Steel Fibre Reinforced Shortcrete For Underground Support

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1.0 HISTORICAL BACKGROUND

Dry-mix shotcrete had its origins in the development of the Cement Gun (also referred to as the gunite process) by Carl Akeley in Chicago in the USA around 1910. Rabecewicz working in Central Europe and Iran was largely responsible for the introduction of shotcrete for tunnel support in the 1930's. (Rabecewicz, 1969). In the late 1950's Rabecewicz introduced the so-called New *Austrian Tunnelling Method* for tunnel excavation and reinforced shotcrete support in weak ground. Wet-mix shotcrete, while experimented with in the early part of the century, was not utilized in any significant way for civil engineering applications until about 1942, with the development of the *True Gun* (Austin & Robins, 1995).

The development of steel fibre reinforced shotcrete (SFRS) is even more recent. The first practical application of SFRS was not until 1972, when the US Army Corps of Engineers used the dry-mix shotcrete process to line tunnel adit at the Ririe Dam in Idaho (Kaden, 1977). The first use of SFRS for underground support in Canada was in 1979, when SFRS, applied by the dry-mix shotcrete process, was used to rehabilitate deteriorating rock tunnels on the Canadian Pacific Railway Fraser Canyon line, in British Columbia (Morgan, 1991).

The demonstrated success of these early applications lead to a rapidly increasing use of SFRS for both primary and final tunnel linings, including final tunnel linings, including final lining of railroad tunnels through the Rocky Mountains in Canada in 1982-83 (Morgan and McAskill, 1984). At the same time the Norwegians had discovered the technical and economical advantages of using steel fibre reinforcement in lieu of mesh reinforcement in tunnels lined with wet-mix shotcrete. From virtually zero use of SFRS in

* This paper was presented by the Authors at Novocon International Inc. Shotcrete Seminars held in Nov. 1997 at New Delhi, Nagpur & Mumbai, India.

Norway in 1980, by 1986 approximately 70 percent of all shotcrete used in tunnelling in Norway was wet-mix SFRS (Garshol, 1990). Other countries also started to discover the benefits of SFRS and by the 1990's large quantities of both wet and dry-mix SFRS were being used in tunnelling and mining applications around the world (Vandewalle, 1990).

2.0 APPLICATIONS

The principal objective in the design of underground support is to help the rock mass support itself. Traditional ground support in tunnelling and mining applications has relied on techniques such as :

* steel and timber sets and lagging (blocking);
* rock and/or cable bolting in conjunction with meshing;
* cast concrete linings in large openings, or tunnels requiring a smooth final profile.

The use of shotcrete together with rock bolting and various types of reinforcement has become a technical and cost-effective alternative to traditional ground support methods in tunnels and mines. (Barton et al, 1995, Daws, 1995, Hoek et al, 1995, Windsor, 1996).

When applied to the rock mass, the shotcrete is forced into fissures and open joints and helps to bond the features together. Movement of rock block is prevented by a combination of bond strength and shear strength of the shotcrete in the immediate vicinity of joints. This, together with membrane or arching action of the lining (particularly in circular or horseshoe-shaped openings) helps the rock mass to support itself. The appropriate selection of shotcrete and reinforcing systems together with rock and/or cable bolting has now made tunnelling and mining possible in very weak ground and some highly deforming ground, where traditional ground support systems might not be tenable (Barton et al, 1995, Daws, 1995, Hoek et al, 1995, Barton et al, 1996, Struthers and Keogh, 1996). The new Austrian Tunnelling Method which traditionally has used mesh reinforcement and the Norwegian method of Tunnelling (NMT) which is based on the use of SFRS (Barton et al, 1995), have proven valuable in this regard. Additional useful references are provided in the series of engineering foundation (New York) publications on shotcrete for underground support (Sharp and Franzen, 1990; Wood and Morgan, 1993, Klapperich et al, 1995).

Other benefits also accrue from the use of SFRS in the tunnelling and mining environment. These include :

* control of water when the lining is constructed in conjunction with appropriate drainage systems;
* prevention of oxidation and deterioration in rock quality, especially in rock types vulnerable to slaking;
* reduction in maintenance costs, relative to the costs required to rehabilitate bolt and mesh supported ground;
* enhanced durrability and safety of underground openings subjected to rock bursts or repeated blasting stresses (Wrixon and Semkowski, 1995; McCreath & Kaiser, 1992).

The following is a brief summary of some of the areas of use of SFRS in tunnelling and mining applications :

* primary (initial) and final linings in road, rail, sewer and water conveyance and drainage tunnels (Vandewalle, 1990);
* permanent linings in drives, declines, ramps, raises and shafts in mines (Morgan 1990, Windsor, 1996);
* ground support in mine production areas, such as stopes, pillar mining, sub-level caving, etc.
* strengthening of production brows and draw points in ore passes and remote shotcrete lining of entire ore passes;
* lining of large underground cavities such as powerplants in hydroelectric projects and crusher stations, hoist stations and pump rooms in mines;
* more economical construction of stoping seals, fill barricades and other types of structures which would conventionally be constructed by formed and cast concrete (Windsor, 1996).

3.0 DESIGN OF SHOTCRETE SUPPORT

The design shotcrete for underground support is an inexact science. Design options can generlly be divided into empirical and analytical methods. (Wood, 1996, Hoek et al, 1995, Vandewalle, 1996). Empirical methods can be further sub-divided into rules of thumb and rock mass classification systems. Analytical methods vary from simplistic closed-form support interaction analyses to complex analytical computer-based programs. (Hoek et al, 1995; Maidl, 1992).

3.1 Empirical Methods

The simplest form of empirical design is the rule of thumb or observational method (Wood, 1996). Essentially this method relies on experience and precedence. e.g. in a given set of ground conditions, a particular combination of SFRS of a particular thickness with rock bolts (or other reinforcement) behaved in a certain way. The assumption is then made that given a similar set of conditions, a given lining would behave in a predictable manner. This approach creates challenges when developing a new tunnel, or mine, where the ground conditions vary from previous experience. Some comfort can, however, be taken from the comments of (Hoek et al, 1995) who state that :

> *"One observation that is commonly made by practical engineers, with years of practical experience in using shotcrete underground, is that it almost always performs better than anticipated".*

They also note that :

> *"There are many examples where shotcrete has been used as a last act of desperation in an effort to stabilize the failing rock around the tunnel and to most peoples surprise, it has worked".*

The writer has witnessed such situations, particularly in severe ground conditions, in mines. There are examples where mines with orebodies with high stress fields, low rock mass strength and weak geological structures and consequent extreme ground behaviour on mining, have only been able to be economically mined by the use of SFRS in conjunction with rock and cable bolting. Without the use of SFRS it is unlikely that some of these mines in question could have continued to operate. (Strutchers and Keogh, 1996).

A major advantege of SFRS, is that it acts as an excellent tell-tale i.e., if the lining is being subjected to excessive load and/or deformation, the shotcrete lining will typically provide visible indications of the location of distress. With the possible exception of some high energy rock-burst events, sufficient warning is generally provided to enable the design engineer to implement a program of additional support or strengthening in affected areas. Thus the rule of thumb approach becomes an interactive experience-based procedure.

3.2 Rock Mass Classification Systems

Rock mass classification systems have been used since the 1940's to characterize excavated ground conditions in an attempt to formalize an empirical approach for determining support requirements for civil engineering tunnels.

(Hoek et al, 1995; Wood 1996). More recently rock mass classifications systems have also been applied in mining. (Struthers & Keogh, 1996). A number of different rock mass classification systems have been developed including.

* Terzaghi's rock mass classification (Terzaghi, 1946)
* Rock quality designation index (RQD), (Deere et al, 1967)
* Rock Structure Rating (RSR) (Wickham et al, 1972)
* Rock mass rating system (Bieniawski, 1989)
* Rock mass quality index (Q system) (Barton et al, 1995).

While any of these methods can be used to assist in the empirical design of tunnel linings, the method which is most directly applicable to design with SFRS is the Rock Mass Quality Index (Q system). (Barton et al, 1995). Fig. 1 shows recommended design systems for a wide range of different rock mass quality (Q). For reinforcement categories 5 through 8, SFRS of various thicknesses, in conjunction with rock bolting (and for category 8 other reinforcement) is recommended. It is also worth noting that for reinforcement category 4 (i.e., systematic bolting and plain shotcrete) while not necessarily required for load control reasons, some engineers prefer to use SFRS instead of plain shotcrete, for reasons of controlled shrinkage cracking and hence enhanced quality of the shotcrete lining.

At the other extreme, in some mining applications, severely stressed and shattered squeezing ground, with Q ratings of 0.001 or worse (i.e. ground which would normally require reinforcement category 9 cast concrete linings), has been stabilized using combinations of SFRS with mesh reinforcement together with rock bolts and cable bolting. While this approach may not suffice for permanent civil engineering tunnels, it has proven technically viable and economically effective in production work in extreme ground conditions in some mines where the openings are only required to remain serviceable for periods of one to two years. (Struthers & Keogh, 1996).

3.3 Analytical Methods

A number of engineers have attempted to develop analytical methods for design of shotcrete linings for support of underground openings. Such methods vary from relatively simple sliding wedge kinematic calculations (Daws, 1995) to sophisticated two dimensional hybrid finite element/boundary element programs which analyze the stresses, deformation, progressive failure and the behaviour of the support in the rock mass surrounding underground openings (Hoek et al, 1995; Maidl, 1992) has proposed an analytical method, based on eccentric thrust on SFRS linings for rational design of underground support. Also a German Guideline for SFRS in Tunnels, also based on ecentric thrust has been developed (Schmidt-Schleicher, 1995). Such methods are however, likely only applicable to underground openings with a well defined profile, such as circular tunnel boring machine (TBM) excavations, or horse-shoe shaped openings with close control over the arch profile. For the usual very irregular drill and blast underground openings encountered in many tunnels and mines it is questionable whether this analytical design approach will suffice.

Hoek et.al., 1995 state that:

"it will require many more years in the use of, and in the interpretation of the results obtained from modern analytical programs before a clear understanding of shotcrete behaviour is obtained. They also point out that it is important to recognize that shotcrete is seldom used along for underground support and that its use in conjunction with rock bolts, cable bolts, and sometimes lattic girders or even steel sets, further complicates the problem of analyzing shotcrete's contribution to support".

Thus, while the development and application of analytical methods of shotcrete lining design is to be lauded, for the present, any design recommendations arising from such methods should be checked against recommendations based on empirical methods, i.e., rely on precedence and experience.

3.4 Toughness Test

A number of different test methods have been developed to characterize the toughness of SFRS. More details of which are given in Section 10.0 of this paper. These methods, however, are really only suitable of comparing the relative behaviour of shotcretes made with different fibre types and addition rates. The results of these tests are of limited value in design of SFRS linings. These tests are thus best suited for quantifying the quality of SFRS, as an item in developing empirical experience of the behaviour of SFRS in underground support. Some of these tests are also suitable for routine quality control testing purposes.

