specifications

The general properties for POLYSTAL (Construction Profile) and its' constituent materials are listed in Table 10.

Table 10. POLYSTAL Composite and Constituent Material Properties (Preis, 1986)

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>DIMENSION</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>POLYSTAL Rod (construction profile)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass fibre content</td>
<td>% by weight</td>
<td>80 ± 2.5</td>
</tr>
<tr>
<td>coefficient of thermal exp.</td>
<td>change in length per °C</td>
<td>6.6 * 10^-6</td>
</tr>
<tr>
<td>water absorption in 24 hrs</td>
<td>@ 20 °C, %</td>
<td>0.1</td>
</tr>
<tr>
<td>axial tensile strength</td>
<td>MPa</td>
<td>1,600</td>
</tr>
<tr>
<td>transverse compressive strength</td>
<td>MPa</td>
<td>140</td>
</tr>
<tr>
<td>shear strength</td>
<td>MPa</td>
<td>45</td>
</tr>
<tr>
<td>modulus of elasticity</td>
<td>MPa</td>
<td>52,000</td>
</tr>
<tr>
<td>failure strain</td>
<td>%</td>
<td>3</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>--</td>
<td>0.28</td>
</tr>
<tr>
<td>density</td>
<td>g/cm³</td>
<td>2.1</td>
</tr>
<tr>
<td>Glass Fibre</td>
<td></td>
<td></td>
</tr>
<tr>
<td>axial tensile strength</td>
<td>MPa</td>
<td>2,300</td>
</tr>
<tr>
<td>modulus of elasticity</td>
<td>MPa</td>
<td>74,000</td>
</tr>
<tr>
<td>failure strain</td>
<td>%</td>
<td>3</td>
</tr>
<tr>
<td>Polyester Resin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>axial tensile strength</td>
<td>MPa</td>
<td>75</td>
</tr>
<tr>
<td>modulus of elasticity</td>
<td>MPa</td>
<td>300</td>
</tr>
<tr>
<td>failure strain</td>
<td>%</td>
<td>4</td>
</tr>
</tbody>
</table>

The Construction Profile POLYSTAL has been developed specifically for chemically aggressive environments and was selected for this evaluation. Table 11 lists the potential diameters which can be manufactured and corresponding mass per unit length, maximum length, tensile force at 0.5% elongation and breaking force.
Table 11. Typical POLYSTAL - Construction Profile Specifications
(Con-Tech Systems, 1991)

<table>
<thead>
<tr>
<th>Type</th>
<th>Diameter [mm]</th>
<th>Mass per unit length [g/m]</th>
<th>Maximum Length [km]</th>
<th>Tensile Force at 0.5% elongation [N]</th>
<th>Breaking Force [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P10</td>
<td>1.00</td>
<td>1.6</td>
<td>15</td>
<td>200</td>
<td>1,100</td>
</tr>
<tr>
<td>P12</td>
<td>1.22</td>
<td>2.3</td>
<td>15</td>
<td>290</td>
<td>1,630</td>
</tr>
<tr>
<td>P14</td>
<td>1.40</td>
<td>3.0</td>
<td>15</td>
<td>380</td>
<td>2,500</td>
</tr>
<tr>
<td>P16</td>
<td>1.56</td>
<td>3.7</td>
<td>16</td>
<td>480</td>
<td>3,200</td>
</tr>
<tr>
<td>P17</td>
<td>1.70</td>
<td>4.4</td>
<td>16</td>
<td>570</td>
<td>3,700</td>
</tr>
<tr>
<td>P20</td>
<td>1.95</td>
<td>5.9</td>
<td>16</td>
<td>750</td>
<td>5,000</td>
</tr>
<tr>
<td>P21</td>
<td>2.10</td>
<td>6.8</td>
<td>16</td>
<td>860</td>
<td>5,700</td>
</tr>
<tr>
<td>P24</td>
<td>2.40</td>
<td>8.6</td>
<td>16</td>
<td>1,100</td>
<td>7,600</td>
</tr>
<tr>
<td>P26</td>
<td>2.57</td>
<td>10.2</td>
<td>16</td>
<td>1,300</td>
<td>8,900</td>
</tr>
<tr>
<td>P28</td>
<td>2.75</td>
<td>11.5</td>
<td>16</td>
<td>1,460</td>
<td>10,300</td>
</tr>
<tr>
<td>P29</td>
<td>2.90</td>
<td>12.4</td>
<td>14</td>
<td>1,470</td>
<td>10,500</td>
</tr>
<tr>
<td>P30</td>
<td>3.08</td>
<td>14.8</td>
<td>16</td>
<td>1,820</td>
<td>13,000</td>
</tr>
<tr>
<td>P33</td>
<td>3.30</td>
<td>17.8</td>
<td>16</td>
<td>2,100</td>
<td>14,900</td>
</tr>
<tr>
<td>P35</td>
<td>3.45</td>
<td>18.8</td>
<td>16</td>
<td>2,340</td>
<td>16,900</td>
</tr>
<tr>
<td>P36</td>
<td>3.60</td>
<td>20.5</td>
<td>16</td>
<td>2,510</td>
<td>17,100</td>
</tr>
<tr>
<td>P40</td>
<td>4.05</td>
<td>26.3</td>
<td>13.5</td>
<td>2,850</td>
<td>20,000</td>
</tr>
<tr>
<td>P45</td>
<td>4.50</td>
<td>33.0</td>
<td>13.5</td>
<td>3,696</td>
<td>22,440</td>
</tr>
<tr>
<td>P50</td>
<td>5.00</td>
<td>42.0</td>
<td>13.5</td>
<td>4,704</td>
<td>28,560</td>
</tr>
<tr>
<td>P62</td>
<td>6.20</td>
<td>60.8</td>
<td>13.0</td>
<td>6,400</td>
<td>45,000</td>
</tr>
<tr>
<td>P70</td>
<td>7.00</td>
<td>75.4</td>
<td>10.0</td>
<td>9,072</td>
<td>55,080</td>
</tr>
<tr>
<td>P77</td>
<td>7.75</td>
<td>96.0</td>
<td>10.0</td>
<td>10,000</td>
<td>70,000</td>
</tr>
<tr>
<td>P115</td>
<td>11.50</td>
<td>225.0</td>
<td>3.0</td>
<td>--</td>
<td>155,000</td>
</tr>
<tr>
<td>P160</td>
<td>16.00</td>
<td>444.0</td>
<td>4-6m</td>
<td>--</td>
<td>296,000</td>
</tr>
</tbody>
</table>

3.3 Properties of Polystal

A comparison of mechanical properties for reinforcing and prestressing steel to POLYSTAL is listed in Table 12. Composites have various grades of strength available depending on their volume fraction and fibre type. For future reference, the reader should be careful not to confuse composite properties with fibre properties and ensure equal dimensioned test specimens are used to compare mechanical properties. Initially, the low modulus of composites was considered a
disadvantage to cable bolt performance, but the extensive test work presented in this thesis has proven the overall modulus of a cable bolt system is primarily dependent on bond strength. However, in view of the fact that POLYSTAL does not have a yield strength, the bond strength must be low enough to allow for residual frictional strength to develop. Residual strength is critical when maintaining mining operations in cable bolted areas.

Table 12. Typical Mechanical Properties for Rebar, Steel Strand and POLYSTAL (Preis, 1986)

<table>
<thead>
<tr>
<th>Property</th>
<th>Reinforcing Steel BST 420 S</th>
<th>Prestressing Steel ST 1470/1670</th>
<th>POLYSTAL (68% Glass-fibres)</th>
<th>E-glass Fibre</th>
<th>Unstaturated Polyester Resin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Strength (MPa)</td>
<td>500</td>
<td>1670</td>
<td>1520</td>
<td>2300</td>
<td>75</td>
</tr>
<tr>
<td>Yield Strength (MPa)</td>
<td>420</td>
<td>1470</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Strain, ε (%)</td>
<td>10</td>
<td>6</td>
<td>3.3</td>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Elastic Modulus (GPa)</td>
<td>210</td>
<td>210</td>
<td>51</td>
<td>74</td>
<td>0.3</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>7.85</td>
<td>7.85</td>
<td>2.0</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

One of the decisive properties for the selection of a rock support member is tensile strength. Polystal compares favourably with prestressing steel in terms of tensile strength, however, there are considerable differences in their stress-strain behaviours. A typical POLYSTAL stress-strain curve as compared to steel is illustrated in Figure 9. The tensile strength of POLYSTAL is nearly equivalent to that of prestressing steel. Steel typically has a stiffer linear elastic behaviour than POLYSTAL. Steel exhibits plastic deformation to failure whereas POLYSTAL is completely elastic to failure. The absence of yield strength in composites must be considered during design since no warning of failure is realised. The elongation at failure for POLYSTAL is approximately one half that of steel, but its' elastic elongation and recovery is as much as 3 times greater than steel. This is illustrated by Figure 10 which is an example of identical loading and unloading of two prestressed concrete beams, one reinforced with POLYSTAL and the other with prestressing steel.

Fatigue tests on POLYSTAL reinforced beams have proven its' superior elastic recovery.
over steel in concrete reinforcing applications. This benefit would also be realised in the FCB.

POLYSTAL's *elastic modulus* is about one fourth that of prestressing steel which was considered a disadvantage prior to the laboratory pull-tests, but it was discovered that reinforcement modulus was less important to the overall modulus of the FCB than bond strength.

POLYSTAL's *specific weight* is also one quarter that of steel and could potentially save on installation, handling and freight charges.

![Stress Strain Curves for Polystal and Steel (Preis, 1986)](image)

**Figure 9. Stress Strain Curves for Polystal and Steel (Preis, 1986)**
Creep is a function of time, fibre content and temperature. POLYSTAL alone will creep 2-3% of the initial elastic elongation over a period of 60 years. Creep of the bond strength between POLYSTAL and Portland cement is vital to FCB design. It is expected that laced, polyamide coated FCB's will creep less than conventional SCB due to their higher bond strength. On the other hand, creep could be beneficial to support where yielding is required.
3.4 Costs

The current cost (F.O.B. Vancouver) of a laced FCB, where the POLYSTAL is imported from Germany in small quantities and the secondary lacing fabrication is completed by hand, would be approximately $10-11 per metre (Figure 11). This cost could be reduced significantly if commercial quantities were manufactured in Canada. Import and overseas freight charges which account for 16% of the overall cost would be eliminated.

![Cost Breakdown for the FCB in 1991 Dollars - FOB Vancouver, Canada](image)

Based on total FCB cost per metre = $10.33 (1991)

Figure 11. Cost Breakdown for the FCB in 1991 Dollars - FOB Vancouver, Canada (Con-Tech, 1991)

Currently, the total cost of constituent materials (glass fibre and resin) in Canada are in the order of $5 CAN per kilogram. Large-scale production costs are more difficult to estimate than raw material costs. Consultations with the manufacturer of POLYSTAL, BAYER, have revealed the potential cost of a FCB could be equivalent to the cost of a conventional SCB. Conventional
and birdcaged SCB's cost $2.15 and $3.00 to $3.25 per metre respectively. Considering the improved bond strength and other unique properties such as corrosion resistance and light weight of FCB's, a reduction in the overall support cost as compared to SCB's could also be realised. As a result, raw material costs were investigated further.

An exercise was completed to analyse the raw material cost of POLYSTAL versus its' selling price of $2.56 per metre. The approximate cost for the polyester resin used in POLYSTAL construction profiles is $3.00/kg. The cost of E-glass fibre is approximately $2/kg. The mass of a 7.5 mm diameter uncoated POLYSTAL rod with a glass content of 80% by weight as measured in the laboratory was approximately 75 grams. On a raw material basis then, it costs approximately $0.21 per metre of 7.5 mm diameter, uncoated POLYSTAL. The thermoplastic coating would cost in the order of $0.18 per metre. Therefore, the raw material cost of POLYSTAL per metre has been estimated as $0.39 per metre. This amounts to a staggering 640% margin over the raw material cost (excluding all other manufacturing, production and marketing costs). From this analysis, it is obvious there is great potential for the development of an economically competitive FCB.

4. FAILURE MODES AND BOND STRENGTH MECHANISMS

4.1 Introduction

Understanding common cable bolt failure modes under pull-out loads is essential to properly installed and designed systems. SCB failure mode theory has been applied to develop the FCB. Laboratory and in situ pull-tests were conducted to evaluate the FCB.

As with most materials under load, the FCB will exhibit time dependent behaviour. The strength of a FCB can be determined by short-term or long-term tests and, depending on the application, either may be necessary for design. This investigation concentrates on evaluating the short-term strength of the FCB. For example, the laboratory pull-tests conducted at UBC
determined short-term strength values since the cure times were low and the strain rate relatively high (15 mm/min). Such tests are directly applicable to the design of stopes where support is only required for a few months to a year. An example of a long-term test might cover a period of a number of years, and usually reveals such properties as creep, corrosion and fatigue resistance. Creep can be of particular interest in permanent hangingwall installations and is defined here as the gradual deformation under static load below the ultimate short-term capacity of the support. Although this investigation has quantified short-term FCB capacities; a qualitative assessment of the long-term capacity has been conducted using trial installations (Section 8). Other failure modes considered important to the strength of a FCB, but not investigated were stress corrosion and notch sensitivity. POLYSTAL's protective coating has been developed to resist these failure modes. The coating also helps to reduce inter laminar failure between fibre and resin. The coating was observed to delaminate from the tendon under high pull-out loads where the inter-tendon angle was extreme.

4.2 Driving Forces

Typically, underground excavations are dominated by: Case (1) tension, Case (2) shear and Case 3) dynamic driving forces. It is possible that at any one time during the history of a mine's life, a cable bolt system could experience a combination of driving forces. In Canadian hardrock mining, the most common failure mode occurs along the grout/tendon interface (Vancouver, 1991). The developments presented in this thesis have concentrated on bond strength improvements to the FCB.

To improve the bond strength of the FCB, various configurations were tested. Each configuration was carefully selected to exploit three main resistance mechanisms which affect bond strength: surface asperities, tendon configuration and surface area. The selection of node spacing, spacer diameter and turns per metre were crucial to the prevention of premature tendon failure or surface coating delamination.
For Case (2) driving forces, a [±45] bidirectional tendon has been recommended for evaluation. Some preliminary laboratory shear tests have been conducted at the University of British Columbia to ascertain the potential of the FCB.

Case (3) driving forces are often observed during blasts, stress relief or rockbursts. In general, the performance of cable bolts under these conditions is less understood. The application of the FCB in Case (2) and (3) driving force applications require further evaluation and trial installations.