4.0 SHOTCRETE MATERIALS

4.1 Cement

A variety of different types of cement have been used for both wet and dry-mix shotcretes. In North America the various types of cements commonly used in conventional concrete construction are also used in shotcrete for underground support. ASTM Type I and CSA Type 10 Normal Portland Cements are most commonly used in North America. ASTM Type II and CSA Type 20 (moderate heat of hydration and moderete sulphate resistance) cements are sometimes specified and used. In high sulphate exposure conditions ASTM Type V and CSA Type 50 sulphate resisting portland cements are sometimes used. In recent years CSA Type 10 SF Portland silica fume blended cements (typically with 8 to 9% silica fume by mass of portland cement) are increasingly being specified and used in parts of Canada.

In Europe special shotcrete cements, with rapid setting and hardening characteristics have been developed for use in dry-mix shotcrete (Schmidt, 1995). Rapid setting and hardening cements, suitable for use in both wet and dry-mix shotcrete are available in North America. (Gebler, 1989). They have, however, to date only had limited use in underground applications because of their generally higher cost. High alumina cements have been used for shotcrete lining in mines in permafrost in Arctic Canada and in intentionally frozen ground in uranium mines in Canada. This is because of their very rapid rate of setting and hardening and the higher heat isotherm, which enables the shotcrete to gain early strength such that it is not damaged by freeze back.

4.2 Supplementary Cementing Materials

The supplementary cementing materials most commonly used in shotcrete are silica fume and flyash. Morgan, 1988 provides an overview of the reasons for using these materials in wet and dry-mix shotcretes. Briefly, silica fume is used for the significant benefits it imparts to plastic and hardened shotcretes, including the following:

* improved adhesion to rock surfaces and cohesion to itself;
* build-up of thicker layers of shotcrete before sloughing on both vertical and overhead surfaces with a reduction in the amount of accelerator required;
* improved adhesion to rock and resistance to wash-out and sloughing in wet underground openings (particularly true of the dry-mix shotcrete process).
* improved economy through substantial reductions in overall rebound and fibre rebound, with associated increased productivity;
* improvements in the properties of the hardened shotcrete, including compressive and flexural strength;
* enhanced durability, including increased resistance to leaching (called elution by the Europeans) and sulphate attack.

Flyash is sometimes used in shotcrete in underground applications. It has mainly been used in wet-mix shotcrete for the same reasons it is used in concrete; e.g. to improve pumpability of mixes made with harsh aggregates and provide more paste volume to coat the steel fibres. Additional benefits include enhanced resistance of the hardened shotcrete to sulphate attack, and alkali aggregate reactivity (Morgan, 1988).

4.3 Aggregates

Selection of aggretates with suitable gradation, shape, texture and physical quality is important in the production of quality SFRS. The aggregate should be of such quality that it conforms to the requirements of concrete aggregate standards such as ASTM C 33 or CSA A 23.1-94 or other appropriate national standards. The most user-friendly aggregates are natural rounded fluvial and glacio-fluvial sands and gravels. Quarried rock coarse aggregates and manufactured (crushed rock) sands are used in certain locations because of the lack of availability of natural gravels and sands. Quarried rock must, however be carefully selected and processed in a crushing plant which produces suitable aggregate shape and texture; the use of coarse aggregates which have excessive amounts of flat, elongated and shard-like particles should be avoided, as they can adversely affect the pumpability and shootability of wet-mix shotcrete, as well as, increased rebound. In dry-mix shotcrete such meterial can result in marked increases in both aggregate and steel fibre rebound and degradation in hardened physical properties, particularly absorption and volume of permeable voids.

Requirements for aggregate gradation are detailed in various national guides and standards, e.g. (AT 506.2-90) and the (Austrian Guideline Shotcrete, 1997). The most commonly used shotcrete aggregate gradation for underground support in North America is ACI 506R-90 Gradation NO.2. The Austrian Guideline provides a gradation envelope which falls approximately within the coarser side of the ACI envelope. This is graphically illustrated in Fig.2. It is interesting to note that the specified aggregate gradation for shotcrete in the Channel Tunnel Project connecting England and France, was quite close to the Austrian Guideline (Maidl, 1992).

Manufactured sands (made from crushed rock) are not the best materials for shotcrete production. They can be used, but particular attention must be paid to their shape and gradation. Sands with excessive shard-like particles and/or excessive amounts of fines should be avoided. CSA A23.1-94 limits the amount of material passing the 80 μm sieve in manufactured sands to 5% maximum, provided the fines are free of clay particles; ASTM C33 is more generous and permits up to 7% passing the 80 μm sieve. Excessive amounts of fines result in marked increases in water demand of both dry and wet-mix shotcretes. This not only adversely affects the water/cement ratio and hence properties of the hardened shotcrete, but also reduces the thickness of build-up and increases the tendency to sloughing and required accelerator dosage in the plastic (fresh) shotcrete.

4.4 Chemical Admixtures

Other than for dust suppressants and shotcrete accelerators, chemical admixtures are seldom used in dry-mix shotcrete. By contrast admixtures are routinely used in wet-mix SFRS. Water-reducing admixtures are used to reduce water demand of the mix. Set retarders are sometimes used in shotcretes with long delays from the time of batching to completion of discharge, or in warm temperatures, to offset rapid rates of loss of workability. With silica fume wet-mix shotcretes, the use of superplasticizers to control water demand is strongly recommended. (Wolsiefer and Morgan, 1993).

Many road and rail tunnels in North America are exposed to freezing and thawing conditions in winter. Air entraining agents are commonly used in wet-mix SFRS in such situations to provide the shotcrete lining with freeze-thaw durability. The shotcrete application process results in about half of the as-batched air content being lost during pumping and impact on the receiving surface. Consequently in order to attain in-situ air contents in the range of 4 1/2 + 1%, (found necessary to produce freeze-thaw durable wet-mix shotcrete) the air content of the shotcrete as discharged into the shotcrete pump should be about 8 to 10%. The loss of air content during shooting also results in a stiffening of the in-place shotcrete, i.e. the loss of air acts as a slump killer, reducing the amount of accelerator needs to achieve a given thickness of build-up of SFRS in-situ. (Beauper, 1997).

A more recent development in wet-mix SFRS for underground support is the use of cement hydration control admixtues (sometimes referred to in the industry as stabilizers or sleepers). (Melbye, 1994). When added at the batch plant such admixtures inhibit cement hydration reactions for extended periods of time, ranging from hours, to days, depending on the addition rate. An activator, is then added to the shotcrete at the nozzle, in the same way as a shotcrete accelerator, to reactivate the mix and allow setting and hardening of the in-situ SFRS to proceed in the norml way. The use of this system has added considerably to the versatility of use of wet-mix shotcrete in tunnels and mines with long haul times, or long delays between the time of batching and completion of shotcrete discharge (Jay and Boyce, 1996).

4.5 Shotcrete Accelerators

Shotcrete accelerators are routinely used in SFRS for underground support, particularly in overhead applications in order to:

* enhance the rate of stiffening and hence thickness of build-up in a single pass;
* reduce the incidence of shotcrete sloughing and fall-out;
* accelerate the rate of setting and hardening, and early strength development;
* reduce the potential for damage to SFRS from exposure to blasting stresses at early ages.

There are a wide variety of different types of shotcrete accelerators in the market (Bracher, 1995; Melbye, 1994; Loevlie and Micke, 1996). They can generally be classified as:

* Chemical accelerators; examples include:
  - sodium and potassium aluminates and carbonates;
  - organic salts, e.g. triethanolamine;
  - calcium aluminates;
  - new, low causticity, alkali free accelerators.

* Rhelogy modifiers; examples include:
  - sodium silicates (water glass);
  - modified sodium silicates;
  - precipitated colloidal silica.

Other types of accelerators are being used in underground SFRS applications, but these are the major types being used at this time. Both the chemical accelerators and rhelogy modifiers can be effective in promoting rapid stiffening, enhancing thickness of build-up and resistance to sloughing; some are more effective than others. Also, it should be cautioned that the effect of a given accelerator can be quite cement-specific, i.e. it may work quite well with certain brands of cement, but not with others. The chemical set accelerators are, however, generally more effective in enhancing the rate of early strength development (say 2 to 8 hours) than the rhelogy modifies. Some of the caustic accelerators are potentially injurious to health and so their use should either be avoided or they should be used with appropriate protective measures. A final caution; the use of accelerators at additional rates which promote flash setting or instantaneous siffining should be avoided unless essential to the construction process (e.g. rapid sealing of mud seams, or water control) as it can lead to a marked increase in overall rebound and steel fibre rebound as well as downgrading of physical properties of the hardened shotcrete. This is paricularly true of the dry-mix shotcrete process.

5.0 SHOTCRETE REINFORCEMENT

5.1 Mesh Vs Fibre Reinforcement

Prior to the 1980's welded wire mesh fabric was the most commonly used means of reinforcement of shotcrete for underground support. It was generally used in conjunction with rock bolts and, in NATM, with lattice rib girders or sometimes steel sets. Since the 1980's there has been continuously increasing use of steel fibre reinforcement in lieu of mesh reinforcement in shotcrete for underground support. There are also some projects where both mesh and fibre reinforcement have been used in the shotcrete in severe ground conditions.

The question is often asked: How does steel fibre reinforced shotcrete perform compared to mesh reinforced shotcrete in underground applications. A number of different studies have been conducted in North America (Morgan and Mowat, 1984; Little, 1983); Scandinavia (Holmgren, 1983, Opsahl, Morch, 1993); South Africa (Kirsten, 1993) and Australia (Clements, 1996) in an attempt to answer this question. The test methods used in the comparative evaluations of mesh and steel fibre have included:

* shotcrete plates simply supported on all sides on a steel frame, with central point loading to destruction, e.g., the EFNARC test (Clements, 1996);

* shotcrete plates with simulated rock bolts (with no bond to a substrate) with either central point loading (Morgan and Mowat, 1984, Little, 1983; Kristen, 1993) or distributed loading (Kirsten, 1993);

* shotcrete bonded to granite blocks, with displacement of the central granite block (Holmgren, 1983; Opsahl, 1981).

Some results from (Clements, 1996) studies are shown in Figs. 4 and 5. Fig. 3 shows the EFNARC test setup. Fig. 4 shows load vs deflection curves for different fibre addition rates. Fig. 5 shows load vs deflection curves for two different types of mesh commonly used in mining in Austraila. If Figs. 4 and 5 are superimposed on one another, it can be seen that at the higher fibre addition rate (70 kg/m^3) at deflections of up to about 10 mm the SFRS carries higher load than the heavier gauge F82 welded wire mesh; at greater deflections performance is similar. The SFRS at the intermediate fibre addition rate (50 kg/m^3) shows superior load bearing capacity to the F82 welded wire mesh at deflections up to about 7 mm. The SFRS at the lower fibre addtion rate (30 kg/m^3) shows similar performance to the lighter F41 welded wire mesh reinforced shotcrete at deflections up to about 17 mm; thereafter the mesh reinforced shotcrete displays higher residual load carrying capacity.

Morgan and Mowat (1984) tested 1.52 m x 1.52 m x 64 mm plain, mesh, and steel fibre reinforced shotcrete panels with simulated rock-bolts at 1.22 m on centre in the corners of the panels. The panels were loaded to destruction with central point loading and deflections and crack patterns recorded. Panels were tested in both a restrained and pin-ended condition. Fig. 6 shows a schematic of the unrestrained condition test set-up. Figs. 7 and 8 show the load vs deflection responses for the restrained and pin-ended test assemblages respectively. For this particular 2 in x 2 in x 12/12 mesh it can be seen that the fibre reinforced shotcretes provided better residual load carrying capacity after first crack compared to the mesh reinforcement at deformations of up to about 15 mm. Thereafter performance of the mesh and fibre reinforced panels is similar. Clearly behaviour with a heavier gauge mesh would be different.

In the simulated falling block tests conducted in Norway, the test set-up shown in Fig. 9 was used (Morch, 1993). Fig10 shows the relative load vs deflection response of the K131 mesh and SFRS with a 26 mm steel fibre added at 70 kg/m^3. The generally superior performance of the SFRS in this test is apparent. Fig. 11 shows potential failure modes in such tests.

In practical applications the mode of failure of the shotcrete lining (if any) will depend on factors such as :

* the characteristics of the substrate rock, including: stress level, rock mass strength, rock structure (joint spacing and orientation), etc.;
* quality of bond of the shotcrete to the substrate rock;
* the mode of loading of the shotcrete e.g. quasi-static loading of the lining by slow convergence of the opening, or dynamic impact loading from blasting or seismic forces.
* the pattern and spacing of rock bolts and adequacy of mechanical connection of the rock bolts to the shotcrete.

The authors have observed the mode of failure of shotcrete linings in underground opening in mines with severe ground deformation and convergence of the openings. Observation of the behaviour of shotcrete linings in such extreme loading conditions provides useful information regarding the mode of failure of mesh and steel fibre reinforced shotcrete. In most cases failure appears to be initiated by a combination of bond failure to the rock substrate or sometimes failure (rubblizing) of the rock behind the shotcrete lining. Once bond failure is initiated, bending and/or tension cracks form in the shotcrete lining. Shear failure can also occur at wall/roof corners if there is differential displacement at these locations. As ground deformation and convergence of the opening continues, the cracks become progressively wider. Depending on the design life of the opening, additional support may then have to be installed. Such support may take the form of installation of lattice girders and SFRS, with or without additional rock and/or cable bolting. In some cases, for short-life openings, the installation of bolts and mesh, as a safety measure to catch any scates of delaminated shotcrete, may suffice.

The decision as to whether to use mesh or steel fibre reinforced shotcrete for underground support will depend on both technical and economical considerations. In smooth profile, soft ground excavations where mesh is relativey easily installed, such as many NATM type constructions, mesh has been the preferred shotcrete reinforcing system. By contrast, in drilled and blasted rock, with its typically irregular profile, steel fibre has increasingly become the preferred shotcrete reinforcing system. It can often take two to three times as long to install mesh in irregular ground compared to the time required for shotcreting. Also, rebound is higher in mesh reinforced shotcrete and it takes more shotcrete to fill the voids in behind the mesh, and provide the ncessary cover to the mesh, as shown in Fig. 12. Thus the generally higher materials cost of steel fibre compared to welded wire mesh is typically more than offset by the savings in shotcrete quantities and installation time achieved. This accounts in part for the increasing use of SFRS for underground support worldwide.

5.2 Steel Fibre Reinforcement

The effectiveness of any particular type of steel fibre reinforcement in shotcrete is dependent on how it behaves in both the plastic and hardened shotcrete. In wet-mix shotcrete the fibre should be capable of being batched, mixed, pumped and shot without creating fibre balls, or blockages in the pump or hose. Similarly, in dry-mix shotcrete, the fibre should be capable of uniform dispensing and mixing without creating fibre balls. This is best achieved by controlling the aspect ratio (length/equivalent diameter) of the fibre. Most fibres used in SFRS today have lengths in the 25 to 40 mm range and aspect ratios in the 40 to 60 range, although fibres outside this range of parameters are used. Nearly all steel fibres used in shotcrete today have either continuous deforamtions, or some form of end deformation, e.g. enalargd ends, flattened ends, hooked ends, etc. The purpose of the defomations is to enhance resistance to pull-out of the fibres.

Another important consideration in the selection of a steel fibre for shotcrete is the tensile strength. The best toughness (residual strength after cracking) is provided by high tensile strength steel fibres, i.e. fibres made with prestressing steel quality drawn wire (or equivlent) with a minimum tensile yields strength exceeding 1000 MPa. The use of low tensile strength steel fibres, or fibres which are brittle (either because of the type of steel of fibre manufacturing pocess used) should be avoided. In North America steel fibres for shotcrete are often required to conform to the ASTM A820, Type I, *cold-drawn wire* standard, but with the additional requirement of a minimum *1000 MPa* tensile yield strength.

Besides the fibre type, the other important consideration is the fibre addition rate. A wide range of steel fibre addition rates have been used in shotcete for underground support depending on the fibre type, shotcrete method, and ground conditions. Vandewall (1990) cites exmples of over 80 tunnelling projects around the world (road, rail, hydraulic, nuclear waste storage) where fibre addition rates ranged from 30 to 80 Kg/m^3. In North America most SFRS used in underground applications has used fibre addition rates in the 50 to 80 kg/m^3 range with 60 Kg/m^3 being common. (Rose, 1985; Morgan, 1996). It should, however be remembered that these are as-batched fibre contents. In-place fibre contents will be lower, because of fibre rebound during shooting. Both overall rebound and fibre rebound is much higher in dry-mix shotcrete than in wet-mix shotcrete and this should be taken into consideration in SFRS mixture design. For a well designed and applied wet-mix shotcrete, fibre rebound (relative to the as-batched quantity) may be only 5 to 10 kg/m^3. By contrast, in dry-mix shotcrete, particularly if poor shooting technique is used (shot too dry, too low or too high an impact velocity, or too acute a shooting angle), as much as half of even more of the as-batched fibre may be lost as rebound (Armelin et al, 1997).

There has been a tendency by some specifiers to overspecify the requirements for fibres, e.g. give a very detailed prescription specification for the fibre. (length, aspect ratio, type of deformations, tensile strength) as well as a performance requirement. e.g. some toughness parameter. This can be counterproductive and result in unnecessary costs and should be discouraged. It is suggested that the best means of achieving technically satisfactory SFRS at least cost is the use a performance specification, with the additional proviso that the steel fibre meet the ASTM A802 standard specification requirements and have a minimum tensile yield strength of 1000 MPa. The performance specification would require a minimum level of toughness at a given age.

In North America, a commonly used procedure is to specify testing to the ASTM C1018-94b test method i.e. flexural toughness testing of a 100 x 100 x 350 mm beam on a 300 mm span in third point loading, with plotting of a load vs deflection response. Various toughness prameters can then be calculated from this curve. The Toughness Performance Level method developed by (Morgan et al, 1995) and now also being adapted as an Austrian Standard has been specified on number of projects in North America.

Toughness testing is typically done on SFRS test panels shot during the preconstruction phase of the work. In this way the contractor can select the fibre type and addition rate which most economically satisfies the performance specification for the project. Toughness testing can also be used for routine quality control. The only situations where the authors would recommend the use of a pure prescription specification would be on small projects, or remote sites, where suitable access to a qualified testing laboratory, capable of property conducting toughness testing, was not available.

6.0 SHOTCRETE MIXTURE PROPORTIONING

Shotcrete mixture proportioning is governed by the same principles that apply to conventional concrete mix design, i.e. Abrams' Law applies and the prime factors controlling strength and quality are the water/cementing materials ratio, degree of consolidation and air content of the in-place material. There are, however, some significant differences in proportioning of shotcrete compared to conventional cast concretes. Concrete is typically poured into forms and then consolidated; shotcrete is consolidted by the shotcrete impacting process and then has to stay adhered to the receiving surface without sagging, sloughing or fall-out. To achieve this the shotcrete requires a high cementing materials content; typically in the 360 to 500 kg/m^3 range for the as-batched material. The in-place cementing materials contents will be even higher because more aggregate rebounds than cement. This is particularly true of the dry-mix shotcrete process, with its higher overall rebound.

There are also differences in aggregate proportioning in shotcrete, compared to concrete. Most structural concretes have coarse aggregate contents (expressed as a percent of the total combined mass of coarse and fine aggregates) in the range of about 52 to 68 percent. By contrast, most shotcretes made with coarse aggregate have coarse aggregate contents in the 20 to 30 percent range. Also, the maximum aggregate size in shotcrete is limited to no more than 10 to 14 mm. In North America most SFRS has been batched with combined aggregate gradations meeting the ACI 506R-90 Table 2.1 gradation limits shown in Fig. 2. The use of about 25 percent by mass of a 10 mm maximum size natural rounded aggregate with about 75 percent of a natural river sand, is the preferred composite for SFRS. Crushed aggregates and manufactured sands have been used where the natural materials are not available, but they typically require more mixture fine-tuning.

Silica fume is now widely used in both wet and dry-mix shotcrete for underground support in North America and elsewhere in the world, e.g. Scandinavia, Central Europe, Australia and South Africa. It is used because of the enhanced benefits it imparts to the plastic and hardened shotcrete, as decribed in section 4.2. *It has been used in addition rates ranging from about 8 to 15 percent by mass of cement*, with addition rates of 40 to 50 Kg/m^3 being common. The higher addition rates tend to be used in predominantly overhead shooting, in wet-ground conditions, or where greater lining thicknesses are required. The lower addition rates have been used in predominantly vertical shooting e.g. construction of stoping seals and barricades in mines, and portal and tunnel walls. Silica fume is particularly beneficial in dry-mix SFRS because of the reduction in overall and fibre rebound.

Air-entraining and water reducting admixtures are commonly used in wet-mix shotcrete in North America and elsewhere for the same reasons they are used in concrete. In hot ambient conditions retarding admixtures or water reducing retarders are sometimes used. When using silica fume, the use of superplasticizers (also called high range water reducers) is strongly recommended, in order to control water demand of the mixture and hence the qulity of the plastic and hardened shotcrete. *Superplasticizer addition* rates in the 3 to 6 L/m^3 range are common.