4.3 Pull-Test Resistance Mechanisms

The following five mechanisms were varied to improve the bond strength of the FCB under pull-test conditions:

- surface area (S.A.)
- surface roughness (S_r)
- adhesive bond (A.B.)
- tendon geometry (ϕ)
- number of turns per metre (T)

The unlaced configuration utilised the first three mechanisms. The laced FCB provided pull-out resistance by utilising all five mechanisms. An explanation for each mechanism has been listed below:

- **S.A.:** An exercise was completed where a total cross-sectional area of 176.71 mm² was kept constant (four unit lengths of 7.5 mm diameter POLYSTAL tendons) while tendon diameter and number (n) were varied and related to surface area (Figure 12). It was found for circular profiles, surface area increases exponentially as tendon diameter
decreases and "n" increases. Since bond strength is directly related to surface area, it follows that bond strength should increase exponentially as tendon diameter decreases and "n" decreases. The majority of the effort to develop composites for mining should concentrate on taking advantage of this factor.

Figure 12. Surface Area vs Tendon Diameter

- $S_r$: Bond strength increases as the tendon roughness, or microscopic interlock, increases (coating thicknesses varied between 0.5 and 1.0 mm for POLYSTAL, therefore ultimate
tendon diameters varied between 8.0 and 9.5 mm). Uncoated POLYSTAL has a smooth surface profile except for a single layer of helically wrapped fibres which adds to its overall mechanical interlock with the grout.

- *A.B.:* The adhesion between the cement and the polyamide coating can be divided into four components: microscopic mechanical interlock, adsorption theory, electrostatic theory and chemical bonding. According to the manufacture, BAYER, the polyamide coating was selected to improve the cement adhesion.

- The inter-tendon angle, $\phi$, has been defined as the angle in degrees at the antinode between any two tendons directly opposite one another. The introduction of the inter-tendon angle reduces interfacial shear and improves the mechanical interlock between tendon and grout. **Figure 13** is a free-body diagram that illustrates the effect of lacing on the bond strength of the FCB. It is believed straight tendon configurations tended to have higher interfacial shear forces between the tendon and grout and lower normal forces acting on the tendon. This might explain the lower bond strengths experienced with straight tendon configurations. However, by introducing an inter-tendon angle it was found premature tendon failure occurred at the critical bond length. Therefore, a compromise between ultimate capacity and premature tendon failure was sought.
The most favourable laced FCB possessed approximately 1 turn per metre for tendons separated 11 mm at the node and a node spacing of 127 mm. Practically, as the spacer diameter increased, so did the number of turns per metre.

### 4.4 FCB Failure Mode Categories

During the evaluation of the FCB, a number of failure modes were observed and categorised according to the driving force and environment (Table 13).
Table 13. Summary of Observed FCB Failure Modes

<table>
<thead>
<tr>
<th>MODE CLASS</th>
<th>DRIVING FORCE</th>
<th>ENVIRONMENT TESTED</th>
<th>OBSERVATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>pull-test</td>
<td>laboratory</td>
<td>pipe/grout</td>
</tr>
<tr>
<td>II</td>
<td>pull-test</td>
<td>laboratory in situ</td>
<td>tendon/grout</td>
</tr>
<tr>
<td>III</td>
<td>pull-test</td>
<td>laboratory in situ</td>
<td>tendon</td>
</tr>
<tr>
<td>IV</td>
<td>shear at 90°</td>
<td>laboratory</td>
<td>tendon</td>
</tr>
</tbody>
</table>

Mode I was observed for the laboratory pull-tests and w:c ratios of 0.65 (using Portland Type 30). Goris (1990) states to prevent such failures with Portland Type I/II, water cement ratios of less than or equal to 0.45 must be used.

Mode II was most common for laced FCB's with embedment lengths less than 432 mm and for unlaced FCB's with embedments less than or equal to 914.4 mm.

Mode III, tendon failure, was most common where the critical embedment was reached or exceeded. Tendon failure can vary from single tendon failures with residual strength to failure of all tendons and no residual strength. An example of complete tendon failure can be seen in Photo Plate 1. The failure of the tendon appeared to initiate at the collar of the pipe and propagate towards the resin chuck. For the most part, Mode III was characterised by catastrophic fibre breakage and inter-facial shear between fibre and resin.
Preliminary laboratory tests for failure Mode IV have been completed and require further study. Laboratory shear tests were completed to evaluate a shear load applied 90° to the axis of a FCB (Section 10).

5. UBC LABORATORY PULL-TEST PROGRAM

5.1 Introduction

 Having selected a composite for reinforcement, a prototype for testing was developed. This
was accomplished using four 7.5 millimetre diameter POLYSTAL tendons which gave a total combined ultimate tensile strength of 27.3 tonnes and allowed for more direct comparisons between FCB's and SCB's. As a result, preliminary pull-tests were conducted to ascertain the potential of POLYSTAL for cable bolting. It was found that the FCB could effectively resist pull-test loads in excess of 20 tonnes verifying the selection of POLYSTAL as a potential product for mine support. This was proven with test Series A and later verified at the United States Bureau of Mines, Spokane with test Series FG18-7 to 11. Series A consisted of 6 laced samples with the following design parameters:

- Four 7.5 mm diameter POLYSTAL tendons.
- 203 mm (8 inch) node spacing.
- \( w:c \) ratio of 0.35.
- Portland Type 30 cement.
- 58 mm (2.3 inch) diameter Schedule 80 pipe.
- Displacement rate of 15 mm per minute.

Series A was the first successful test over 20 tonnes and indicated an effective FCB could be developed with POLYSTAL. Once this series was completed, plans were established to optimise the configuration with available POLYSTAL materials. Table 14 summarises the ultimate pull-out load for Test Series A.
Table 14. Summary of Ultimate Pull-out Loads for Test Series A

<table>
<thead>
<tr>
<th>TEST NUMBER</th>
<th>ULTIMATE PULL-OUT LOAD, TONNES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.32</td>
</tr>
<tr>
<td>2</td>
<td>20.65</td>
</tr>
<tr>
<td>3</td>
<td>20.11</td>
</tr>
<tr>
<td>4</td>
<td>19.61</td>
</tr>
<tr>
<td>5</td>
<td>20.71</td>
</tr>
<tr>
<td>6</td>
<td>20.58</td>
</tr>
<tr>
<td>AVERAGE</td>
<td>20.33</td>
</tr>
</tbody>
</table>

During the preliminary testing stages, it was also discovered, as a rule of thumb, the embedment length should be at least two times the node spacing before a significant bond strength increase over straight FCB's configurations could be achieved. Under these conditions, the tendon failure mode predominated which indicated a relationship between critical embedment length and tendon configuration.

The laboratory tests performed evaluated the effect of the following design parameters on the ultimate pull-out load of a FCB:

- Embedment length
- Water:cement ratio
- Cure time
- Confinement
- Node spacing

The most significant factors as determined using fractional factorial design experiments and with high early strength cement were: embedment length, water:cement ratio and node spacing/location. It was observed that higher pull-out loads corresponded with samples where the antinode was located at the simulated joint plane. It was also recognized that increasing the
surface area (e.g. increase the number of tendons while decreasing the tendon diameter) and roughness (e.g. presence of a silicon grit coating) would greatly enhance the bond strength. Goris, 1990, has determined that silicon coatings increase conventional SCB bond strength by 30%. These changes were beyond the scope of the investigation. Control of tendon fabrication was not available to vary the FCB profile diameter and roughness for optimal bond strength.

Although the factors affecting the pull-out characteristics for SCB's are well documented, such data did not exist for FCB's. Having proven the axial potential of POLYSTAL for cable bolting, one of the next goals of the pull-tests at UBC was to determine the most significant bond strength mechanisms for the FCB.

5.2 Objectives

The objectives of the UBC pull-test program have been summarised below:

1. Develop a prototype and acceptable test procedure for pull-testing.
2. Determine significant parameters using design experimentation to guide further testing.
3. Determine critical embedment length curves for laced and unlaced polyamide coated POLYSTAL grouted in Portland Type 30 cement with a w:c ratio of 0.35 and 7 day cure time (Failure Mode III).
4. Evaluate premature tendon failure.

5.3 Apparatus

The pull-test apparatus consisted of a shaft-mounted load cell, 30 tonne ram and strand chuck housing. The ram was driven by an electric motor (not shown) while the feed was controlled by a needle valve. An average displacement rate of approximately 15 mm/min was maintained. The 50 tonne load cell (± 1.0 kg) and LVDT (linear voltage difference transducer, ± 0.01 mm) were
connected to separate digital readouts. The test samples were inserted strand chuck first, locking screw tightened and the slack taken up by the threaded shaft so that the embedded portion of the sample rested against the apparatus frame (Figure 14).

![UBC Pull-Test Apparatus and Sample](image)

**Figure 14. UBC Pull-Test Apparatus and Sample**

### 5.4 Sample Preparation

All pull-test samples were cured at room temperature and humidity. Grout/pipe slippage was observed for all samples with a 0.65 w:c ratio and 77 mm pipe diameter (FFD-I runs 5,8,13 and
Two spot welds were placed on the inside of the pipe to prevent grout/pipe slippage. The rest of the UBC test samples did not exhibit grout/pipe slippage. All samples exhibited micro-shrinkage cracks which were considered detrimental to the pull-out resistance. Goris states that water to Portland Type I/II cement ratios less than or equal to 0.40 are required to prevent significant amounts of shrinkage in "fully cured" (28 days) samples. UBC samples with water to Portland Type 30 cement ratios greater than 0.45 did not have grout/pipe slip after 7 days of curing. This was likely due to the use of the high early strength cement. It was also visually observed during hand mixing that the cement grout consistency was difficult to maintain below a 0.35 w:c ratio for Portland Type 30 cement. The pull-test samples were cut open longitudinally to observe the grout consistency and failure mode.

In order to achieve as consistent results as possible, strict sample preparation steps were followed:

**Sample preparation:**

**Stage A. Resin Stage (Figure 15)**

1. Cut tendons to desired length.
2. Peel polyamide coating off to a length of 96 mm.
3. Force a 7 mm i.d. vinyl tube centralizer over peeled end.
4. Cut cross-hatch in peeled end of the POLYSTAL to a depth of 20 mm.
5. Insert aluminum, or similar type, wedge.
6. Combine tendons, four at a time, into desired configuration using PVC spacers.
7. Resin peeled ends into strand chuck using G2 unsaturated polyester resin (2A:1B, Industrial Formulators Vancouver, B. C.) ensuring the lock nut is between lacing and strand chuck.
8. Allow to cure overnight prior to Stage B.
Stage B. Grouting Stage

1. Cut pipe to desired embedment length plus 50 mm.

2. Wash pipe with soap and water, rinse and dry.
3. Hand mix cement at the desired w:c ratio.
4. Place pipe in stand, centre over plastic covered hole.
5. Fill pipe with cement to approximately 100 mm from top.
6. Insert bolt into grouted column and push through plastic covered hole.
7. Visually align sample.
8. Use clay to plug the hole from beneath.
9. Top off or remove excess cement from column.
10. Place wet rag on top of cement.

5.5 Test Procedures

On the average, six samples could be tested per day. This resulted in an average cure time difference between the first and last sample of approximately 9 hours. The test procedures were as follows:

1. Clean resin chuck and pipe surfaces thoroughly.
2. Insert sample into test apparatus and tighten lock nut.
3. Arrange LVDT telescopic arm with respect to ram stroke.
4. Apply initial load of approximately 451 N (or 46 kg mass).
5. Attach dial gauge at tail end of sample.
6. Record initial load and displacement.
7. Turn hydraulic pump on and tap the needle valve lightly to open and adjust so that the displacement rate was approximately 15 mm/min.
8. Record load at 1 mm intervals.
9. Run test for 20-30 minutes unless tendon failure occurs.
10. Remove sample and clean machine.
5.6 Design Experiments

Design experiments are of significant value for (1) exploratory work where the individual and joint influence of several variables must be determined quickly and (2) experimental programs to obtain empirical models over a range of operating or testing conditions. As a rule, the design results should not be extended beyond the test conditions or range of factor levels unless significant calibration data is available (Mular, 1989).

Design experimentation was used as a tool to assist in determining the effect and significance of design parameters in the development of the FCB. The design experimentation results provided research direction and streamlined test-work.

5.6.2 Terminology

Before continuing, the following terminology has been explained:

- A factor refers to a controllable, test variable which can be set at predetermined values for each test. Factors are generally quantitative.
- A level is the value at which a factor is set for a particular run. High and low level factors are coded with positive (+) and negative (-) signs respectively. Centre point levels are coded by a zero (0).
- Runs are experimental tests where the factors are set at design levels.
- A response is a numerical test result, such as pull-out load or displacement. The responses are used to determine the "effect" of each factor on the response.
- An effect is defined as the overall average change in response produced by an increase from a low to a high level of that factor.
- A mean effect is the average of all responses.
- A main effect is the difference between the average response of all runs carried out at the
higher level of the factor and that of all the runs at the lower level.

- **An interaction effect** between two factors $x_1$ and $x_2$ is the average difference between the effect of an increase in level of $x_1$ at the higher level of $x_2$ and the effect of an increase in level of $x_1$ at the lower level of $x_2$.

- **Resolution.** A design of resolution $R$ is one in which no $q$-factor effect is confounded with any other effect containing less than $R - q$ factors.

- **Confounded.** In a fractional factorial design, where not all the required runs are tested, the estimated effect, $L_{ijk}$ can represent more than one effect of the complete factorial design, $l_{ijk}$. It is then said that the estimated effects of a fractional factorial design are confounded.

- **An alias structure** is a list of estimated effects and their confounded partners. The addition signs in the alias structure represent the confounded partners, not the actual addition of effect values. The alias structure is used as a guide for determining an effect from its confounded partners.

Hence, a factorial design varies the level of a number of factors and completes a run for each variation. The selection of an appropriate alias structure must be guided by the objective of the experiment. In this case, the main effects were sought with the lowest number of acceptable runs. It is sometimes necessary to replicate a design to improve confidence.

Once all runs of a design are complete, the main and interaction effects of all factors are determined. In other words, the statistical significance of each factor is found and assessed. From this process, a predictive equation is generated using the least squares method.

### 5.6.2 Two Level Fractional Factorial Design Basics

This design procedure is one of the simplest and leads to an estimated linear relationship between responses and factors. Usually under the range tested, a linear equation sufficiently approximates the true response:
where the $y_i$'s are the estimated response, $a_i$'s are the constant coefficients determined by the least squares fit method, $x_i$'s are the factors, $n$ equals the number of experimental factors to be assessed and $e_i$'s are the residual error associated with each estimated response. All the possible combinations of high and low levels of the chosen factors are tested in a complete factorial design. Clearly, in order to test all the possible combinations of factor levels for FFD-I, $2^7 = 128$ runs were necessary. It was decided a fraction of the complete factorial design, FFD-I, would be completed. As a result, the number of significant factors was reduced to three and more time was spent evaluating their effect on the pull-out of the FCB.