Accelerators are commonly used in underground shotcrete operations, particularly when shooting on overhead surfaces, or where young shotcrete will be subjected to blasting stresses, and early age strength development is important. The required accelerator addition rate will depend on the particular job requirements and type and brand of cement and accelerator being used. *Accelerator addition rates in the 2 to 5 percent by mass of cement range are common.* Where flash setting is required, higher acelerator addition rates may be used, but with a general down-grading of the physical properties of the shotcrete.

Table 1 gives a performance specification for a wet-mix SFRS for a Canadian civil engineering tunnelling application. The mixture design used to satisfy this performance requirement is listed as Mix No. B1 in Table 3. Typical plastic and hardened properties for this SFRS mix design (average of a set of 9 test panels, 3 tests per panel) are given in Tables 3 and 4. Similar performance specifications are given for dry-mix SFRS, except that there is obviously no specification for slump and seldom any specification for the in-place air content.

The major difference between wet-mix proportioning is that *chemical admixtures, such as water reducers, superplasticizers etc. are not used in dry-mix shotcrete.* Also, it is usually necessary to start with a higher as-batched steel fibre content in dry-mix shotcrete in order to meet a specified toughness requirement, because of the higher fibre rebound.

7.0 BATCHING MIXING AND SUPPLY

7.1 Wet-Mix Shotcrete

Any of the batching, mixing and supply systems used for conventional concrete production have been used for SFRS production underground. Mixtures have been batched, mixed and supplied using all of the following systems :

* central mix batched, with transit mixer supply;
* transit mixer batched and supplied;
* volumetric site batching in mobile batcher units.

Ingredients such as silica fume and steel fibre can be added at the batch plant or on site. Accelerators are added in a liquid form at the nozzle using special accelerator dispensing units. Wet-mix SFRS has been supplied underground using a variety of different systems, including the following:

* In mines with ramped access, taking the shotcrete underground in transit mixers (ready mix trucks) or agitator cars e.g. Moran cars.

* Dropping the shotcrete down pipes set in haulage shafts or dedicated raise-bore shafts, with the shotcrete being caught at the bottom in transit mixers or agitator cars. A variety of ignenious systems have been developed to facilitate this process with minimal maintenance requirements.

7.2 Dry-Mix Shotcrete

Dry-mix shotcrete used in tunnelling and mining applications has been batched, mixed and supplied by a range of different systems, including the following :

* central or transit mixer batched, with transit mixer supply;
* site-batching, using either volumetric or mass-batching technique;
* dry bagged premix materials, supplied in either small paper bags (30 kg typical) or large synthetic cloth bulk bin bags (1600 kg typical)

While central or transit mixer batching and transit mixer supply is sometimes used, it is considered the least desirable batching and supply system for modern dry-mix SFRS mixtures. Experience has shown that the more fresh the dry-mix shotcrete (i.e. shorter the time from first contact of moisture with the cementing materials until the time of impact on the receiving surface), the better the quality of the plastic and hardened shotcrete. With longer periods of time before discharge, the cement can start to prehydate and numerous small pellets of non-homogeneous material can be formed in the transit mixer. This can result in a reduction in the adhesive and cohesive quality of the shotcrete. Also, lesser thicknesses of build-up are achievable on vertical and overhead surfaces and the degree of rebound increases significantly. Properties of the hardened shotcrete, such as permeability and strength can also be adversely affected.

Site batching is the predominant means of supply of dry-mix SFRS to mines. Site-batched shotcrete usually has the advantage of a shorter time from first contact of water with the cementing materials, to the time of application, compared to transit mixer supply.

Dry-bagged premix supply is particularly well suited for supply of modern SFRS with its more numerous ingredients than conventionl dry-mix shotcrete. For example, dry-bagged premix SFRS mixtures commonly used in underground applications in Canada typically contains: Portland cement, silica fume, 10mm maximum size coarse aggregate, concrete sand, steel fibres, dry-powdered accelerators and sometimes dust suppressants. All ingredients are precision mass-batched in a controlled batch-plant environment. With site batching, particularly with volumetric site batching, there is always a danger of mis-batching one or more of ingredients in such multiple-component mixtures. Another major advantge of dry-bagged premix supply is very short time from first contact of moisture with the mixture, until it impinges on the receiving surface. Being totally bone-dry it is, however, desirable to premoisturize the shotcrete prior to discharge into the shotcrete gun. This can be done using either a premoisturizer auger or a long hydronozzle with initial wetting of the shotcrete 1 to 2 m before the end of the nozzle.

Small (30 kg) paper bags have been used for supply of premixed SFRS, but the system which is most widely used underground in North America is supply in large synthetic cloth bulk bin bags (1600 kg typical). This method of supply is particularly well suited to use in remote and difficult to access locations. Being totally bone-dry the material can be used at any time after batching. The bags do, however, have to be transported and stored so as to prevent moisture from causing prehydration of the cement. Also, during periods of cold weather the bags should be stored in a protected location. The in-place shotcrete temperature at the time of application should not be allowed to fall below 5° C; otherwise rebound tends to increase and the shotcrete may be slow in setting and developing strength. The use of excessively hot shotcrete (say greater than 35°C) should also be avoided.

8.0 PROPERTIES OF PLASTIC SHOTCRETE

8.1 Wet-Mix Shotcrete

Table 2 shows wet-mix SFRS mixture designs for :

* a SFRS research project conducted in Canada (Morgan, 1997);
* a tunnelling project completed in Canada in 1997;
* a SFRS optimization study conducted at a mine in Australia in 1997;

All of this work was conducted by the author's company.

It can be seen that SFRS can be pumped and shot at slumps as low as 35 mm. Generally, however it is desirable to keep the slump in the range of 80-30mm. Higher slumps are possible when using the high air volume concept and/or accelerator addition at the nozzle.

As previously mentioned the use of high air contents (8 to 10 percent at the nozzle) can be beneficial in enhancing workability, reducing pumping pressures, and acting as a slump killer, as the air content is reduced as the shotcrete impacts on the receiving surface. In frost exposure environments (e.g. many tunnels and portals in northern climates and high mountain regions) the use of a high air content in the as-batched shotcrete is important in order to produce a satisfactory air void system in the in-place shotcrete for freezing and thawing durability. (Beaupre et al, 1994; Morgan, 1988).

8.2 Dry-Mix Shotcrete

Clearly, slump is not pertinent to the dry-mix shotcrete process. The shotcrete should, however, be shot at the wettest stable consistency in order to provide optimum hardened shotcrete properties. This state refers to the condition where there is sufficient water added at the water ring to properly wet-out the dry-mix materials, without excessive sagging or sloughing. If the shotcrete is shot too dry, porous layers (commonly referred to as sand lenses) can result and overall and fibre rebound can increase markedly. (Armelin, 1997). Dry-mix shotcrete can be air-entrained, either by the purposeful addition of dry powdered air entraining admixtures to the mix, or by addition of a liquid air entraining admixture to the mix-water added to the nozzle. This system is, however, mainly only used in infrastructure rehabilitation in aggressive freezing and thawing and deicer chemical exposure environments e.g. bridge rehabilitation in Quebec, Canada (Beauppre et al, 1997).

9.0 PROPERTIES OF HARDENED SHOTCRETE

9.1 Compressive and Flexural Strength

Table 3 and 4 give the results of tests on hardened shotcrete for the wet-mix SFRS mixture design detailed in Table 2. These tables give an appreciation of the typical performance characteristics of range of different modern SFRS mixture in research, tunnelling and mining applications. The specified compressive strength of 30 MPa at 7 days and 40 MPa at 28 days is commonly achieved with a well-designed SFRS mixture made with good quality materials and application procedures. In some mining projects, where the shotcrete is only required to perform its required function for a year or two before the opening is backfilled, or allowed to collapse, a less stringent compressive strength specification may be used, e.g. 20 MPa at 7 days and 30 MPa at 28 days. Attempts to make very lean, (low cementing materials content) lower strength shotcretes should, however, be avoided, as the shotcrete may fail to perform satisfactory; adhesio in and thickness of build-up may be inadequate and rebound and sloughing is likely to become excessive.

Flexural strength is usually only specified and measured as part of a flexural toughness test, such as the ASTM C1018-94b test or JSCE SF-4 test. If a flexural strength and toughness is specified, it is recommended that it be conducted at an age of 7 days after shooting. In most underground applications the owner cannot afford to wait 28 days to find out whether there is a problem with the shotcrete. A minimum flexural strength of 4.0 MPa at 7 days is commonly specified in SFRS underground projects in North America. In some mining projects this may be relaxed to 3.5 MPa. Flexural strength and toughness is seldom measured at both 7 and 28 days; the testing simply becomes too costly. Also, the change in toughness from 7 to 28 days is typically small.

9.2 Permeability

The ASTM C642 test for boiled absorption and volume of permeable voids has proven useful for quntifying the quality and durability of both concrete and shotcrete. The Victoria, Roads Department (VICROADS, 1996), Australia has incorporated this test method into their specifications for cast concrete. They conduct the test on cast concrete cylinders at age 28 days. For shotcrete it is recommended that the test be conducted on cores extracted from shotcrete test panels, at age 7 days. Table 5 details the VICROADS Durability Classifiction for cast concrete cylinders at 28 days and compares these to the suggested Indicators of Shotcrete Quality proposed by (Morgan, 1988) a decade earlier for extracted shotcrete cores. This ASTM C642 test has proven valuable in identifying shotcrete which has suffered from poor consolidation, because of either inadequate shotcrete materials or mixture design, or poor shooting technique. It has also been able to identify mixtures which have been burned-out by excessive accelerator addition. Form examination of the test data in Table 3, it is apparent that all of the shotcretes tested satisfied the Table 2 performance limits of : max boiled absorption of 8% and maximum volume of permeable voids of 17.0%. Less stringent limits of max. boiled absorption of 9.0% and max. volume of permeabale voids of 19.0% have been allowed in some mining applications where long life is not required of the shotcrete. Note that shotcretes with higher than specified values for these prameters are vulnerable to leaching (elution) and deterioration in wet installations, particulrly if sulphates or other aggressive salts are present in the ground water.

9.3 Shrinkage Crack Control

Extensive experience in the field has demonstrated that at appropriate addition rates, steel fibre reinforcement is very effective in mitigating restrained drying shrinkage and thermally induced cracking in shotcrete. The ability of steel fibres to keep crack widths tight or even totally eliminate cracking, is well demonstrated in the restrained ring shrinkage test results shown in Fig. 13, conducted on plain and steel fibre reinforced concretes (Gryzbowski, 1989). The use of fibre reinforcement in itself may however, not be sufficient to control cracking. There must be proper SFRS mixture design, with control of the water demand of the mixture (e.g. use of water reducers and superplsticizers) and the use of moist curing is recommended.