The rules for FFD's and factorial designs are basically the same. We denote the number of runs in a two level FFD as, $2^n - P$, where "$n$" is the total number of factors and "$P$" represents the number of half-fractions of a complete factorial design desired. For example, a $2^{7-3}$ FFD completes three half-fractions, or one-eighth, of the total number of the possible outcomes of a complete, $2^7$ factorial design. The primary reason for selecting the $2^{7-3}$ FFD of RJV was that for as few as 20-24 runs, the main effects were not confounded with one another and therefore could be estimated with a fair degree of confidence. Since the two-factor effects were confounded for FFD-I, certain ambiguities arose when deciding which estimated two-factor effect was represented within the alias structure. Three factor interaction effects were assumed negligible. This simplified the statistical analysis and was considered the most likely approach to successfully conclude the main effects using a limited number of runs. A summary of the steps taken to construct the FFD-I were as follows:

1. Select: a high, low and centre point level for each factor.
2. Determine total number of economical runs = $2^n - P + ($centre point runs$)$.
3. Code variables using $x_i = +$ (for hi) or $-$ (for low).
4. Construct design matrix of coded levels using $2^n-p$ rows, in standard order where + and - signs are alternated along $x_i$ column using the $2^{j-1}$ rule.

5. Construct matrix of effects in coded units.

6. Calculate effects.

7. Perform tests of significance on each effect.

8. Eliminate insignificant effects.

9. Calculate coefficients for significant effects.

10. Obtain predictive equation in coded units.

11. Obtain predictive equation in real units.

12. Check the fit of the linear predictive equation.

5.6.3 Fractional Factorial Design I (FFD-I) Results

The levels of each factor were determined from operating ranges of steel cable supports and can be found in Table 15.

<table>
<thead>
<tr>
<th>FACTOR</th>
<th>LOW LEVEL</th>
<th>CENTRE POINT</th>
<th>HIGH LEVEL</th>
<th>RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$ (min.) mix time</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>$V_2$ (mm) emb. length</td>
<td>152</td>
<td>305</td>
<td>457</td>
<td>305</td>
</tr>
<tr>
<td>$V_3$ (mm) pipe diam.</td>
<td>48</td>
<td>58</td>
<td>77</td>
<td>29</td>
</tr>
<tr>
<td>$V_4$ (days) cure time</td>
<td>2</td>
<td>6</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>$V_5$ w:c ratio</td>
<td>0.35</td>
<td>0.5</td>
<td>0.65</td>
<td>0.3</td>
</tr>
<tr>
<td>$V_6$ (mm) spacer diam</td>
<td>20</td>
<td>23</td>
<td>26</td>
<td>6</td>
</tr>
<tr>
<td>$V_7$ (mm) node spacing</td>
<td>0</td>
<td>305</td>
<td>610</td>
<td>610</td>
</tr>
</tbody>
</table>
The variables, \( x_i \), were coded by inserting the values of Table 15 into the following equation:

\[
x_i = \frac{V_i - \text{centrept}}{0.5 \times \text{range}}
\]

where \( V_i \) equalled the actual low or high value of a factor. This resulted in \( x_i \)'s being coded as either +1 or -1 respectively.

All factor levels for the centre point runs were coded as 0. Runs 17 to 23 were also referred to as Series I. The seven factors, coded \( X_i = 1 \to 7 \), are defined below:

- \( x_1 \) Mix time - the hand-mixing time in minutes from the moment the water was added to the first pouring of a sample.
- \( x_2 \) Embedment length - distance in millimetres from one end of the grout column to the other.
- \( x_3 \) Pipe diameter - the inner pipe diameter in millimetres of a Schedule 80 steel pipe.
- \( x_4 \) Cure time - the number of days the cement was allowed to cure.
- \( x_5 \) w:c ratio - the dimensionless ratio of the weight of water to the weight of cement.
- \( x_6 \) Spacer diameter - the inner diameter of a PVC spacer that determines the inter-tendon angle, \( \phi \).
- \( x_7 \) Node spacing - the distance in millimetres between any two successive nodes or antinodes.

There were a total of 23 total runs, 7 of which were externally tested centre point runs used to determine the error variance, \( S_e^2 = 0.846 \).

The matrix of coded levels, measured responses, \( Y_{\text{est}} \) from the predictive equation and associated residual errors for FFD I are found in Table 16. The predictive equation developed
by FFD-I reasonably approximated actual test results. Each residual error value was plotted versus its associated predicted response in order to check the adequacy of the fitted model (Figure 16). From this figure, two general trends were apparent:

- The predictive equation over-estimated pull-out loads less than 5 tonnes or greater than 15 tonnes.
- The predictive equation under-estimated pull-out loads between 5 and 15 tonnes.

Figure 16. Plot of Residuals vs Predicted Pull-out
Table 16. Matrix of Coded Levels, Responses, Estimated Responses and Residual Errors  
FFD-I

<table>
<thead>
<tr>
<th>Run No.</th>
<th>mix x₁</th>
<th>emb x₂</th>
<th>pipe x₃</th>
<th>cure x₄</th>
<th>w:c x₅</th>
<th>spacer x₆</th>
<th>node x₇</th>
<th>Y_measured tonnes</th>
<th>Y_estimate tonnes</th>
<th>e tonnes</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.80</td>
<td>7.75</td>
<td>-0.45</td>
</tr>
<tr>
<td>2</td>
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<td>-</td>
<td>-</td>
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<td>+</td>
<td>3.74</td>
<td>3.99</td>
<td>-0.25</td>
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<td>3</td>
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<td>+</td>
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<td>+</td>
<td>+</td>
<td>+</td>
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<td>-1.85</td>
</tr>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
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<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>5.04</td>
<td>1.74</td>
<td>3.30</td>
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<td>-</td>
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<td>+</td>
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<td>-</td>
<td>+</td>
<td>-</td>
<td>16.71</td>
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<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
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<tr>
<td>9</td>
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<td>-</td>
<td>+</td>
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<td>+</td>
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<td>+</td>
<td>5.04</td>
<td>7.00</td>
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<td>2.00</td>
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<td>+</td>
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<td>-</td>
<td>-</td>
<td>5.53</td>
<td>7.42</td>
<td>-1.89</td>
</tr>
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<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
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<td>+</td>
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<td>+</td>
<td>+</td>
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<td>+</td>
<td>15.92</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10.50</td>
<td>10.42</td>
<td>0.08</td>
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<tr>
<td>18</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>12.76</td>
<td>10.42</td>
<td>2.34</td>
</tr>
<tr>
<td>19</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>11.21</td>
<td>10.42</td>
<td>0.79</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>21</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>10.14</td>
<td>10.42</td>
<td>-0.28</td>
</tr>
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<td>0</td>
<td>10.23</td>
<td>10.42</td>
<td>-0.19</td>
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<td>23</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>11.23</td>
<td>10.42</td>
<td>0.81</td>
</tr>
</tbody>
</table>

For this particular FFD there were p=3 principle generators which were calculated by  
multiplying x₅ by itself to yield x₅x₅ = I = x₁x₂x₃x₅, x₆ by itself to yield x₆x₆ = I = x₂x₃x₄x₆,  
and x₇ by itself to yield x₇x₇ = I = x₁x₂x₄x₇. The principle generators were multiplied by each  
other two and three at a time to yield a complete defining relation:

\[ I = x₁x₂x₃x₅ = x₂x₃x₄x₆ = x₁x₂x₄x₇ = x₃x₄x₅x₇ = x₁x₄x₅x₆ = x₁x₃x₆x₇ = x₂x₅x₆x₇ \]
From the complete defining relation, the alias structure was constructed by multiplying the factor(s) involved in the effect times each term of the defining relation noting any factor times itself equals one (Table 17). For example, \( L_1 \) was calculated by multiplying \( x_1 \) by each term in the complete defining relation to give:

\[
L_1 = l_1 + l_{235} + l_{247} + l_{456} + l_{367} + l_{12346} + l_{13457} + l_{12567}
\]

Since by definition, a \( 2^{7-3} \) FFD assumes all third and fourth order effects negligible, \( L_1 \) simply estimates \( l_1 \). In a similar manner, the remaining alias structure was calculated. A complete factorial design has \( n=7 \) main effects, \( n(n-1)/2!=21 \) two factor effects, \( n(n-1)(n-2)/3! \) three factor effects and so on. For FFD-I, seven main effects, seven two factor effects and only one three factor effect could be estimated. Judgement was used to interpret which confounded two factor effect, \( l_{ij} \) was estimated by \( L_{ij} \). The mean, main and three factor effects were straightforward representations. Figure 17 illustrates the configurations tested.

**Table 17. Alias Structure, FFD-I**

\[
\begin{align*}
L_1 & = l_1 \\
L_2 & = l_2 \\
L_3 & = l_3 \\
L_4 & = l_4 + (\text{higher order effects assumed negligible}) \\
L_5 & = l_5 \\
L_6 & = l_6 \\
L_7 & = l_7 \\
L_{12} & = l_{12} + l_{35} + l_{47} \\
L_{23} & = l_{23} + l_{46} + l_{15} \\
L_{34} & = l_{34} + l_{26} + l_{57} \\
L_{45} & = l_{45} + l_{16} + l_{37} + (\text{higher order effects}) \\
L_{56} & = l_{56} + l_{14} + l_{27} \\
L_{67} & = l_{67} + l_{13} + l_{25} \\
L_{17} & = l_{17} + l_{24} + l_{36} \\
L_{123} & = l_{123} + l_5 + (\text{higher order effects})
\end{align*}
\]
The centre point runs were external (completed separate from) to FFD-I and as a result were not included in the calculation of the mean, main, two-factor and three factor effects. The standard equations used to calculate the effects are contained in Appendix A. A summary of the estimated effects, their ranks and normal scores is listed in Table 18.

Figure 17. FCB Configurations - FFD-I
Table 18. Estimated Effects and Normal Scores

<table>
<thead>
<tr>
<th>Effect</th>
<th>Effect Magnitude</th>
<th>Rank, i</th>
<th>( \pi = (i - 0.5)/m )</th>
<th>Normal Scores ( z_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_5 )</td>
<td>-3.14</td>
<td>1.5</td>
<td>0.07</td>
<td>-1.48</td>
</tr>
<tr>
<td>( L_{123} )</td>
<td>-3.41</td>
<td>1.5</td>
<td>0.07</td>
<td>-1.48</td>
</tr>
<tr>
<td>( L_{23} )</td>
<td>-2.99</td>
<td>3</td>
<td>0.17</td>
<td>-0.96</td>
</tr>
<tr>
<td>( L_{34} )</td>
<td>-2.04</td>
<td>4</td>
<td>0.23</td>
<td>-0.74</td>
</tr>
<tr>
<td>( L_3 )</td>
<td>-1.30</td>
<td>5</td>
<td>0.30</td>
<td>-0.53</td>
</tr>
<tr>
<td>( L_{67} )</td>
<td>-0.87</td>
<td>6</td>
<td>0.37</td>
<td>-0.40</td>
</tr>
<tr>
<td>( L_6 )</td>
<td>-0.63</td>
<td>7</td>
<td>0.43</td>
<td>-0.18</td>
</tr>
<tr>
<td>( L_4 )</td>
<td>-0.12</td>
<td>8</td>
<td>0.50</td>
<td>0</td>
</tr>
<tr>
<td>( L_{56} )</td>
<td>0.46</td>
<td>9</td>
<td>0.57</td>
<td>0.18</td>
</tr>
<tr>
<td>( L_{17} )</td>
<td>1.02</td>
<td>10</td>
<td>0.63</td>
<td>0.33</td>
</tr>
<tr>
<td>( L_7 )</td>
<td>1.45</td>
<td>11</td>
<td>0.70</td>
<td>0.53</td>
</tr>
<tr>
<td>( L_1 )</td>
<td>2.25</td>
<td>12</td>
<td>0.77</td>
<td>0.74</td>
</tr>
<tr>
<td>( L_{12} )</td>
<td>2.37</td>
<td>13</td>
<td>0.83</td>
<td>0.96</td>
</tr>
<tr>
<td>( L_{45} )</td>
<td>2.99</td>
<td>14</td>
<td>0.90</td>
<td>1.28</td>
</tr>
<tr>
<td>( L_2 )</td>
<td>8.65</td>
<td>15</td>
<td>0.97</td>
<td>1.89</td>
</tr>
</tbody>
</table>

Note:
- \( m \) = total number of estimated effects excluding \( L_0 \)
- \( z_i \) : \( P(Z \leq z_i) = P_i = \Phi(z_i) \) for probabilities \( \geq 0.50 \) OR
  \[ = \Phi(-(z_i)) \] for probabilities \( < 0.50 \)
- \( i \) : if effect magnitudes were tied, an average rank was assigned.

Figure 18 plots the normal scores versus the value of each estimated effect in order to determine significant effects. From this graph, three significant main effects were found: mix time (\( L_1 \)), embedment length (\( L_2 \)), w:c ratio (\( L_5 \)) and one significant two-factor interaction effect between cure time and w:c ratio, \( L_{45} \). The coefficients for the predictive equation were determined from the significant effects and the coded units were transformed back to real units to give the following relationship:

\[ Y_{est} = 12.7 + 0.226*V_1 + 0.0284*V_2 - 26.4*V_5 + 2.5*V_4*V_5 - 1.25*V_5 \text{ (tonnes)} \]

where \( V_1 \) was mix time in minutes, \( V_2 \) was embedment length in millimetres, \( V_4 \) was cure time.
in days and $V_5$ was w:c ratio.

![Graph](image)

Figure 18. Normal Scores vs Estimated Effect Values - FFD-I

A summary of the conclusions drawn from FFD-I is listed below:

- An increase in embedment length from 152 mm to 457 mm increased pull-out load significantly. However, critical embedment lengths were not determined.
- A decrease in water cement ratio from 0.65 to 0.35 increased pull-out load significantly.
- A cure time increase from 2 to 10 days did not significantly increase pull-out load for Portland Type III cement (high early strength).
- An increase in pipe diameter from 48 mm to 77 mm did not significantly increase pull-out
load. This corresponds to tests with conventional steel cables (Milne 1988-90).

- An increase in node spacing above 305 mm did not significantly increase pull-out load.
- An increase in mix time increases pull-out load.
- The effects of node spacing and spacer diameter required further investigation.
- The effects of increasing or decreasing the factors tested in FFD-I are similar to steel cable bolts (Goris, 1990).

The pull-test curves for FFD-I are contained in Appendix B. For all runs, the FCB slipped with respect to the grout.

5.7 Embedment Length Relationships

5.7.1 Introduction

Critical embedment length has been defined as the embedment length of a pull-test sample required to cause tendon failure. Comparisons of laced POLYSTAL, straight POLYSTAL, conventional steel strand and birdcaged steel strand have been made. The critical embedment length is particularly important to cable bolt designs in highly fractured ground.

5.7.2 Codes and Variables

The ultimate pull-out loads resulting in tendon failure of Series A, Series II to IV and those conducted by Peterson, 1991 were combined to form the critical embedment length relationships presented here (Table 19). All samples were tested under the following conditions:

1. Cement was hand-mixed for 15 minutes.
2. Grouted in a 58 mm pipe diameter.
3. Cured 7 days at a 0.35 w:c ratio.
(4) Spacer inside diameter equal to 11 mm for 127 mm node spacings or 20 mm otherwise.

(5) Portland Type 30 cement.