10.0 TOUGHNESS OF SFRS

Measurement of the post first-crack residual load carrying capacity of fibre reinforced shotcrete is probably the most meaningful way of evaluating the relative effects of different fibre types and addition rates in SFRS. A variety of different methods have been developed for this purpose. These include:

* ASTM toughness indices and residual strength factors (ASTM C1018-94b)
* Japanese toughness and toughness factor (JSCE-SF4, 1984).
* Norwegian residual flexural stress method (Nowegian Concrete Association, 1993).
* EFNARC energy absorption method (EFNARC, 1996).
* Toughness Performance Level (Morgan et al, 1995) and (Austrian Draft Shotcrete Guide, 1997).

The ASTM C1018, JSCE-SF4 and Toughness Performance Levels can all be calculated from a load vs deflection plot generated from a flexural test in third point loading on a 100 x 100 x 350 mm beam loaded on a 300 mm span. Results of toughness tests on the mixes given in Table 2 are detailed in Table 4 and Figs. 14 and 15. While some engineers in North America still continue to specify ASTM C1018 toughness index values for SFRS the trend is increasingly to not use toughness indices, but to specify residual strengths, such as in the Toughness Performance Level method (Morgan et al, 1995) and (Austrian Draft Shotcrete Guide, 1997). Table 6 defines these toughness performance level (TPL) values. Figures 14 and 15 show the TPL values achieved with different steel fibre types at different fibre addition rates.

In a low stress environment, where the steel fibre is used primarily for thermal and shrinkage crack control a TPL III might be specified. In an underground tunnelling or mining application with the potential for large rock stresses and/or deformtions, a TPL IV might be specified. It is believed that the TPL method will be increasingly used in specifications as engineers build up empirical experience of the behaviour of SFRS with different TPL values in various practical applications.

11.0 SHOTCRETE APPLICATION

Key to any successful SFRS construction is the use of a well-trained and experienced shotcrete application crew. One can have the best quality steel fibres and shotcrete making materials, with good shotcrete mixture designs, but the quality of the end-product will only be as good as the competence of the shotcrete crew. The skills of the nozzleman are paramount in this regard, especially for the dry-mix shotcrete process. The nozzleman must apply the shotcrete at the correct consistency; SFRS mixtures which are shot too dry will have large increases in overall and steel fibre rebound.

Similarly, SFRS mixtures which are not applied at the correct velocity, or shooting orientation (i.e. at right angles to the receiving surface), will display increases in overall and steel fibre rebound (Armelin et al, 1997). This will downgrade the properties of the in-place SFRS, including toughness, impact resistance and shrinkage crack control.

It is thus incumbent on the owner to implement an appropriate shotcrete quality assurance (Q.A.) program to ensure that the required end-product is achieved. Such QA program should include rigorous monitoring of the contractors quality control (Q.C.) procedures, including results of all Q.C. testig during both preconstruction and construction testing; (Morgan, 1997) provides a comprehensive review of shotcrete quality management (QA plus QC) programs adopted in North America. Good guidance is also given in the ACI 506.2R-95 Specification for Shotcrete.

It is strongly recommended on any major shotcrete project the preconstruction testing be conducted to :

* Verify the conformance of the applied shotcrete to the project specifications i.e. acceptability of the shotcrete materials and mixtures design; and
* Prequalify the shotcrete nozzleman and crew, proposed for use on the project.

Preconstruction testing is built into most major shotcrete Q.A. programs in North America. It is usually only waived on small projects, or where the contractor can demonstrate suitable previous experience on similar projects, with the same crew and similar materials.

In closure, while SFRC has been demonstrated to be a technically and economically viable alternative for underground support in many tunnels and mines, the cost of the in-place SFRS is substantial and implementation of rigorous Q.A./Q.C. program is necessary to protect the Owner's investment.

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Table 1: Wet - Mix SFRS Peformance Specification for a Canadian Tunnelling Project

Shotcrete Properties	Test Method	Age (Days)	Specified Limits
Maximum Water/Cementitious Materials Ratio		-	0.45
Air Content - As Shot, %*	CSA A23.2-4C	-	4 ± 1%
Slump at Discharge into Pump, mm	CSA A23.2-5C	-	80 ± 30
Minimum Compressive Strength, MPa	CSA A23.2-14C	7 28	30 40
Maximum Boiled Absorption, % Maximum Volume of Permeable Voids, %	ASTM C642	7 7	8 17
Minimum Flexural Strength, MPa Minimum Flexural Toughness	ASTM C1018 & Morgan et al 1995	7 7	4.0 Toughness Perforamnce Level III
Shotcrete Core Grade	ACI 506.2-95	-	Mean Core Grade not greater than 2.5 No individual Core Grade greater than 3.

*Determine air content on shotcrete shot into a CSA-A23.2-14C air pressure meter base.

Table 2: Wet-Mix SFRS Mixture Designs Proportions in Kg/m³ Based on SSD Aggregates

Project	Research Study			Tunnel Canada	Mine Australia		
Mix No.	A1	A2	A3	B1	C1	C2	C3
Cement	401	398	394	385	420	420	420
Silica Fume	40	40	39	49	40	40	40
Coarse Aggregate 10 mm Max. size, mm	305	265	300	524	420	420	420
Fine Aggregate	1373	1402	1351	1207	1260	1260	1260
Water	172	177	171	160	190	190	190
Steel Fibre	60	60	59	59	40	50	60
Type							
Water Reducer (L)	-	-	-	1074	2.0	2.0	2.0
Superplasticizer (L)	2.0	2.0	2.0	3.5	4.0	4.0	4.0
Air Entraining admixture (L)	0.005	0.005	0.005	Yes	No	No	No
Accelerator	No	No	No	Yes	No	No	No
Total	2354	2344	2317	2389	2336	2346	2356

Note : Steel Fibre Type
A1 : 30 mm Corrugated
A2 : 30 mm Enlarged End
A3 : 30 mm Hooked End
B1 : 30 mm Hooked End
C1,C2,C3 : 30 mm Enlarged End

Table 3: Wet-Mix SFRS:Properties of Plastic and Hardened Shotcrete

Project	Research Study,Canada*			Tunnel Canada**	Mine Australia*		
Mix No.	A1	A2	A3	B1	C1	C2	C3
Slump mm	40	35	75	80 ± 30	70±20	70±20	70±20
Air Content, %							
As Batched	5.5	6.2	13.0	8.6	2.0	2.0	2.0
As Shot	4.1	4.1	5.5	4.2	-	-	-
Compressive Strength, MPa							
7 days	38.5	38.4	40.1	40.1	22.6	25.1	22.6
28 days	56.8	50.5	55.5	60.9	41.5	39.4	32.6
ASTM C642							
Boild Absorpion,%	2.4	3.6	2.5	4.8	7.4	6.6	7.4
Vol. of Permeable Voids, %	6.7	8.8	6.4	11.0	15.7	14.4	15.5

Notes:
* Average of 3 sets of test per panel
** Average of 9 sets of panels (3 tests per panel)

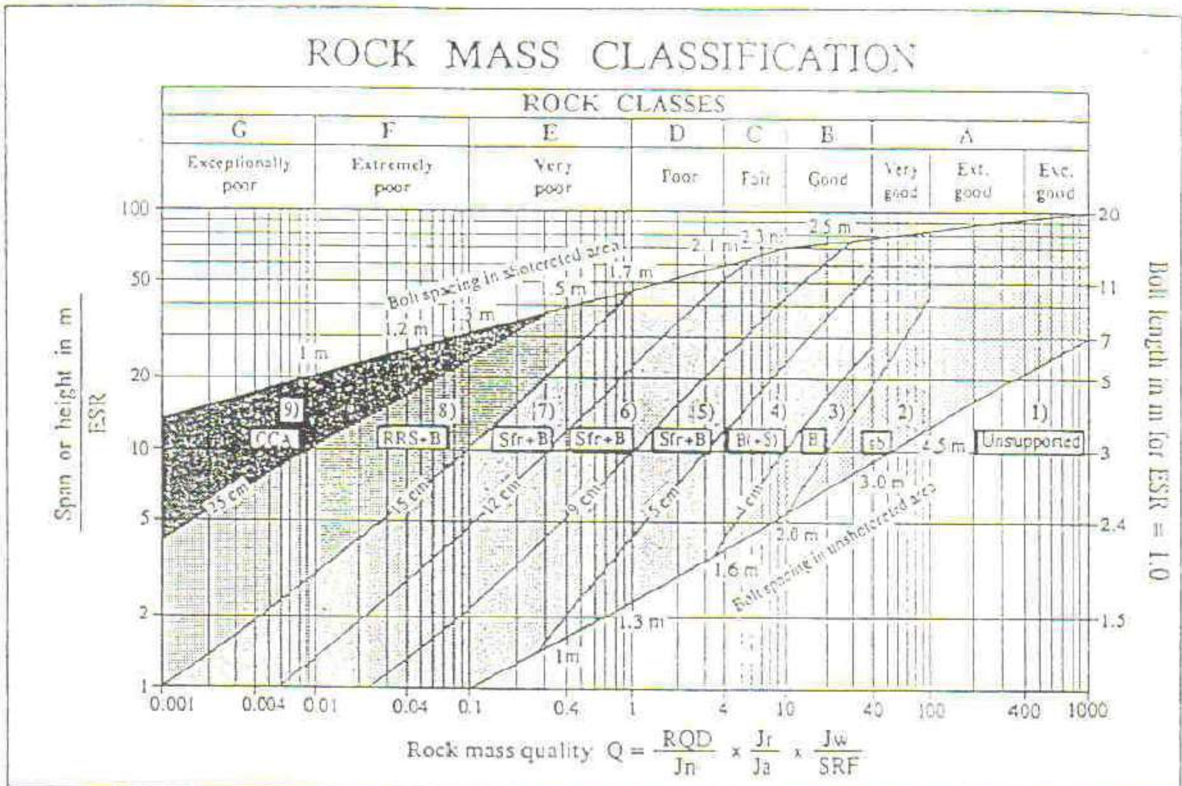
Table 4: Flexural Toughness of Wet-Mix SFRS

Project	Research Study,Canada*			Tunnel Canada**	Mine Australia*		
Mix No.	A1	A2	A3	B1	C1	C2	C3
Steel Fibre Content . kg/m^3	60	60	59	59	40	50	60
Flexural Srength, MPa at 7 days	5.1	5.1	5.8	5.4	4.1	4.7	4.9
ASTM C1018-94b Toughness Indices I_{10}	6.4	8.1	9.4	8.8	5.7	9.1	8.3
IP_{30}	14.8	24.6	29.6	25.6	13.6	23.3	22.7
I_{60}	25.7	50.9	57.0	46.2	25.4	44.1	44.0
Residual Strength Factor $R_{10,30}$	41.9	82.8	100.7	84.1	39.5	71.0	72.0
$R_{30,60}$	36.3	87.5	91.5	68.8	39.3	69.3	71.0
JSCE-SF4 Toughness,KN;mm	14.6	29.1	32.0	21.9	9.7	17.0	19.9
Toughness, Factor, MPa	2.1	4.4	4.6	3.2	1.7	3.0	3.5
Toughness Performance Level (Morgan et al, 1995)	III	V	V	IV	II-III	IV	IV

Note : Steel Fibre Type A1 : 30 mm Corrugated
A2 : 30 mm Enlarged End
A3 : 30 mm Hooked End

Table 5: ASTM C642 Durability Classification for Cast Concrete and Shotcrete Quality Indicators

<table>
<tr><th colspan="3">Durability Classification for Cast Concrete (VICROADS, 1996)</th><th colspan="3">Quality Indicators for Shotcrete (Morgan, 1988)</th></tr>
<tr><th>Durability Classification Ranking</th><th>VPV %</th><th>Boild Absorption %</th><th>VPV %</th><th>Boiled Absorption %</th><th>Suggested Quality indicator</th></tr>
<tr><td>1. Excellent</td><td><14</td><td><6</td><td><14</td><td><6</td><td>Excellent</td></tr>
<tr><td>2. Good</td><td>14-16</td><td>6-7</td><td rowspan="2">14-17</td><td rowspan="2">6-8</td><td rowspan="2">Good</td></tr>
<tr><td>3. Normal</td><td>16-17</td><td>7-7.5</td></tr>
<tr><td>4. Marginal</td><td>17-19</td><td>7.5-8.5</td><td>17-19</td><td>8-9</td><td>Fair</td></tr>
<tr><td>5. Bad</td><td>>19</td><td>>8.5</td><td>>19</td><td>>9</td><td>Marginal</td></tr>
</table>



REINFORCEMENT CATEGORIES:

1) Unsupported
2) Spot bolting, sb
3) Systematic bolting, B
4) Systematic bolting, (and unreinforced shotcrete, 4-10 cm), B(+S)
5) Fibre reinforced shotcrete and bolting, 5-9 cm, Sfr+B
6) Fibre reinforced shotcrete and bolting, 9-12 cm, Sfr+B
7) Fibre reinforced shotcrete and bolting, 12-15 cm, Sfr+B
8) Fibre reinforced shotcrete >15 cm, reinforced ribs of shotcrete and bolting, Sfr,RRS+B
9) Cast concrete lining, CCA

Figure 1: Rock mass classification permanent support recommendation (Barton et al., 1995).

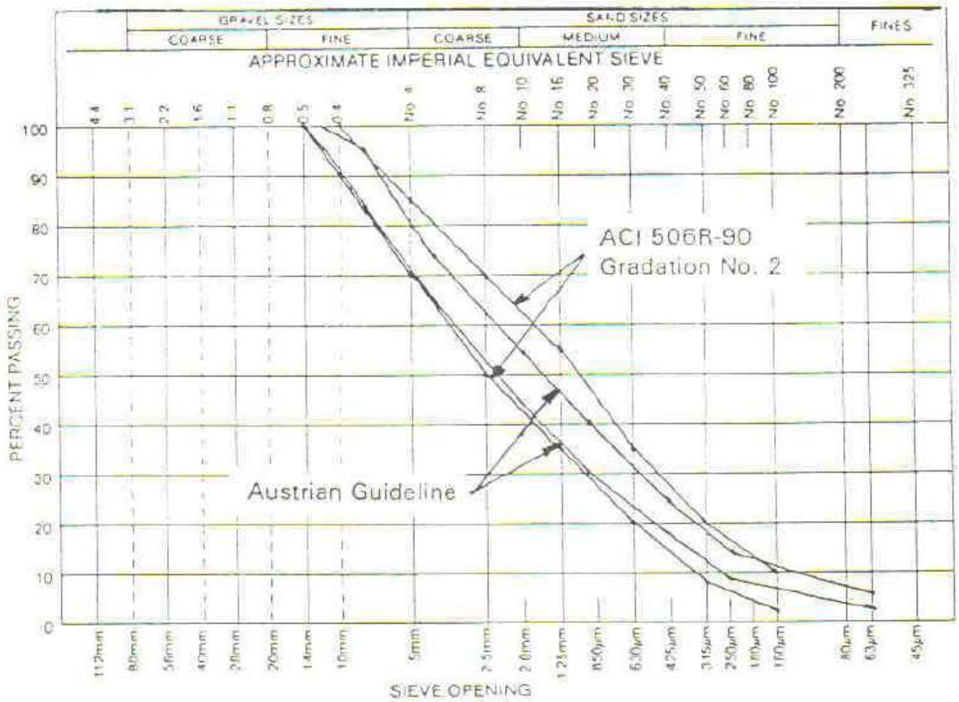


Figure 2: Shotcrete aggregate: ACI 506R-90, Table 2.1, Gradation No.2 for shotcrete aggregate and Austrian specification.

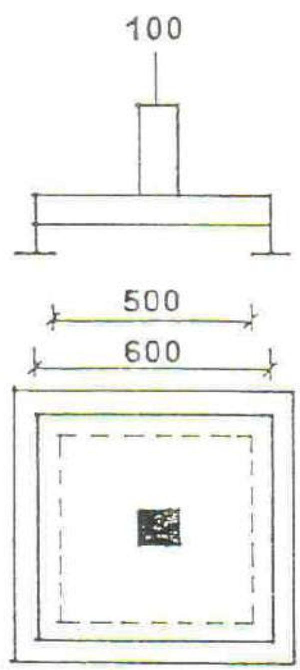


Figure 3: EFNARC fibre reinforced shotcrete toughness test set-up.

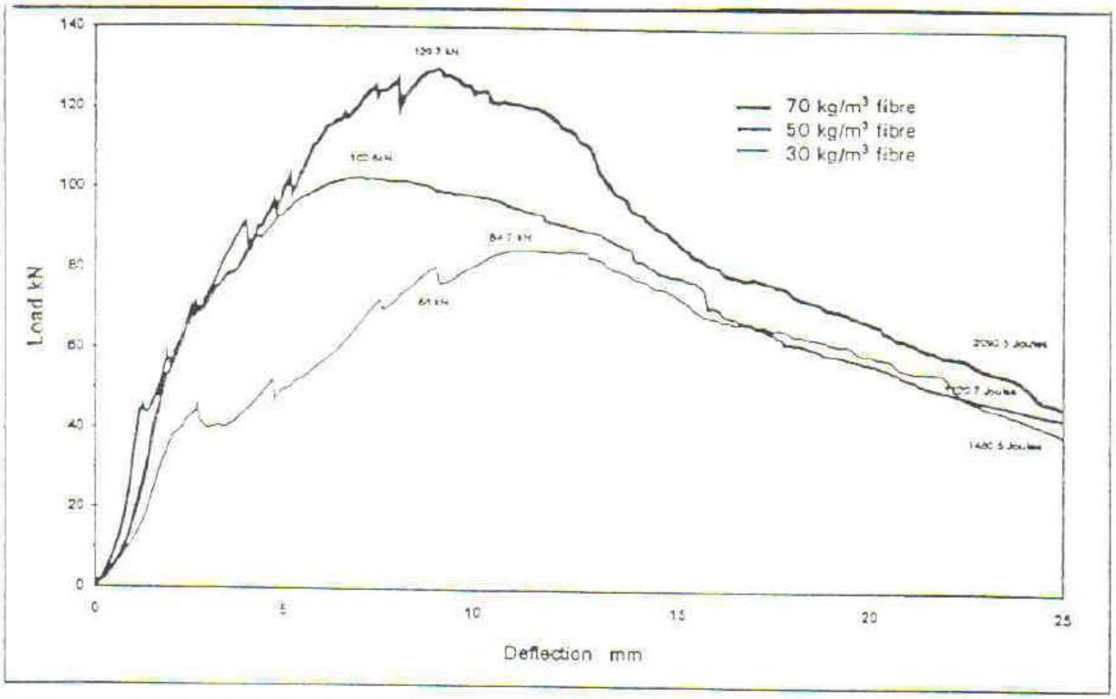


Figure 4: Load vs. deflection curves for SFRS with hooked end fibres at three different addition rates in EFNARC test.

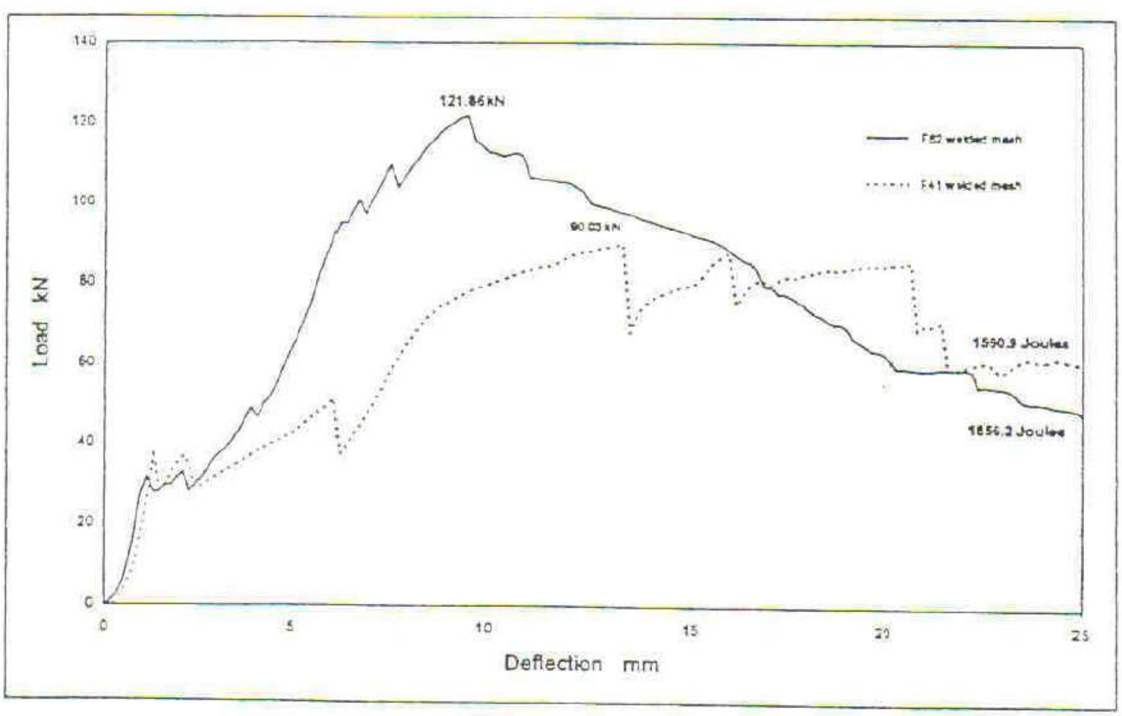


Figure 5: Load vs. deflection curves for two different mesh reinforced shotcretes in EFNARC test.