Table 19. Series A & Series II-IV Design Parameters and Ultimate Load

<table>
<thead>
<tr>
<th>SERIES - SAMPLE No.</th>
<th>EMBEDMENT LENGTH (mm)</th>
<th>NODE SPACING (mm)</th>
<th>RATIO OF EMBEDMENT TO NODE SPACING</th>
<th>ULTIMATE PULL-OUT LOAD, tonnes</th>
</tr>
</thead>
<tbody>
<tr>
<td>IIIa-1</td>
<td>508</td>
<td>254</td>
<td>2.0</td>
<td>21.32</td>
</tr>
<tr>
<td>IIIa-2</td>
<td>508</td>
<td>254</td>
<td>2.0</td>
<td>21.33</td>
</tr>
<tr>
<td>IIIa-3</td>
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<tr>
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<td>254</td>
<td>2.0</td>
<td>20.00</td>
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<tr>
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<td></td>
<td>20.63</td>
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</tr>
<tr>
<td>IVb-1</td>
<td>432</td>
<td>127</td>
<td>3.4</td>
<td>22.33</td>
</tr>
<tr>
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<td>127</td>
<td>3.4</td>
<td>23.35</td>
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<td>IVb-3*</td>
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<td>127</td>
<td>3.4</td>
<td>22.50</td>
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<td></td>
<td>22.73</td>
<td></td>
</tr>
<tr>
<td>A-1</td>
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</tr>
<tr>
<td>Portland Type I/II - 0.35 w:c ratio, 7 day cure (for comparison)</td>
<td></td>
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<td>FG18-7</td>
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<td>457</td>
<td>203</td>
<td>2.25</td>
<td>21.90</td>
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<td>22.40</td>
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</tr>
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<tr>
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<td></td>
<td>21.75</td>
<td></td>
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Note:
* LVDI slipped off pull-test unit and only load was recorded.
A minimum embedment length to node spacing ratio of 2:1 was necessary to result in tendon failure. Critical embedment lengths ranged from 432 mm to 508 mm for laced FCB's. For comparison, the average ultimate pull-out load of Series FG18 was 7% higher than for Series A despite the differences in cement type.

5.7.3 Pull-Test Curves

Six pull-tests were completed in Series A (Figure 19). The samples had 203 mm node spacings and 457 mm embedment lengths. One (1) to three (3) tendon failures were observed in all the samples. The approximate stiffness of the average Series A pull-test curve was 1 tonne per millimetre of displacement.

![Figure 19. Average Pull-Test Curve for Series A](attachment:figure19.png)
Pull-test curves for Series II to IV are contained in Appendix C. A summary of the results from the critical embedment length investigation are listed in Table 20.

Table 20. Series A & Series II-IV Failure Mode

<table>
<thead>
<tr>
<th>SERIES</th>
<th>EL (mm)</th>
<th>NS (mm)</th>
<th>EL: NS RATIO</th>
<th>Average Ultimate Load (tonnes)</th>
<th>Normalised Load (tonnes/m)</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - coated</td>
<td>457</td>
<td>203</td>
<td>2.25</td>
<td>20.33</td>
<td>44.49</td>
<td>tendon</td>
</tr>
<tr>
<td>II - uncoated</td>
<td>457</td>
<td>203</td>
<td>2.25</td>
<td>10.10</td>
<td>22.10</td>
<td>slip</td>
</tr>
<tr>
<td>IIIa - coated</td>
<td>508</td>
<td>254</td>
<td>2.00</td>
<td>21.05</td>
<td>41.44</td>
<td>tendon</td>
</tr>
<tr>
<td>IIIb - coated</td>
<td>914</td>
<td>254</td>
<td>3.60</td>
<td>19.70</td>
<td>21.55</td>
<td>tendon</td>
</tr>
<tr>
<td>IVa - coated</td>
<td>305</td>
<td>127</td>
<td>2.4</td>
<td>19.34</td>
<td>63.41</td>
<td>slip</td>
</tr>
<tr>
<td>IVb - coated</td>
<td>432</td>
<td>127</td>
<td>3.4</td>
<td>22.72</td>
<td>52.60</td>
<td>tendon</td>
</tr>
</tbody>
</table>

Note:
EL = embedment length.
NS = node spacing.
EL:NS = embedment length to node spacing ratio.
Normalised Load = average ultimate load divided by embedment length, EL.

The uncoated test Series II was dominated by the "slip-stick" failure mode as observed during the pull-test on sample FG18W-6 at the United States Bureau of Mines, Spokane. The Series II sample were cut open longitudinally to investigate this failure mode. It was observed a "skin" containing the helically wrapped fibres had delaminated from the tendon and remained bonded to the cement. As compared to coated tendons, uncoated tendons tend to have lower ultimate strengths and normalised loads.

Coated tendon failure occurred at tested embedment lengths between 432 mm and 914 mm. Ultimate loads were greater than 19 tonnes for all the series where tendon failure occurred.
Normalised load, defined as the average ultimate load divided by the embedment length ranged from 21.55 tonnes to 52.60 tonnes. Series IVb had the greatest bond strength at tendon failure.

5.7.3 Critical Embedment Length Curve

Figure 20 illustrates the critical laboratory embedment lengths for various FCB configurations. Ultimate pull-out loads and critical embedment lengths for the FCB configurations tested ranged from 20 to 23 tonnes and 432 to 914 mm respectively. For comparison purposes, SCB's grouted with Portland Type I/II cement and cured for 28 days at a w:c ratio of 0.45 have a critical embedment length and ultimate pull-out load of 1067 mm and 26.4 tonnes respectively (Goris, 1990). A clear trend towards higher pull-out loads at lower embedment lengths was apparent as the node spacing is decreased.

Lower ultimate loads were associated with larger node spacings, larger spacer diameters and unlaced tendon configurations. By increasing the spacer diameter (node diameter), it has been suggested that the transverse shear component introduced to the tendon is increased. In such cases, with the addition of the differential tendon displacement effects, premature tendon failures on the average ranged from 75% to 84% of the ultimate theoretical tensile strength of POLYSTAL. The optimal critical embedment length achieved was 432 mm (Series IVb). This configuration achieved the highest bond strength as determined by this investigation while minimising premature tendon failure. For comparison, conventional SCB at an embedment length of 432 mm have an ultimate pull-out load of 10 tonnes (Goris, 1990). Despite the differences in test parameters for the above comparisons, it is clear FCB's exhibit dramatic improvements in bond strength over conventional SCB's. The critical embedment length for unlaced FCB's is 914 mm at 21 tonnes.
5.8 Premature Tendon Failure (PTF)

PTF has been defined as the abrupt failure of one or more members of the reinforcement configuration during a pull-test prior to developing the total combined UTS (in this case four POLYSTAL rods) and is a measure of the detrimental effect caused by lacing a UD composite. This phenomena is more predominant in POLYSTAL reinforced cable bolts than those reinforced with steel. For a tendon under ideal unconfined tensile loading conditions, the ultimate tensile stress a POLYSTAL tendon can achieve is 1520 MPa. A pull-test introduces confinement, transverse shear and less than ideal anchoring conditions otherwise not associated with ideal tensile tests. As a result, the ultimate theoretical tensile strength of POLYSTAL is rarely reached in mining. A tendon configuration was required to minimise this effect which was assumed to be
associated with the introduction of non-tensile forces and differential tendon displacement. The rod configuration for Series IVb limited premature tendon failure to 84% of the combined ultimate tensile strength. The introduction of shear, torsion and bending force components to the driving force increases the likelihood of premature tendon failure. In most of the samples tested, the tendency for one or more of the grouted POLYSTAL rods to displace differentially with respect to one another was unavoidable. This caused tendon overload and eventually failure before the combined UTS was reached. Differential tendon displacement was promoted by two sources:

(1) Non-uniform bond between cement and POLYSTAL.

(2) Differential loading at the collar of a pull-test sample where exposed POLYSTAL meets cement grouted POLYSTAL.

Uneven bond distribution between the four POLYSTAL rods was likely the most significant factor contributing to premature tendon failure. The addition of differential loading at the collar aggravated the situation. It was observed that tendon failure originated at the collar of the pipe or bottom of the resin chuck and propagated throughout the remainder of the exposed tendon. The failed tendon resembled a "broom-like" structure (Photo Plate 1). The following is an excerpt from Mah et al, 1991:

"PTF was more prominent in the UBC test results where the tendon failure mode occurred. First and foremost, one tendon often displaced with respect to the grout more than the others causing tendon overload leading to premature failure. Second, the difference in displacement between the free portion of the tendon and the grouted portion caused stress peaks. This coincided with stiffer grouts as a result of lower water:cement ratios and higher cure times introducing larger transverse shear forces into the tendon and less grout crushing. It is suspected that this phenomenon contributed to premature tendon failure
before the ultimate theoretical tensile strength of 27.3 tonnes was reached. The free tendon in the UBC test apparatus promoted differential displacement. Premature tendon failure was much less pronounced in the USBM and Queen's results since the samples were fully grouted minimizing the amount of free tendon to less than 10 mm."

The study has shown Series IVb was the best compromise between high bond strength and greatest utilisation of ultimate tensile strength of the 7.5 mm diameter POLYSTAL tendons. However, this does not represent a fully optimised, high bond strength FCB configuration. Future research should concentrate on increasing the number of tendons (surface area) in an unlaced fashion to reduce transverse loads.

5.9 Summary of Critical Embedment Length Determinations

Table 21 summarises the relationship between pull-out load, inter-tendon angle, critical embedment length, normalised pull-out load, inside diameter of spacer, embedment length to node spacing ratio, stiffness and premature tendon failure (PTF). By reducing the inter-tendon angle and node spacing at the same time, it was possible to increase the pull-out load and percentage of combined ultimate tensile strength used. The optimal configuration tested was Series IVb which had an average ultimate load of 23 tonnes at a critical embedment length of 432 mm. Generally, a minimum embedment length to node spacing ratio of 2.0 is required to achieve tendon failure. Further research supporting these results has been conducted by Peterson, 1991.
Table 21. Summary of Critical Embedment Length Determinations

<table>
<thead>
<tr>
<th>NODE SPACING</th>
<th>127 mm (5 inches)</th>
<th>Straight*</th>
<th>254 mm (10 inches)</th>
<th>203 mm (8 inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Series IVb</td>
<td></td>
<td>Series IIIa</td>
<td>Series A</td>
</tr>
<tr>
<td>Pull-out Load, tonnes</td>
<td>23</td>
<td>21</td>
<td>20.63</td>
<td>20.33</td>
</tr>
<tr>
<td>Inter-Tendon Angle $\phi$</td>
<td>9.9°</td>
<td>–</td>
<td>10.4°</td>
<td>13°</td>
</tr>
<tr>
<td>Critical Embedment Length (mm)</td>
<td>432</td>
<td>914</td>
<td>508</td>
<td>457</td>
</tr>
<tr>
<td>Normalised Load tonnes/metre</td>
<td>53</td>
<td>23</td>
<td>41</td>
<td>46</td>
</tr>
<tr>
<td>Spacer i.d. (mm)</td>
<td>11</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Approximate Stiffness at failure (tonnes/mm)</td>
<td>1.53</td>
<td>0.88</td>
<td>1.20</td>
<td>1.00</td>
</tr>
<tr>
<td>Embedment length to node spacing ratio.</td>
<td>3.4</td>
<td>–</td>
<td>2.0</td>
<td>2.25</td>
</tr>
<tr>
<td>% of Combined UTS (PTF)</td>
<td>84%</td>
<td>77%</td>
<td>77%</td>
<td>74.5%</td>
</tr>
</tbody>
</table>

Note:
UTS = ultimate tensile strength of POLYSTAL 1520 MPa (Preis, 1986)
PTF = premature tendon failure.
* Peterson, 1991

6. USBM LABORATORY PULL-TEST PROGRAM

6.1 Introduction

The United States Bureau of mines (USBM), Spokane Washington, is presently conducting research to determine the properties and design guidelines for the installation of SCB's. The project leader, John M. Goris, has assisted in the development of the FCB.

An initial consultation took place with Goris in October, 1989 and plans for a FCB pull-test program at the USBM were established. The samples were prepared by Goris and Mah in late June, 1990. Subsequent testing and data reduction was completed one week later. The sample
preparation and testing of the FCB's were identical to the methods used by Goris for previous tests on SCB's. This allowed for more direct comparisons.

6.2 Objectives

The objectives of the laboratory tests completed at the U. S. Bureau of Mines were:

1. Compare laced FCB's to "standard" USBM birdcaged and conventional SCB's.
2. Test one laced uncoated FCB.
3. Test one straight coated FCB.
4. Compare Series A and FG18 results despite different cement types.

Objective (1) and (4) have allowed definite conclusions. Objectives (2) and (3) were limited to one sample each and completed for comparison purposes only.

6.3 Pull-Test Apparatus and Sample

The pull-test apparatus shown in the schematic Figure 21 (Goris 1990, Fuller and Cox 1975) consisted of two, 58 mm i.d. Schedule 80 pipes separated by a rubber washer. The bottom pipe, or test column, was embedded either 305 mm or 457 mm (depending on the test) in Portland Type I/II cement. The upper pipe consisted of a 914 mm grout column and acted as an anchor. An additional 102 mm of tendon was left extended from the bottom pipe ungrouted to ensure constant embedment length once the tendons fully mobilized with respect to the grout. Two potentiometers were attached to either side of the pipe and an LVDT was stationed at the head of the machine. The upper head, coupling and anchor pipe moved away from the bottom bearing plate during a test.
6.4 Sample Preparation

First, the laced or straight POLYSTAL configurations were placed in the anchor pipe and centred with a donut shaped No. 11.5 rubber stopper (Photo Plate 2 (a) and (b)). The anchor pipe was filled with continuously mixed Portland Type I/II cement. A 3 mm thick petroleum coated rubber washer was placed on top of the anchor pipe. This helped seal the pipe. Next, the test column was placed on top of the washer covered anchor pipe and held firmly in place by a sleeve clamp. The test column was then grouted and the POLYSTAL centred with either tape or a screw cap.
Photo Plate 2 (a). Series FG12 Sample Preparation

Photo Plate 2 (b). Series FG18 Sample Preparation
6.5 Test Procedure

The samples were selected at random and threaded onto a 1.8 million Newton hydraulic stiff pull-test machine. The displacement rate of the upper plate with respect to the stationary lower plate was set at 15 mm/min. Axial loads and displacements were recorded by a load cell and linear variable differential transformer (LVDT) respectively. Two potentiometers were attached to the pipes and served as a backup to the LVDT; the displacement readings agreed. A third potentiometer was attached to the free tendon of the test column tail end and indicated when total mobilisation with respect to the cement grout occurred in the test column. Grout/pipe slippage was not detected. Pipe rotation was monitored visually by etching reference lines on the pipes and bearing plates. No rotation was detected. Progressive debonding occurred in both pipes, but by design, the test column reached peak pull-out load and displacement first due to its shorter embedment length. The displacement of the tendon with respect to the grout was assumed equal for the anchor length and test column. Hence, the displacement was calculated by dividing the total measured displacement by two.

Longitudinal strain tests were performed near the pipe/coupling interface at 27 tonnes by Goris prior to the pull-test program and indicated the pipes were not overstrained. Actual strains were less than the theoretical limits of the steel.

6.6 Wick Effect

Eleven samples were grouted and very little bleeding or sedimentation took place. This verified the absence of the "wick effect" which has been known to cause the grouted column length to decrease by approximately 8% for SCB's (Table 22). Over a 20 metre conventional SCB this equates to 1.6 m. The samples were cured in place for 24 hours and then moved to a humidity controlled room for the remaining six days at 21°C and 100% humidity. The FCB, epoxy covered conventional SCB and birdcaged SCB eliminate potential failures associated with
the wick effect.

### Table 22. Wick Effect - Conventional SCB's
(Goris, 1990)

<table>
<thead>
<tr>
<th>w:c</th>
<th>0.30</th>
<th>0.35</th>
<th>0.40</th>
<th>0.45</th>
</tr>
</thead>
<tbody>
<tr>
<td>decrease in grout column length&lt;sup&gt;1&lt;/sup&gt;</td>
<td>15.85</td>
<td>32.51</td>
<td>63.32</td>
<td>95.83</td>
</tr>
</tbody>
</table>

**Note:**

<sup>1</sup> values represent the decrease of a 1 m grout column in mm.

### 6.7 Codes and Variables

**Table 23** is a list codes, strand types, configurations, embedment lengths and w:c ratios for the USBM test samples.

### Table 23. USBM Pull-Test Samples

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Polyamide Coating</th>
<th>Node Spacing (mm)</th>
<th>w:c Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>FG12-1</td>
<td>yes</td>
<td>178</td>
<td>0.45</td>
</tr>
<tr>
<td>FG12-2</td>
<td>yes</td>
<td>178</td>
<td>0.45</td>
</tr>
<tr>
<td>FG12-3</td>
<td>yes</td>
<td>178</td>
<td>0.45</td>
</tr>
<tr>
<td>FG12-4</td>
<td>yes</td>
<td>178</td>
<td>0.45</td>
</tr>
<tr>
<td>FG12S-5</td>
<td>yes (straight)</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>FG18W-6</td>
<td>no</td>
<td>203</td>
<td>0.35</td>
</tr>
<tr>
<td>FG18-7</td>
<td>yes</td>
<td>203</td>
<td>0.35</td>
</tr>
<tr>
<td>FG18-8</td>
<td>yes</td>
<td>203</td>
<td>0.35</td>
</tr>
<tr>
<td>FG18-9</td>
<td>yes</td>
<td>203</td>
<td>0.35</td>
</tr>
<tr>
<td>FG18-10</td>
<td>yes</td>
<td>203</td>
<td>0.35</td>
</tr>
<tr>
<td>FG18-11</td>
<td>yes</td>
<td>203</td>
<td>0.35</td>
</tr>
</tbody>
</table>

**Note for Sample numbers in Table 23:**

- **FG** = Fibreglass
- **12** = 305 mm (12 inch) embedment length
- **18** = 457 mm (18 inch) embedment length
- **-1** = Sample number 1 of 11
- **S** = Straight strands (not laced)
- **W** = Uncoated fibreglass strands

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"Standard" SCB samples previously tested by Goris and used for comparison purposes in this investigation consisted of single 15.88 mm (5/8") conventional or birdcaged SCB grouted with a 0.45 w:c ratio in Portland Type I/II cement (Goris, 1990).

6.8 Unconfined Compressive Strength of Grout

Ten compression samples were poured into ASTM standard 2 cubic inch brass molds and cured for seven days under identical conditions as the pull-test samples at 21° C and 100% humidity (Table 24).

Table 24. Unconfined Compressive Strength of Grout
(7 Day Cure)

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>w:c = 0.45 (MPa)</th>
<th>w:c = 0.35</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32.75</td>
<td>43.97</td>
</tr>
<tr>
<td>2</td>
<td>33.80</td>
<td>39.92</td>
</tr>
<tr>
<td>3</td>
<td>29.65</td>
<td>39.01</td>
</tr>
<tr>
<td>4</td>
<td>32.50</td>
<td>40.46</td>
</tr>
<tr>
<td>5</td>
<td>33.44</td>
<td>42.06</td>
</tr>
<tr>
<td>Average</td>
<td>32.42</td>
<td>40.98</td>
</tr>
</tbody>
</table>

The average unconfined compressive strengths for the FCB tests (7 day cure) with water to cement ratios of 0.45 and 0.35 were 32.42 MPa and 40.98 MPa respectively. For comparison, tests conducted previously by Goris, 1990 on SCB with water to cement ratios of 0.45 and 0.35 revealed average 28 day cure unconfined compressive strengths to be 50 MPa and 56 MPa respectively. Therefore, the cement strengths for the FCB pull-tests using 0.45 and 0.35 water to cement ratios were 65% and 73% of the 28 day cure SCB pull-test cement strengths. Despite lower cement strengths, it has been shown the FCB has comparable pull-out strengths to steel.
6.9 Results and Analysis

Figure 22 illustrates the typical behaviour of an uncoated laced fibreglass cable bolt with two nodes spaced 203 mm apart. The curve displays some unique, and particularly adverse, characteristics for uncoated POLYSTAL. The initial stiffness, defined as load per unit displacement, of the uncoated system closely follows coated behaviour, but at approximately 9 tonnes there was an abrupt reduction in stiffness followed by what has been termed the "slip/stick" failure mode. This failure mode was characterized by three stages which were dominated by different failure mechanisms as compared to the polyamide coated FCB's:

- **Stage 1** was dominated by a progressive adhesion failure between the tendon and grout.
- **Stage 2** was dominated by what appeared to be resin/fibre interfacial shearing where a "skin" of POLYSTAL, consisting of a layer of helically wrapped fibre and perhaps few layers of unidirectional fibre, remained bonded to the grout. Alkali corrosion of the POLYSTAL was suspected to contribute the reduced stiffness in this area. Hence, the polyamide coating not only enhances surface roughness, but it also reduces corrosion and distributes load to the tendon. In fact, some of polyamide's virtues include toughness, ductility and abrasion resistance. A large displacement of 300 mm was accommodated before rapid unloading.
- **Stage 3** was dominated by a "slip-stick" failure mode between the cement and POLYSTAL. At this point, the tendon was completely mobilized.
Figure 22. A Typical Load/Displacement Curve for Uncoated POLYSTAL

The slip/stick behaviour was also observed in tests performed at the University of British Columbia (Series II), but the reduction in stiffness was not. More test work is required to determine the extent to which the slip/stick failure mode reduces the support capacity of uncoated POLYSTAL in FCB's. In general, it is recommended surface treatments be used to aid in the load-transfer between grout and a fibre reinforced composite. Uncoated tendons have the potential for yielding support applications.

Figure 23 shows the load/displacement curves for samples FG18-7 to FG18-11. Each sample was dominated by the tendon failure mode where at least one tendon failed before all adhesion was lost. This resulted in high precision of the results since the tendons themselves were considered to have consistent properties. An average peak load of approximately 21.75 tonnes or 78% of the theoretical strength was reached. Under the same laboratory load conditions and
embedment lengths, conventional SCB's exhibited grout/tendon bond failure at 14 tonnes (Goris, 1990). This translates to a 50% increase in bond strength for series FG18 over conventional SCB's. These results were very similar to the Series A results at the University of British Columbia.

![Load/Displacement Curves for Series FG18](image)

**Figure 23. Load/Displacement Curves for Series FG18**

From a practical viewpoint, the FG18 series has some drawbacks. Although its bond strength was approximately 50% greater than conventional SCB's, it had virtually no residual strength. The average displacement at the ultimate pull-out load was 15 mm (1/2 inch). As a result, the FG18 series is more suited to non-yielding applications.

**Figure 24** illustrates the load/displacement curves for samples FG12-1 to FG12-4 and
failure mode. This was likely due to the nature of the failure mode and the high water:cement ratios. The plot of FG12S-5, an unlaced tendon configuration, has similar load/displacement characteristics as laced tendons FG12-1 to FG12-4.

![Graph showing load/displacement curves for Series FG12](image)

**Figure 24. Load/Displacement Curves for Series FG12**

**Figure 25** is a comparison of average load displacement curves for laced FCB's and conventional and birdcaged SCB's. Both the FCB and SCB samples were grouted in Portland Type I/II cement with a w:c ratio of 0.45. The major differences were: (1) the fibreglass samples were cured for 7 days while steel samples were cured for 28 days and (2) POLYSTAL's elastic modulus was one quarter that of steel. The 7 day FCB had the same stiffness as the standard conventional SCB samples, but a pull-out load equivalent to the standard birdcaged
samples. This evidence implies that reinforcement modulus is less important than bond strength to the overall grouted reinforcement stiffness. The FCB pull-out load was greater than conventional SCB's by a factor of two and closely followed birdcaged SCB's at one-quarter the cure time.

In general, the FCB is a unique combination of "elastic" yielding capacity such as that supplied by conventional SCB's and high ultimate pull-out resistance like birdcaged SCB's.

Figure 25. Comparison of Average Load/Displacement Curves for FCB's and SCB's
7. IN SITU PULL-TESTS

7.1 Introduction and Objectives

The two primary objectives of this section were to estimate reasonable *in situ* bond strengths prior to the planned trial installations and to establish potential problem sources outside the laboratory for the FCB. The factors deemed most significant aside from those established by the laboratory pull-tests were: rock mass quality, confinement and quality control. Although quantification of the effects of these factors is highly desired, the number of pull-tests feasible precluded any such results. It is recommended that prior to designing any cable bolt system that the effect of the above factors on the capacity of that system be investigated through *in situ* testing.

7.2 Pull-Test Apparatus and Sample Preparation

The test samples were prepared by the author while actual grouting and testing was performed by Dr. Andrew Hyett and Randy Reichart both of Queen's University under the direction of Dr. William Bawden. The pull-test apparatus was designed by Hyett and Reichart for their conventional steel cable testing program at Queen's Figure 26. A hand operated hydraulic jack connected to a ram supplied the axial driving force to dislodge the grouted cables. A load cell and LVDT measured the pull-out load and displacement respectively. An average pull rate of 15 mm/min was maintained. Each sample contained 100 mm of debonded tendon to ensure continuous embedment length once complete cable mobilization was reached. The FCB's were grouted in Portland Type 10 cement at a water to cement ratio of 0.40 and cured for 28 days.
Fourteen tests were attempted in order to estimate reasonable bond strengths under various node spacings and rock units. Three samples were unsuccessful. Since tendon failure did not occur in any of the test samples, a critical embedment length relationship was not derived. The design parameters and resulting ultimate loads have been listed in Table 25. A large variation in ultimate pull-out load was observed. The normalised bond strength (tonnes/metre) varied from
roughly 45 to 60 tonnes per metre.

Table 25. *In Situ* Pull-Test Results at Queen's

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Embedment (mm)</th>
<th>Spacer Diameter (mm)</th>
<th>Node Spacing (mm)</th>
<th>Embedment Length to Node Spacing Ratio</th>
<th>Normalised Bond Strength (tonnes/metre)</th>
<th>Ultimate Load (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QG10-5</td>
<td>254</td>
<td>11</td>
<td>127</td>
<td>2.00</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>QG12-8</td>
<td>305</td>
<td>20</td>
<td>203</td>
<td>2.25</td>
<td>55.74</td>
<td>17.0</td>
</tr>
<tr>
<td>QG15-5</td>
<td>381</td>
<td>11</td>
<td>127</td>
<td>3.00</td>
<td>48.82</td>
<td>18.6</td>
</tr>
<tr>
<td>QG16-8</td>
<td>406</td>
<td>20</td>
<td>203</td>
<td>2.00</td>
<td>44.83</td>
<td>18.2</td>
</tr>
<tr>
<td>QG20-10</td>
<td>508</td>
<td>20</td>
<td>254</td>
<td>2.00</td>
<td>&gt;49.21</td>
<td>&gt;25.0</td>
</tr>
<tr>
<td>QS10-5</td>
<td>254</td>
<td>11</td>
<td>127</td>
<td>2.00</td>
<td>49.22</td>
<td>12.5</td>
</tr>
<tr>
<td>QS12-8</td>
<td>305</td>
<td>20</td>
<td>203</td>
<td>2.25</td>
<td>44.59</td>
<td>13.6</td>
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<td>QS15-5</td>
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<td>QL12-8</td>
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<td>508</td>
<td>20</td>
<td>254</td>
<td>2.00</td>
<td>47.24</td>
<td>&gt;24.0</td>
</tr>
</tbody>
</table>

Key to Sample Number QG15-5:
Q = Queen's
G = Granite (L = Limestone, S = Shale)
15 = 15 inch embedment length
-5 = 5 inch node spacing

Taking a conservative estimate of the normalised bond strength of 45 tonnes per metre and dividing it into 75% of the ultimate tensile strength (to account for premature tendon failure) of the tendons resulted in an estimated ultimate pull-out load of 21 tonnes at a critical embedment length of 470 mm. Therefore, accounting for premature tendon failure, the estimated critical *in situ* embedment length for granite, shale or limestone was approximately 470 mm.

For comparison, FCB's in general developed ultimate pull-out loads 40% greater than conventional SCB's under equivalent test conditions at Queen's (Hyett, 1990-91).

The ultimate *in situ* loads were considerably lower than Series II to IV which were conducted in the laboratory at the University of British Columbia. It is believed the higher w:c ratio of 0.4.
Portland Type 10 cement and larger drill hole diameter of 76.2 mm (3 inch) contributed to the lower *in situ* results.

Displacements at ultimate pull-out load ranged from 20 to 30 mm. The pull-test curves can are shown in Figures 27 to 29. For granite, varying the embedment length from 305 to 406 mm and the node spacing from 127 to 203 mm did not significantly affect the pull-out load. For these embedments and node spacings, slippage of the cable through the grout occurred resulting in reasonable residual strengths. Test QG20-10 reached 25 tonnes before the apparatus failed. Results from the limestone tests were similar to granite. However, for shale, a significant decrease in ultimate pull-out load was observed for embedment lengths below 381 mm.

![Figure 27. *In Situ* Pull-Test Curves for Granite](image-url)
Figure 28. In Situ Pull-Test Curves for Limestone
8. TRIAL INSTALLATIONS

8.1 Introduction

Enough confidence in the ultimate capacity and displacement was generated by the laboratory and \textit{in situ} pull-tests to attempt the trial installations. The FCB's were installed first at Winston Lake Mine. No two cables were installed adjacent to one another. Conventional SCB's were installed around the FCB's. Once it was established that no failures had occurred over approximately 6 months an installation of FCB's was planned to stabilise an unstable section of
the main ore zone at Detour Lake Mine. For this trial, the FCB's were installed on a larger scale without the aid of SCB's. Both installations were very successful and much has been learned about the potential hazards in the design of a FCB system.