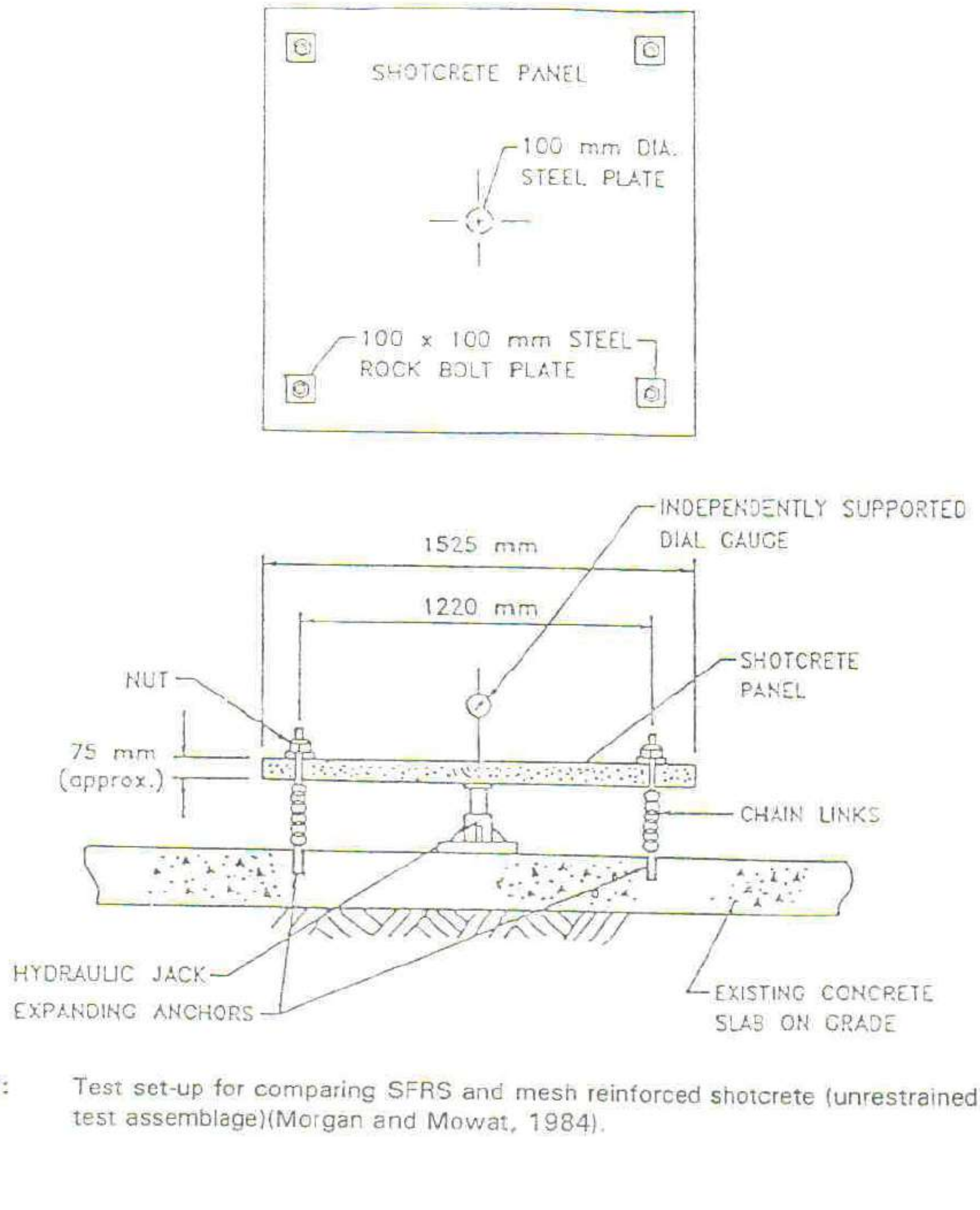


Figure 6: Test set-up for comparing SFRS and mesh reinforced shotcrete (unrestrained test assemblage)(Morgan and Mowat, 1984).

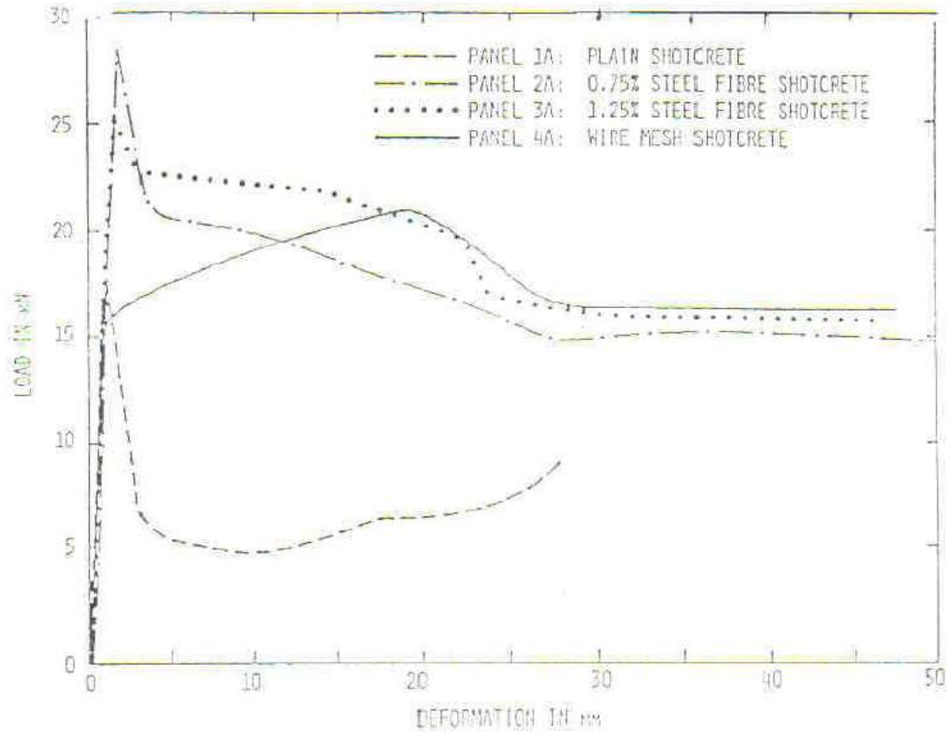


Figure 7: Load vs. deflection curves for restrained test assemblage (Morgan and Mowat, 1984).

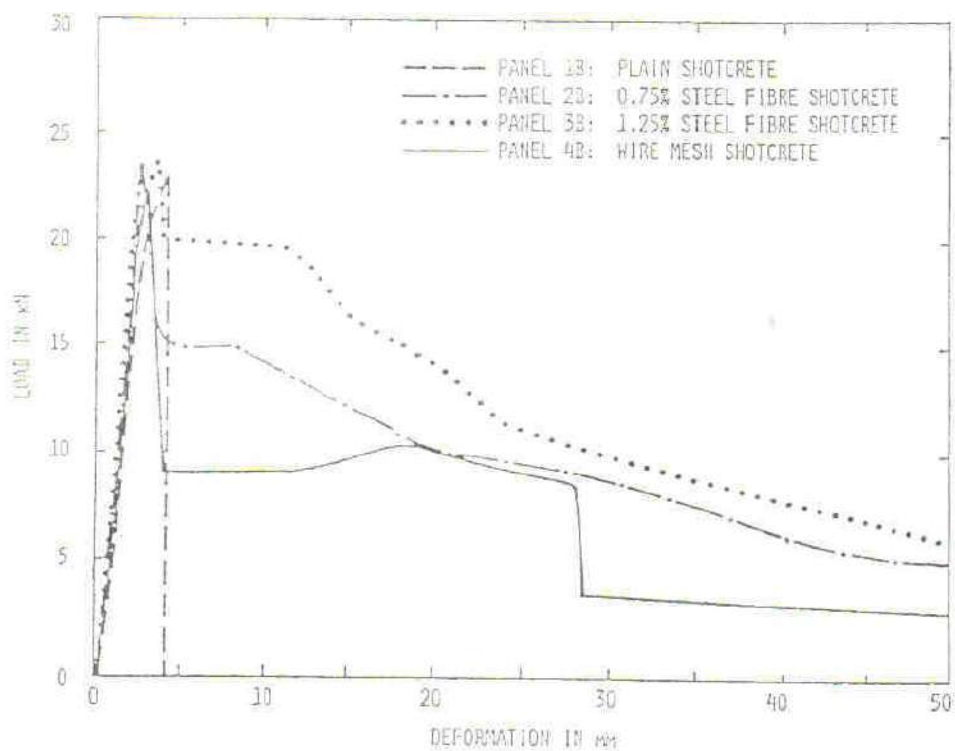


Figure 8: Load vs. deflection response for unrestrained test assemblage (Morgan and Mowat, 1984).

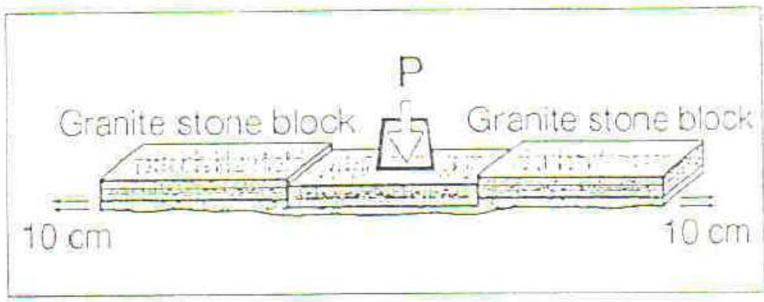


Figure 9: Simulated falling block test on steel fibre and mesh reinforced shotcrete (Morch, 1993).

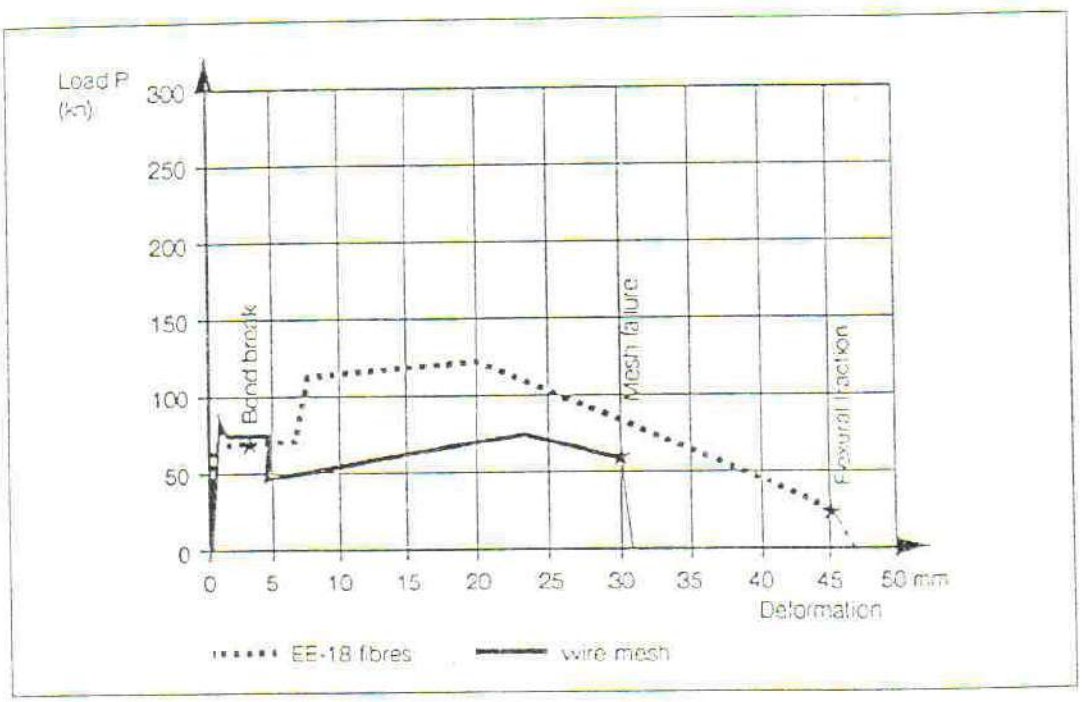


Figure 10: Load vs. deflection response in falling block test (Morch, 1993).

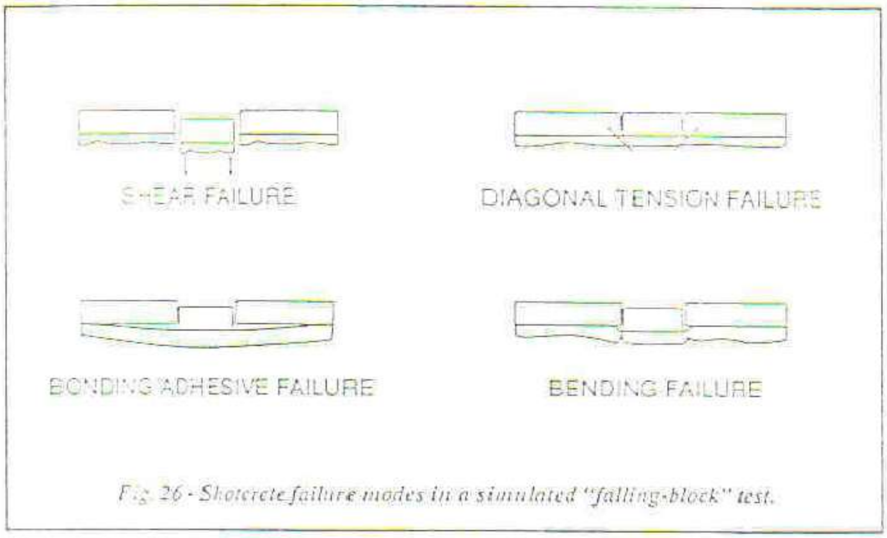


Figure 11: Potential modes of failure in falling block test (Morch, 1993).

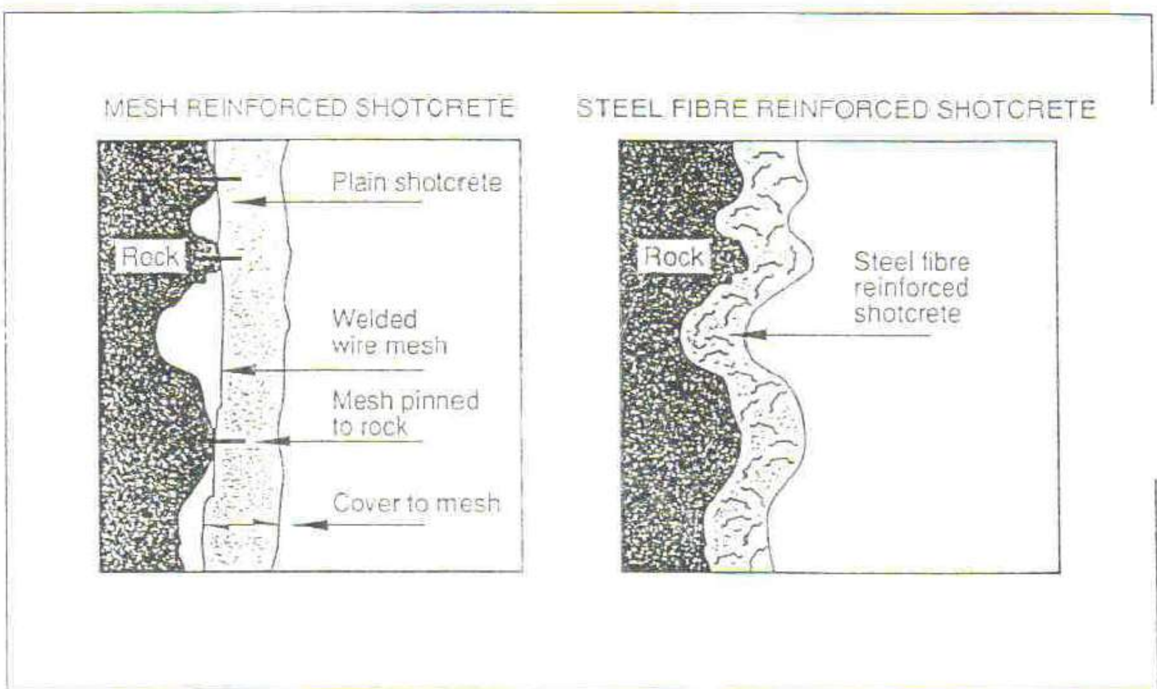


Figure 12: Difference in shotcrete consumption when using wire mesh or steel fibre i shotcrete (Vandewalle, 1990)

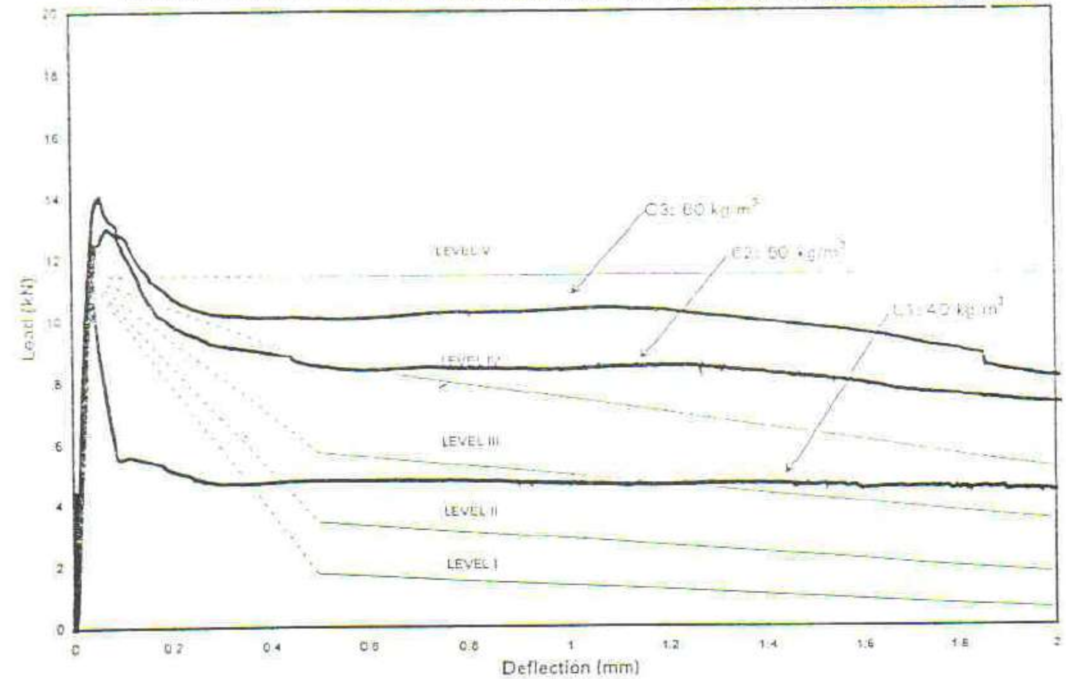


Figure 13: Load vs. deflection response of enlarged end fibres in SFRS at different fibre addition rates and Toughness Performance Levels.

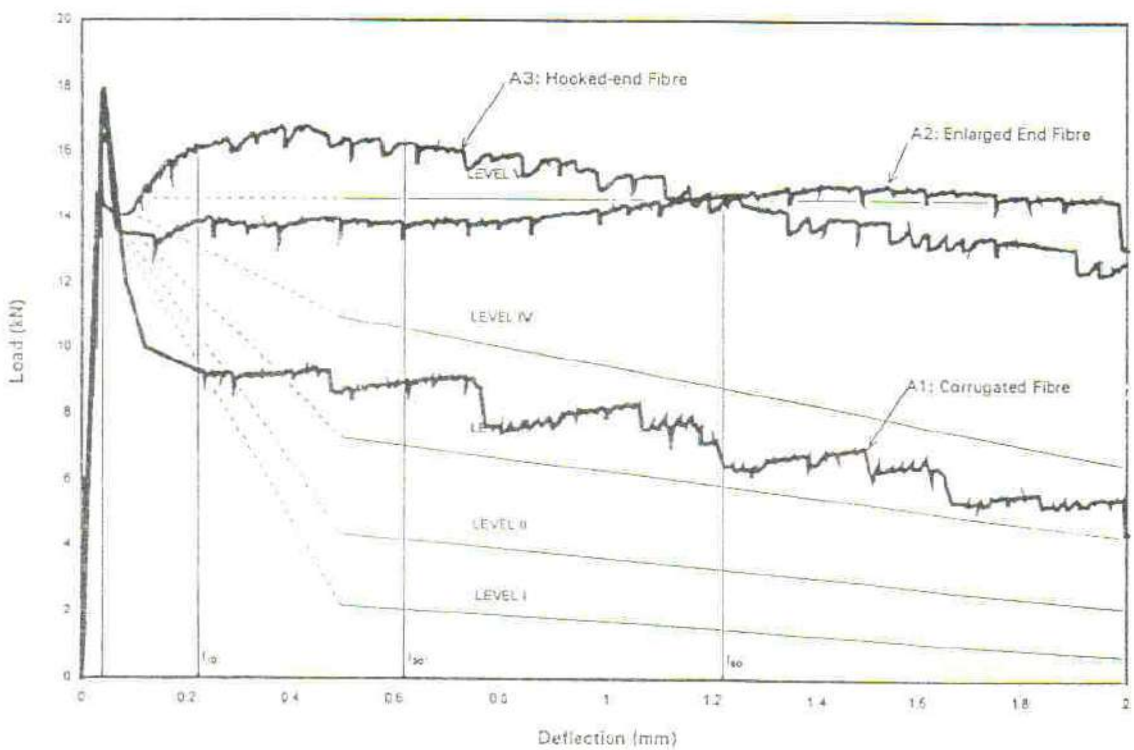


Figure 14: Load vs. deflection response of SFRS with three different types of steel fibres at 60 kg/m³ and Toughness Performance Levels.