8.2 Winston Lake Mine (Noranda) 7 m FCB's

8.2.1 Background

Five, seven metre uncoated POLYSTAL reinforced FCB's were used for back support #3 open stope to assess the ease of installation, effectiveness and acceptability of the FCB's. The orebody consisted of a massive sphalerite deposit dipping at 40 to 60 degrees to the east. The footwall and hangingwall consisted of a gabbro unit with a highly chloritized ore contact. A zone of banded chert-rhyolite-tuff is often present between the ore and the hangingwall gabbro ranging in thickness from 0 to 5 metres. In the wider ore zones the chert disappears and in the thinner ones, it reaches its maximum. The orebody itself ranges from 5 to 17 metres in thickness. Joint spacing in all units was greater than a metre; hence, the massive rock mass did not require cable bolts of high bond strengths.

The mine uses a modified avoca-longhole method. Overcuts and undercuts were separated by twenty (20) metres. Instability in the stope back had been experienced. Conventional SCB's, which have lower bond strengths than laced FCB's and birdcaged SCB's, have been used effectively to rectify such problems.

8.2.2 Historical Instability, Stability Analysis and Design

Structurally controlled instability was observed in stope backs where spans exceeded 10 metres. As a result, overcuts were driven 10 metres wide and a hangingwall pillar left (Figure 30). The hangingwall pillar was later mined with longholes. Upon removal of the hangingwall
pillar over strike lengths of 60 metres or greater, wedge failures frequently occurred in the overcut back/hangingwall contact (Figure 31).

Figure 30. Typical Sill Development Prior to Wedge Failures at Winston Lake

(Milne, 1989)
The wedge failures occurred along Joint Set A, a weak hangingwall/chert contact and Joint Set C, a cross-bedding set parallel to the ore strike. In some failures, the strike length of the wedge was limited by Joint Set B. Figures 32 to 33 illustrate the typical joint sets and potential wedge failures observed at the Winston Lake mine.
Figure 32. Stereonet Representation of Winston Lake Joint Sets in Ore, Gabbro and Chert (Milne, 1989)
An empirical cable bolt support design (Potvin and Milne, 1992) was used to analyse stability of the stope backs. The stability number, N, for the stope backs in ore was estimated to be 1.4. Typical hydraulic radius calculations ranged from 4 to 5 metres for the overcut prior to longhole and greater than 5 metres upon removal of the longhole stope. As a result, cable bolts were recommended for future mining in the area (Figure 34). To ensure stability, a conservative pattern with a 2 x 2 metre spacing was generally used. Pull-tests were conducted on

Figure 33. General Representation of Potential Wedge Failures at Winston Lake (Milne, 1989).
conventional SCB and it was determined the minimum bond strength to develop an ultimate load of 22 tonnes for conventional SCB's, in either the host or the ore, was 1.5 metres. SCB lengths, and subsequently FCB lengths, were then estimated to extend a minimum of 1.5 beyond the weak hangingwall contact. Since FCB's typically have bond strengths in excess of 40% greater than conventional SCB's, anchoring beyond the hangingwall contact was not a problem.

![MODIFIED STABILITY GRAPH](image)

**Figure 34.** Modified Stability Graph for Historically Caved Backs (Milne, 1989)
Due to the large ore width in the test area, a footwall and hangingwall drift had been driven with a pillar between (Figure 35). Five, seven metre FCB were installed with the SCB in the footwall drift. The FCB's were installed in the summer of 1990 and the area remained stable for over a year until September, 1991. At the end of August, 1991, mining below in the 530 #3 stope undercut the unsupported pillar between the hangingwall and footwall drifts. The resulting failure consisted of 3900 tonnes. The failure was attributed to the unsupported ground exposed by the mining below and did not reflect the performance of the FCB's.

![Figure 35. Schematic Cross-section of the FCB's at Winston Lake (Section 10315 N looking north)](image)

8.2.2 Installation Procedure and Acceptance

The FCB installation method was analogous to the one used at the mine-site for conventional SCB's. The quality control at Winston Lake mine was excellent. All five cables were wedged in the hole in 20 minutes. A 25 mm o.d. grout PVC tube ran the full length of the hole. Grouting
commenced from top down using the Minepro pump developed by Inco and took 30 minutes. The grout tube remained in the hole. A water to cement ratio of 0.35 (Portland Type 10) was batch mixed in 30 minutes before pumping. The two metres of FCB closest to the stope face were laced with a node spacing of 127 mm which acted as a "plate." Lacing the remainder of the cable was unnecessary since the critical embedment length for straight tendons was less than the anchor length of 1.5 metres (Figure 36 and Photo Plates 3 to 6).

Figure 36. Uphole Installation Procedure at Winston Lake - Pump Toe to Collar - Ensure pumping is continued until a consistent grout is present at collar to remove air entrained in hole.
Photo Plate 3. Taping 25 mm Grout Tube to Anchor-end of FCB

Photo Plate 4. Looking For a Drill Hole to Insert the FCB
Photo Plate 5. Insertion and Wedging of the FCB

Photo Plate 6. Hand-Scoop Test for 0.35 w:c Ratio (Portland Type 10)
8.2.3 Conclusions

An increase in installation rate was not observed. This was likely due to the relatively short length and few numbers of the FCB's as compared to those installed at Detour. Acceptance was high as the operators involved praised the light weight of the FCB's. The support effectiveness was more difficult to assess due to the surrounding conventional SCB's. A failure did not occur for over one year after installation, however, once the unsupported pillar section was undercut, a 3900 tonne fall of ground was reported. The failure was attributed to the unsupported ground below the FCB's.

8.3 Detour Lake Mine (Placer Dome) 13 m FCB's

8.3.1 Introduction

Detour Lake is a mechanised cut and fill gold mine where four metre lifts are taken per mining cycle. During February, 1991, nineteen laced, polyamide coated FCB's were installed as pre-reinforcement for Detour's 300 M5 stope where production was delayed due to breast failures (Figure 37). The FCB's were laced and shipped to Detour where installation was supervised by mine personnel.
Two successive lifts, sixteen and seventeen, were taken after the FCB's were installed. Approximately 4-5 m of FCB remained as permanent sill pillar support. The FCB's were effective in preventing breast failures.

Each laced FCB consisted of four 7.5 mm (9 mm with coating) POLYSTAL tendons with 127 mm node spacings. The spacers had a 7 mm inner-diameter. The angle between POLYSTAL tendons was equal to 6.76°. This particular configuration had not been tested prior to its use and concern was expressed regarding grout penetration. However, similar configurations had been tested at the University of British Columbia and Queen's with excellent results. The 0.4 w:c ratio was chosen to help facilitate grout penetration at the node.
8.3.2 Past Failure Background

Ground stability problems decreased productivity in the 300 M5 stope. During lift #13, approximately 24 tonnes of loose came down from the back as the result of two previously known intersecting joint sets:

- Striking $160^\circ$-$220^\circ$, dipping $5^\circ$-$15^\circ$, critical joint spacing = 457-610 mm.
- Striking N-S, dipping $80^\circ$-$90^\circ$, critical joint spacing = average is 3-4 m up to 10 m.

The fall of ground occurred several hours after blasting near the face during mucking and prior to rock bolting. As a result, a potential hazard to personnel and equipment was created limiting production from the 300 M5 stope. The fall of ground broke to the last line of 1.8 m long mechanical rock bolts which were installed on a 1.2 m x 1.2 m pattern during the previous breast (Figure 38). The joint sets were observed to extend into the bolt area. It was believed the failure initiated along these joint planes and the resultant bending moment caused the ore to break along the last row of bolts.
Figure 38. Schematic of Typical Detour Fall of Ground

There were no falls of ground from the back during lift #14 despite the presence of the same two joint sets observed during lift #13 were present. However, "popping" and "cracking", which reportedly preceded the previous fall of ground, was heard by the miners. The stope was shut-down and the back was extensively bolted with 2.4 m and 3.6 m long mechanical and super swellex bolts respectively. The mining rate was further slowed as the breast face collapsed onto the fill.
On January 14, 1991 a 36 tonne fall of ground occurred during lift #15. The failure mode was analogous to the lift #13 failure. The following is an excerpt from the monthly ground control report (Detour, 1991):

300 M5 Stope, Lift #15

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RMR</td>
<td>68% (10% deducted for bad structure)</td>
</tr>
<tr>
<td>SPAN</td>
<td>7-21 m (failure occur in wider area of stope)</td>
</tr>
<tr>
<td>SUPPORT</td>
<td>1.8 m mechanical bolts, spot bolting with Super Swellex (for previous breast)</td>
</tr>
<tr>
<td>CONDITION</td>
<td>Unstable</td>
</tr>
</tbody>
</table>

"The stope is currently advancing east and west. The stope span is a maximum 21 metres. A blasting induced fall of ground (FOG) occurred in this stope on January 14, 1991. The FOG occurred in the back and came down shortly after the blast before the next shift arrived in the stope. The FOG occurred as several large blocks approximately 0.4 m thick peeled along a nearly horizontal joint from the breast face to a steeply dipping joint 4 metres back. The FOG occurred in unbolted ground only. It was estimated to contain 36 tonnes. Upon inspection of the area, the flat joint was observed to be open 2-5 cm, but the ground was being held by the rock bolts. There was no deformation of the rock bolt plates so anchor slippage is the probable cause of the slip opening up. An area approximately 7 m x 5.5 m x 0.4 m was blasted down from the back where this open joint was believed to extend. The ground was re-supported with 1.8 m long mechanical bolts. Due to the frequency of ground falls which occur at the breast face before the ground has been bolted in this stope, a pre-support program will be implemented in this stope. Pre-supporting is necessary in this area due to the combination of a flat dipping joint set and continuous N-S vertical joints which are not found in other stopes at DLM."

A reinforcement with a higher bond strength was necessary due to the low critical joint spacing at Detour. The laboratory and in situ tests performed on the FCB's have suggested the
critical bond strength of laced FCB's was approximately 40-50% greater than conventional SCB's and equivalent to birdcaged SCB's. Modelling and historical records revealed the back to be in a relaxed state (Detour, 1991). In view of the modelling results and the combination of near-vertical and near-horizontal joint sets, tensile driving forces were dominant. This represented an ideal application for the FCB.

### 8.3.3 FCB Design

Nineteen (19), thirteen (13) metre FCB's were installed between the centre line and footwall (west side) of the 300 M5 #15 stope to pre-reinforce the back for lifts #16 and #17. The 44.45 mm (1-3/4") up-holes were drilled vertically and staggered on a 2.5 metre pattern. The design was based on traditional conventional SCB spacings - -a conservative approach (Potvin et al, 1992). The support capacity of each FCB was taken as 75% of Series IVb or 17 tonnes. Considering a 2.5 m x 2.5 m x 0.4 m block of ore with S.G. equal to 3.0, a conservative safety factor of approximately 2.3 was reached based on "dead weight" (17 tonnes ÷ 7.5 tonnes). In view the successful FCB program and the potentially large critical joint spacing of the vertical joints, an increase in drill hole spacing could have likely been accommodated. This would have greatly reduced the drilling and subsequently the overall installed cost of the FCB's.

### 8.3.4 Installation Procedure and Acceptance

The stope was filled to within 2 metres of the back. The FCB's arrived to the stope as 1.2 metre individual coils; this aided handling and was common practice for SCB installation at Detour. Uncoiling of the FCB's was much easier and safer than conventional SCB's. A 6.35 mm (1/4") i.d. (9.5 mm o.d.) breather tube was taped to one end of the FCB and then the entire unit pushed up the hole. A 0.25 metre length of 19 mm (3/4") o.d. grout tube was forced into the hole (Figure 39). It was discovered that this entire procedure could be accomplished by one
person whereas conventional SCB's generally required a two men crew. The installation productivity of the FCB's showed a 250% increase over conventional SCB's. Acceptance was high due to their low weight and ease of handling.

Figure 39. Uphole FCB Installation at Detour Lake - Pump Collar to Toe - Minimal Fracturing at Collar

The holes were grouted from the collar up with Portland Type 30 cement at a 0.40 water:cement ratio. The end of the breather tube was inserted into a pail of water where the absence of air bubbles and the expulsion of grout from the tube indicated a "fully grouted" hole and breather tube. The grout tube was then cut and crimped. The cement was allowed to cure for one month before mining continued.
8.3.5 Evaluation of Ground Stabilisation

The rock mass rating and discontinuities of the 16th lift were equivalent to the 15th. To date, the FCB's have successfully stabilised the previously experienced ground problems in the 300 M5 stope. Falls of ground were eliminated resulting in improved mining rates.

8.3.6 Mining Through FCB's

FCB's react differently to blasting than conventional SCB's. First, no "grapes" were observed hanging from the FCB's. Grapes are common at Detour for mined areas supported by SCB's. This eliminated the dangerous task of cutting cables and improved the cycle time over SCB pre-reinforced stopes. Second, the length of FCB projecting from the hole after blasting varied from a few centimetres to 3 metres. Third, the POLYSTAL either remained intact or "broomed" to form large, continuous bundles of resin and fibre. Small fibres were not observed. It is suspected they either settled or were removed by the ventilation system. It is not clear whether a mask would be required on a larger scale. The potential respiratory health risk requires further evaluation. It would appear at this time that a limited amount of air-borne fibre was generated by blasting and that this phenomena increases as the distance between a FCB and blasthole decreases. It has also been postulated that the length of FCB projecting and the ability for grapes to remain attached to the bolt are a function of the distance from the bolt to the blast hole and the shear force exerted on the POLYSTAL due to block rotation. The relatively low shear strength of POLYSTAL as compared to steel promotes effective blasting. Photo Plate 7 is a typical example of a FCB after it was mined through at Detour.
The presence of grout within the nodes was discontinuous for some of the blasted bolts. It was unclear whether the blast or grouting procedure caused this. The former was the most likely explanation since observations of the FCB in the hole between lifts revealed the antinodes were completely filled. Similar laboratory configurations with w:c ratios lower than 0.4 were cut open longitudinally and verified completely filled antinodes. In practice, pumping should continue until a consistent grout is observed through the breather tube and all air is removed from the hole. This is a difficult task to judge when grouting from the collar to the toe. For a given w:c ratio, an analysis of the grout flow characteristics and pressure head variation over the entire length of a grout column would be valuable to determine minimum annulus sizes for completely filled FCB nodes and their boreholes. At this stage, it appears an angle of 6.76° between POLYSTAL
tendons is sufficient to allow a Portland Type 30 grout with a w:c ratio of 0.4 to completely fill the node.

### 8.3.7 Mucking Benefits

At Detour, it is often necessary to attach SCB's to an LHD and pull them from the muck pile to permit mucking. This reduced productivity and represented an annoyance to the mucking crew. Muck piles that were previously supported with FCB's were easier to muck. The FCB's broke more easily than SCB's as the LHD crowded the muck pile. SCB's remaining in the muck pile often required cutting.

### 8.3.8 Mineral Processing Effects

Prior to mining through the bolted section, the mill operators were asked to record any unexplained changes to the mill circuit. There was concern that POLYSTAL or its' fibres would blind the mill screens, but this was not observed. No recovery or grade problems were observed. No other problems were reported. It is suspected if FCB's were used on a larger scale they might have a noticeable impact on the mineral processing circuit. If such a study were performed, the majority of the intact and broomed POLYSTAL could be removed from the conveyor belts or screen decks by a mill operator prior to secondary and tertiary crushing.

### 8.3.9 Cost Effectiveness

Table 26 compares the **installed costs** for laced FCB's and conventional SCB's excluding overhead. The laced FCB's were not commercially available at the time of installation. The FCB's were manually laced and flown from Vancouver to Detour. These costs have been included in the analysis. Lower labour installation costs have been realised. One and two persons were used for the overall installed cost calculations of the FCB and SCB systems.
respectively. Wages per person for the cable bolt crew averaged $20/hr excluding overhead. Polyamide coated POLYSTAL was used.

Table 26. Installed Cost Comparison for the FCB’s and SCB’s at Detour

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>DETAIL</th>
<th>CONVENT’L SCB ($ CDN)</th>
<th>LACED FCB ($ CDN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drilling</td>
<td>13 m @ $10.78/m</td>
<td>140.14</td>
<td>140.14</td>
</tr>
<tr>
<td>Strand/POLYSTAL</td>
<td>13 m</td>
<td>24.88</td>
<td>134.72</td>
</tr>
<tr>
<td>FOB Detour</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cable Insertion</td>
<td>SCB 1 x $40/hr FCB 0.4 x $20/hr</td>
<td>40.00</td>
<td>8.00</td>
</tr>
<tr>
<td>Grouting</td>
<td>SCB 0.5 x $40/hr FCB 0.5 x $20/hr</td>
<td>20.00</td>
<td>10.00</td>
</tr>
<tr>
<td>Materials</td>
<td></td>
<td>34.14</td>
<td>34.14</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>259.16</td>
<td>327.00</td>
</tr>
</tbody>
</table>

Note:
1 Does not include lacing materials and labour or freight from Vancouver to Detour for POLYSTAL
2 Includes cement, breather tube & grout tube

The overall installed cost of the FCB system was 20 percent higher than the conventional SCB system. The FCB material cost included a 13% import tariff and a freight charge of $0.22/kg from Germany to Vancouver.

8.3.10 Continuous Mining Environment

The procedure for controlling air-borne glass fibres would be different for continuous mining methods as compared to drill and blast methods. Continuous miners would tend to generate finer glass fibres. The generation of fine dust and glass fibre is inevitable in a continuous mining operation, but a proper dust collection system such as the "positive air-circulation system" would control the air quality at the face (Figure 40). The balance between fresh air supplied to the face and suction from the dust collector results in a "dust curtain" which remains within 1 metre of the
Experience has shown that typically 1.5 to 2 m³/s of fresh air is required per 0.093 m² of cross-sectional area. For best results, the fresh air duct should be located at approximately 33% of the back height.

Figure 40. Dust/Fibre Collection Using Positive Air Circulation Method for Continuous Mining (Schenk, 1982)

Cutting size is known to increase in naturally fractured rock (Schenck, 1982). This would reduce the amount of air-borne glass fibre.

Degradation of intact POLYSTAL was not observed. Polyamide coated POLYSTAL has a high abrasion resistance. Intact coated POLYSTAL was ground in a laboratory ball mill for 45 minutes with no visible degradation.
9.0 FLOATATION TESTS

9.1 Introduction

Three mining environments have been considered during the development of the FCB: open, cut and fill and continuous stoping. Each method will dictate the degree to which POLYSTAL would enter the mill circuit differently.

First, after completing the trial installations at Winston Lake Mine where open stope hanging wall support was used, no adverse affects to the mill was observed.

Second, after completing the trial installations at Detour Lake Mine, it was concluded, for drill and blast CAF operations, the likelihood of large quantities of POLYSTAL entering the mineral processing circuit would be low. If POLYSTAL should enter the mill circuit, it is likely the majority of the POLYSTAL would be removed by screens during crushing and grinding. However, blinding of screens may pose some operational problems.

Third, it is proposed that the feed size and amounts of POLYSTAL to the mill would be smaller for continuous CAF mining than conventional CAF. This would potentially aggravate screen blinding and, hence, more removal measures would be necessary in the mill circuit. As a result, any mining method where the support must be mined with the ore requires the removal measures such as screen cleaning and conveyor belt picking. Further developments in removal of composite materials from the mill circuit are necessary.

This section evaluates the impact POLYSTAL would have on the floatation of a copper sulphide ore (Newmont samples, 1991) and suggests potential removal measures for the bulk floatation stage, assuming relatively large amounts of POLYSTAL entered with the feed and passed the screen removal measures.
9.2 Test Procedure

Roughly 4000 grams of Newmont ore was riffled into 4 approximately equal sized samples from which three were selected at random for the experiments. Ten (1% by weight of total sample) and thirty grams (3% by weight of total) of POLYSTAL, without the coating, was added to Test samples II and III respectively. The POLYSTAL was cut into approximately 50 mm long pieces and resembled the broom-like, post-failure consistency of resin and fibre as discussed in the laboratory pull-tests. Test 1 was not doped with POLYSTAL and acted as a reference point. Each sample was then individually ground at 60% solids by weight for 15 minutes. Visual inspection revealed the glass fibres were reduced to less than 5 mm. The amount of resin coating the glass fibres did not appear to affect their size reduction. Next, each sample was passed through a simulated bulk floatation stage.

9.2.1 Test I

Test I was emptied into a flotation cell and conditioned with 0.15 g potassium amyl xanthate (KAX) for 10 minutes. The impeller speed was kept at 900 rpm. Compressed air flow was set at 10 litres per minute. Ten drops of DOW FROTH 1012 (1% concentration) were added in order to achieve a stable froth. The pH was adjusted to 8.0. The froth was skimmed for approximately 3 minutes upon which time 10 more drops of frother were added and the air flow was increased to 20 litres per minute. At these setting, the froth was skimmed for an additional 7 minutes giving a total floatation time of 10 minutes.

9.2.3 Test II

Test II was emptied into a flotation cell, the impeller set at 900 rpm and the compressed air turned on to observe the behaviour of the glass fibres. A small greyish mass of fibre appeared to float without the aid of reagents. Flotation procedure was identical to Test I. Large amounts of
fibre could be seen in the concentrate.

9.2.4 Test III

Test III was emptied into a flotation cell under the same conditions as Test II and immediately a large greyish mass appeared on the surface of the pulp. The KAX was added and this appeared to suppress the fibres to a small extent. Large amounts of fibre could be seen in the concentrate.

9.3 Results

Although the composition of glass fibres was predominantly silica (≈60% by weight), they act extremely hydrophobic due to their long, slender shape. As mentioned, large amounts of fibre were observed floating in Tests II and III.

The concentrate and tails of each test were assayed for copper (Cu), total iron (Fe) and silica (SiO₂) (Table 27). The percentage of silica in the concentrate dramatically increased in Tests II and III.

<table>
<thead>
<tr>
<th>TEST</th>
<th>MASS</th>
<th>Copper</th>
<th>Iron</th>
<th>Silica</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>I - concentrate</td>
<td>121.80</td>
<td>11.80</td>
<td>24.40</td>
<td>18.22</td>
</tr>
<tr>
<td>I - tails</td>
<td>871.80</td>
<td>0.18</td>
<td>4.80</td>
<td>44.70</td>
</tr>
<tr>
<td>II - concentrate</td>
<td>134.10</td>
<td>9.05</td>
<td>22.30</td>
<td>20.72</td>
</tr>
<tr>
<td>II - tails</td>
<td>839.10</td>
<td>0.17</td>
<td>4.60</td>
<td>45.12</td>
</tr>
<tr>
<td>III - concentrate</td>
<td>161.20</td>
<td>7.90</td>
<td>18.90</td>
<td>25.98</td>
</tr>
<tr>
<td>III - tails</td>
<td>862.10</td>
<td>0.19</td>
<td>4.70</td>
<td>46.16</td>
</tr>
</tbody>
</table>

The percentage of copper recovered in the concentrate versus the percentage of POLYSTAL in the feed was plotted to illustrate the effect of high concentrations of POLYSTAL (Figure 41).
To put the test results into perspective, if a 10 m x 10 m x 10 m cut and fill stope were supported with FCB's on a 2 m by 2 metre pattern, the tonnage of POLYSTAL mined with the ore would be equal to 0.08 tonnes of POLYSTAL (5 cables/ring * 5 rings * 10 m/cable * 4 strands * 80 g/m). For an ore with S.G. equal to 3.0 and assuming all the POLYSTAL reached the flotation stage, the percentage by weight of POLYSTAL to the mill feed would be 0.0027% or less than one-thousandth (1000th) of that in Test II. According to the laboratory tests completed, this would result in a reduction in copper recovery of less than 0.01%.

![Figure 41. Percent Copper Recovered in the Concentrate vs Percent of POLYSTAL to Feed (by weight)](image)

The addition of extremely large amounts of POLYSTAL did adversely affect the bulk flotation of the Newmont ore (Table 28). A slight decrease in recovery and grade was
observed (Figure 42).

Table 28. Recovery and Grade for Typical Newmont Ore

<table>
<thead>
<tr>
<th>CONCENTRATE</th>
<th>% POLYSTAL</th>
<th>RECOVERY, %</th>
<th>FEED GRADE, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0</td>
<td>90.15</td>
<td>1.6</td>
</tr>
<tr>
<td>II</td>
<td>1</td>
<td>89.50</td>
<td>1.4</td>
</tr>
<tr>
<td>III</td>
<td>3</td>
<td>88.60</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Figure 42. Percent of Copper Recovered vs Percent of POLYSTAL to Feed (by weight)

9.4 Conclusions

In general, it is expected that the glass fibres would pose problems to screening. Removal of the glass fibres should be accomplished prior to flotation stages. According to these results,
POLYSTAL would have little effect on the bulk floatation of a copper sulphide ore. The effect of resin was not investigated.

10. SHEAR TESTS

Photo Plate 8 shows the shear-test apparatus used to evaluate the FCB. The apparatus consisted of a load cell, dial gauge, hydraulic press and metal box to hold the sample. The samples consisted of three segments of pipe with a single FCB grouted over the entire column. The middle segment was loaded vertically at 90° to the FCB axis while the two outer segments were clamped to the metal frame to restrict vertical and horizontal movement of the two end-pipes.

Photo Plate 8. Shear Test Apparatus and Test Sample
Table 29 summarises the shear-test results of four laced FCB's with a 127 mm node spacing (inter-tendon angle of 9.9°) and grouted in a water to cement (Portland Type 30) ratio of 0.35.

### Table 29. Preliminary Shear Test Results

<table>
<thead>
<tr>
<th>SAMPLE NUMBER</th>
<th>CURE TIME, DAYS</th>
<th>VERTICAL SHEAR LOAD(^1), (TONNES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>7.85</td>
</tr>
<tr>
<td>2</td>
<td>29</td>
<td>5.59</td>
</tr>
<tr>
<td>3</td>
<td>47</td>
<td>6.03</td>
</tr>
<tr>
<td>4</td>
<td>120</td>
<td>5.91</td>
</tr>
</tbody>
</table>

**Note:**

1. The vertical shear load per end-pipe was equal to one half the total applied driving force.

The average shear strength of a fully cured FCB was approximately 6.34 tonnes for a driving force oriented 90° to the FCB axis. No residual strength existed. Cure times greater than 29 days did not significantly affect shear strength.

### 11. DESIGN

As with most ground support design procedures, the engineer must evaluate stress, structure (wedge formation) and rockmass characteristics of an excavation. Once the potential failure mode and expected movements have been determined, the proper cable bolt, pattern and length can selected.

The Modified Mathew's Method, an empirical design approach developed by Potvin and Milne, 1992 was used successfully to design the FCB installations at Detour and Winston Lake mines. For discrete wedge failures, a stereonet analysis should be conducted to determine adequate cable lengths. For highly fractured and/or stress induced failures, FCB's should extend beyond historical failure heights and have a low critical embedment length.

Selection of the proper FCB is critical to the design and subsequent extraction of ore. Two
basic FCB's have been developed and field tested: (1) yielding and (2) high bond strength (Table 30).

Table 30. Selection of FCB for Design - Portland Type 30 Cement, 0.35 w:c Ratio, 54 mm hole

<table>
<thead>
<tr>
<th>TYPE</th>
<th>APPLICATION</th>
<th>ULTIMATE CAPACITY (tonnes)</th>
<th>ESTIMATED PEAK ELASTIC RECOVERY (mm)</th>
<th>CRITICAL EMBEDMENT LENGTH (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight* yielding</td>
<td>massive</td>
<td>21</td>
<td>22</td>
<td>914</td>
</tr>
<tr>
<td>Laced** high bond strength</td>
<td>blocky</td>
<td>23</td>
<td>16</td>
<td>432</td>
</tr>
</tbody>
</table>

Note:
* Four POLYSTAL tendons separated by 20 mm i.d. spacer (results for this enclosed in Peterson, 1991).
** Four POLYSTAL tendons separated by an 11 mm i.d. spacer and node spacings of 127 mm.

The FCB's developed in Table 30 do not possess residual strengths above the critical embedment lengths as estimated by laboratory pull-testing. Therefore, to account for this, the operating strengths of the FCB's were taken as 75% of the ultimate laboratory pull-out load. The reduction in operating load was effective in the trial installations at Detour and Winston Lake mines.

Composites have other characteristics that are different from conventional materials. Composites have properties which are dependent on the position and angle of the applied load with respect to the reinforcing fibres. Composites themselves have no yield strength or strain capacity. These differences must be considered when designing safe, ground support systems.

For large scale testing, particularly in entry type methods such as cut and fill, *in situ* pull-tests are recommended to verify ultimate pull-out loads, allowable displacements and critical

130
embedment lengths.

As with SCB installation, cement quality is of primary importance to the effectiveness of a FCB. Water to cement ratios less than 0.35 or greater than 0.45 are not recommended for the FCB.

12. POTENTIAL APPLICATIONS

The FCB exists as a viable alternative to steel cable bolt support in Canadian hardrock mines. Other potential applications which deserve further evaluation include:

- Open stoping support.
- Cut and fill back and overhang support.
- Back support in sill pillar recovery operations.
- Reinforcement for pillars and drawpoints.
- Highly corrosive environments.
- Soft rock support.
- Support of ore where SCB mucking tangles are experienced.
- Burst prone ground.

13. FUTURE RESEARCH DIRECTIONS

The potential for fibre reinforced polymer composites in ground support applications has been proven. The FCB exists as a viable alternative to SCB's in a number of applications such as cut and fill and open stoping. But, the FCB is far from optimized. Likely the major stumbling blocks hampering industry use and acceptance of the FCB is its' high cost and unproven shear strength. Future research should concentrate on the following:
• Locate a lower cost Canadian manufacturer willing to develop mining products.
• Develop higher bond strengths, ultimate capacities and residual strengths.
• Evaluate composite surface coatings and tendon diameter effects.
• Quantify the shear strength with respect to orientation of applied load.
• Investigate the long-term support capacity.
• Quantify design guidelines
• Complete a market analysis.
• Determine manufacturing constraints.
• Assess other existing advanced and low-tech composites in the same manner.
• Application development.

14. CONCLUSIONS

The results in this thesis have been based on over fifty (50) laboratory pull-tests, fourteen (14) in situ pull-tests, four (4) laboratory shear tests, three (3) laboratory floatation tests and two (2) trial installations. The evaluation of potential composite materials and subsequent development of a working prototype has been accomplished.

The fibreglass cable bolt (FCB) exists as a viable alternative to steel cable bolts. The bond strength of the FCB was greater than conventional and equivalent to birdcaged SCB's. The FCB configuration with the greatest bond strength consisted of four, 7.5 mm diameter POLYSTAL rods laced with an internal angle between tendons of 9.9° and 127 mm node spacing. For yielding support requirements, the straight FCB configuration has been recommended where four 7.5mm diameter POLYSTAL rods are separated by a spacer. The overall installed cost of the FCB was a competitive 20% higher than conventional SCB's.

Continuously, fibre reinforced polymer composites have been recommended and categorised
according to the following fibre orientations: unidirectional (UD), bidirectional (BD) and multidirectional all of which have potential for cable bolt reinforcement. All testing in this investigation has been conducted on a member of the UD composite family. The UD composite family has been divided into two further sub-categories according to quality control and mechanical properties: advanced and low technology. Advanced composites, usually reinforced with carbon, aramid or glass fibre, are manufactured with stringent quality control measures to ensure high material properties and near "flawless" end-products. A high degree of quality control was considered vital to the selection of a cuttable reinforcement and the safety of an installation.

Low technology composites are available for as low as $1/m, but with lower mechanical properties (ranging from 500 MPa to 1000 MPa) and decreased quality control. They also tend to have poorly developed bond surfaces and/or corrosion resistances. It has been emphasised that low technology composites appear attractive as ground support based on their low cost, but require more stringent quality control measures in their manufacturing processes. Today, the most economical advanced UD composites available on the market in sufficient quantities to conduct laboratory tests are reinforced with glass (POLYSTAL, construction profile) or aramid (ARAPREE 200) fibre. POLYSTAL is commercially available in Canada (Con-Tech, 1991). POLYSTAL has a thermoplastic, glass filled, resin rich veil which is resistant to corrosion, abrasion and pull-out. ARAPREE possesses a silicon-grit enhanced surface roughness. The largest disadvantage of aramid reinforcements, as compared to glass or carbon, is the formation of "kink bands," or buckling of the fibre under compressive loads (Pigliacampi, 1988). The formation of "kink bands" limits their application to high strain compressive or flexural load requirements. Aramid and glass fibre costs range from $10-100 and $1-5 per kilogram respectively. Carbon fibre composites have superior properties to most materials and appear to be the best reinforcement selection for dynamically loaded support systems, but are currently too expensive for mining ($10-1000/kg). The current downward trend of aramid and carbon fibre cost is expected to continue and will likely improve their feasibility in various applications (U.S.
Department of the Interior • Bureau of Mines, 1990). Of the candidates considered, POLYSTAL was chosen for this investigation based on its' unique combination of high strength, corrosion resistance, low cost, versatility, flexibility and availability as compared to other advanced composites. If manufactured in Canada, the FCB has the potential to be cost competitive with current prestressing steel prices. POLYSTAL's low density equates to easier handling and better acceptability throughout the involved work force as compared to steel cable bolts. Uncoated POLYSTAL has the potential for temporary support (<1 year), but its' performance is questionable and requires further investigation. Polyamide coated POLYSTAL has been recommended for virtually any tension dominated support application where limited shear forces are present. The coated POLYSTAL had a higher bond strength to cement than uncoated POLYSTAL.

Laboratory tests at the University of British Columbia and the United States Bureau of Mines have revealed that axially loaded laced FCB's demonstrated bond strengths 40-55% greater than conventional SCB's. The maximum pull-out load obtained was 23 tonnes at a critical embedment length, defined as the embedment length required for tendon failure, of 432 mm and a node spacing of 127 mm. This configuration caused premature tendon failure at 84% of the combined ultimate tensile strength for four POLYSTAL tendons. Under similar load conditions and test parameters, conventional SCB's developed an ultimate pull-out load of 13 tonnes at an embedment length of 432 mm. Unlaced FCB's had a critical embedment length of approximately 914 mm at 22 tonnes. Unlaced bolts had a lower stiffness and bond strength than laced bolts.

The load/displacement curve for the FCB was a compromise between conventional and birdcaged steel cable bolts. The "elastic" portion of the pull-out curve closely followed conventional cable bolts, but the ultimate load was equivalent to birdcaged steel cable bolts. However, it has been shown that by increasing bond strength of a cable bolt, tendon failure occurred at lower embedment lengths and residual strength was sacrificed.

The fractional factorial design completed at the University of British Columbia evaluated the following factors: mix time, embedment length, w:c ratio, cure time, pipe diameter, spacer
diameter and node spacing. Under the operating levels and conditions of the design, three factors were found most significant: hand-mix time, embedment length and water cement ratio. The following conclusions were made:

- An increase in embedment length from 152 mm to 457 mm increased pull-out load significantly. However, critical embedment lengths were not determined.
- A decrease in water cement ratio from 0.65 to 0.35 increased pull-out load significantly.
- A cure time increase from 2 to 10 days did not significantly increase pull-out load for Portland Type III cement (high early strength).
- An increase in pipe diameter from 48 mm to 77 mm did not significantly increase pull-out load. This corresponds to tests with conventional steel cables (Milne 1988-90).
- An increase in node spacing above 305 mm did not significantly increase pull-out load.
- An increase in mix time increases pull-out load.
- The effects of node spacing and spacer diameter required further investigation.
- The effects of increasing or decreasing the factors tested in FFD-I are similar to steel cable bolts (Goris, 1990).

\textit{In situ} pull-tests conducted at Queen's University revealed the FCB's had a higher bond strength than conventional steel cable bolts. Ultimate pull-out loads were typically 40\% greater than those obtained for conventional SCB's.

Trial installations at Winston Lake and Detour Lake mines have been completed to assess the installation, blasting, mucking and mineral processing of FCB's in open stoping and mechanised cut and fill mining. At the mechanised cut and fill operation at Detour, continual breast failures were experienced. Conventional SCB's did not develop the required bond strength to stabilise the breast. As a solution, nineteen, thirteen metre laced FCB's were installed to pre-reinforce the ore. The FCB's successfully stabilised the back and breast where previous conventional SCB support failed. The installation rate was increased by 250\% and acceptance was high. Blasting
did not degrade the FCB's between lifts. The low shear strength of the FCB resulted in the elimination of cable "tangles" during the mucking cycle. No adverse health or mineral processing effects were observed. Blasted FCB's either remained in tendon form or "broomed" depending on their location with respect to the blast hole. An installed cost analysis was completed for the Detour Lake trial installation and the FCB cost was 20% greater than the conventional SCB. A one man crew with hydraulic fill placed 2 metres from the back was adequate for efficient installation.

At Winston, five, seven metre FCB's reinforced with uncoated POLYSTAL were used to assist SCB's as back and hanging wall support. A hybrid configuration was used where the tendons were unlaced and separated by a spacer except the last 2 metres closest to collar which were laced with a 127 mm node spacing and an inter-tendon angle of 9.9°. No increase in installation rate was observed as at Detour. This was likely due to the short length and small number of FCB's installed as compared to Detour. Acceptance was high. No failures occurred until an unsupported area was undercut. However, the failure did not reflect the performance of the FCB's as the fall of ground was initiated by the unsupported ground.

It has been determined that the use of POLYSTAL would cause minimal problems to the mill screening processes where the FCB's would be mined with ore such as in drill and blast or continuous mines.

To assess the effects of POLYSTAL on the latter portions of mineral recovery, bulk flotation tests were conducted on a typical copper sulphide ore (Newmont mine) doped with KAX, Dowfroth and POLYSTAL were completed. It was found that if the POLYSTAL was in a fibrous failed form, it ground easily in a laboratory ball mill and floated immediately when placed in an aerated flotation cell. Hence, removal of the ground POLYSTAL could be accomplished during floatation if necessary. Grade and recovery decreased slightly as the weight percent of POLYSTAL increased. However, standard cable bolt patterns would not result in significant reductions in grade or recovery.

Immediate applications for the FCB have been established where the back is in a relaxed state
or near-relaxed state and a shear force of not greater than 5 tonnes is exerted 90° to the bolt axis. Such conditions commonly exist in Canadian cut and fill and open stoping operations. The feasibility of the FCB improves as the demand for its' advantages over steel such as high bond strength, efficient installation and corrosion resistance increase. Other potential applications include continuous excavations, rockburst protection, pillar reinforcement and prestressed anchors. The application environment and service life can range from short-term to long-term.

Preliminary laboratory shear tests have been conducted and revealed the FCB's to have a limited shear resistance of five (5) tonnes for a fully cured sample (at least 28 days) with a load applied 90° to the bolt axis. The limitations of the FCB in shear as they relate to the rock mass characteristics, driving forces, confinement, normal force and grout remain to be determined.

Conventional SCB design procedures have been used successfully. However, the selection of to proper FCB is critical to design. Operating strengths for the FCB's are taken as 75% of their ultimate laboratory or in situ pull-tests. Water to cement ratios less than 0.35 or greater than 0.45 are not recommended.

Finally, further research to develop a composite particularly suited for cable bolt support has been justified. The technology exists to develop a composite which meets the requirements of the aggressive cable bolt environment. However, it is highly recommended that future investigations be conducted in conjunction with both a composite manufacturer and the mining industry in order to develop practical, economical composite tendons for cable bolting.
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APPENDIX A - CALCULATION OF EFFECTS FOR FFD-1
Main Effects:

\[ L_0 = l_0 = \frac{\sum x_{oi}y_i}{\sum_i x_{oi}^2} \]

\[ L_1 = l_1 = \frac{\sum_{i=1}^{16} x_{1i}y_i}{\sum_{i=1}^{16} x_{1i}^2 / 2} \]

\[ L_2 = l_2 = \frac{\sum_{i=1}^{16} x_{2i}y_i}{\sum_{i=1}^{16} x_{2i}^2 / 2} \]

\[ L_3 = l_3 = \frac{\sum_{i=1}^{16} x_{3i}y_i}{\sum_{i=1}^{16} x_{3i}^2 / 2} \]
\[ L_4 = l_4 = \frac{\sum_{i=1}^{16} x_{4i} y_i}{\sqrt{\sum_{i=1}^{16} x_{4i}^2}} / 2 \]

\[ L_5 = l_5 = \frac{\sum_{i=1}^{16} x_{5i} y_i}{\sqrt{\sum_{i=1}^{16} x_{5i}^2}} / 2 \]

\[ L_6 = l_6 = \frac{\sum_{i=1}^{16} x_{6i} y_i}{\sqrt{\sum_{i=1}^{16} x_{6i}^2}} / 2 \]

\[ L_7 = l_7 = \frac{\sum_{i=1}^{16} x_{7i} y_i}{\sqrt{\sum_{i=1}^{16} x_{7i}^2}} / 2 \]
Two-Factor Interaction Effects:

\[
L_{12} = l_{12} + l_{35} + l_{47} = \frac{\sum_{i=1}^{16} x_{i1}x_{i2}y_i}{\sum_{i=1}^{16} (x_{i1}x_{i2})^2} / 2
\]

\[
L_{23} = l_{23} + l_{46} + l_{15} = \frac{\sum_{i=1}^{16} x_{i2}x_{i3}y_i}{\sum_{i=1}^{16} (x_{i2}x_{i3})^2} / 2
\]

\[
L_{34} = l_{34} + l_{26} + l_{57} = \frac{\sum_{i=1}^{16} x_{i3}x_{i4}y_i}{\sum_{i=1}^{16} (x_{i3}x_{i4})^2} / 2
\]

\[
L_{45} = l_{45} + l_{16} + l_{37} = \frac{\sum_{i=1}^{16} x_{i4}x_{i5}y_i}{\sum_{i=1}^{16} (x_{i4}x_{i5})^2} / 2
\]
$$L_{56} = L_{56} + l_{14} + l_{27} = \frac{\sum_{i=1}^{16} x_{15}x_{16}y_i}{\sum_{i=1}^{16} (x_{15}x_{16})^2 / 2}$$

$$L_{67} = L_{67} + l_{13} + l_{25} = \frac{\sum_{i=1}^{16} x_{16}x_{17}y_i}{\sum_{i=1}^{16} (x_{16}x_{17})^2 / 2}$$

$$L_{17} = L_{17} + l_{24} + l_{36} = \frac{\sum_{i=1}^{16} x_{11}x_{17}y_i}{\sum_{i=1}^{16} (x_{11}x_{17})^2 / 2}$$

Three-Factor Interaction Effect:

$$L_{123} = l_5 = \frac{\sum_{i=1}^{16} x_{11}x_{12}x_{13}y_i}{\sum_{i=1}^{16} (x_{11}x_{12}x_{13})^2 / 2}$$
APPENDIX B - PULL-TEST CURVES FOR FFD-I
FRACTIONAL FACTORIAL DESIGN
Center Point Runs - Series I

PULLOUT LOAD (tonnes)

TENDON/GROUT DISPLACEMENT (mm)

Run 17
Run 18
Run 19
Run 20
APPENDIX C. PULL-TEST CURVES FOR SERIES II-IV. CRITICAL EMBEDMENT LENGTH DETERMINATIONS
PEAK LOAD
NO TENDON FAILURE
RAPID SLIPPING & UNLOADING

PULLOUT LOAD (tonnes)

TENDON/GROUT DISPLACEMENT (mm)

Series II - 1

Series II - 2

embedded 457.20 mm (1½ feet)
node spacing 203.2 mm (8 inches)
no polyamid coating.
25.00

PEAK LOAD

3 TENDONS FAILED

20.00

NO TENDON FAILURE

15.00

1 TENDON FAILED

10.00

Series IIIa - 1

Series IIIa - 2

Series IIIa - 3

embedded 508.0 mm (20 inches)
node spacing 254.0 mm (10 inches)

TENDON/GROUT DISPLACEMENT (mm)

PULLOUT LOAD (tonnes)
TENDON/GROUT DISPLACEMENT (mm)

PULLOUT LOAD (tonnes)

- Series IIIb - 1
- Series IIIb - 2
- Series IIIb - 3

embedded 914.4 mm (36 inches)
node spacing 254.0 mm (10 inches)
PULLOUT LOAD (tonnes)

PEAK LOAD

NO TENDON FAILURE

TENDON/GROUT DISPLACEMENT (mm)

--- Series IVa - 1
--- Series IVa - 2
--- Series IVa - 3

embedded 304.8 mm (12 inches)
node spacing 127 mm (5 inches)
PEAK LOAD

3 TENDONS FAILED

2 TENDONS FAILED

TENDON/GROUT DISPLACEMENT (mm)

PULLOUT LOAD (tonnes)

Series IVb - 2
Series IVb - 3

embedded 431.8 mm (17 inches)
ode spacing 127 mm (5 inches)