State of the Art of the Fibre Reinforced Shotcrete

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Abstract—The fiber reinforce shotcrete is sprayed concrete reinforced with discrete fibers. The reinforcement of shotcrete by fiber improves toughness, resistance to impact, durability fatigue endurance limits. It is progressively replacing the wire mesh reinforcement. In view of the above, the authors have made an attempt to present with the study of fiber-reinforced shotcrete for supporting underground openings against failure due to rock discontinuity and induced stresses. The main objectives of the work are as follows:
- Comparison of steel fiber Vs Mesh reinforced concrete
- Characterization of different kinds of fibers for application in shotcrete.
- Status of shotcrete support for Underground excavations.

Key words: Fibre, Shotcrete

I. INTRODUCTION

The induced stresses cause severe failure in roof and sides of the opening. Such stress-induced failures are controlled to some extent by rock bolts with wire mesh and steel arches. The shotcrete is an effective means of supporting galleries and underground roadways under high stress and / or poor rock conditions. The fiber-reinforced shotcrete placed on the surface of the opening, form an integral part of the rock mass. Hence it mobilizes and conserves the inherent strength of the rock mass so that it becomes self-supporting. It acts in the same way as the wire mesh; it prevents small pieces of rock from unraveling form surface of the excavation. A thin layer of shotcrete effectively isolates the weathering susceptible rock form coming in contact with the weathering agents, e.g. air and water. It thus maintains integrity of the rock mass around the openings.

The shallow deposits are gradually vanishing and we have to go deeper for sustaining the future ore demand. Besides other important technological problems, high rate of advance, proper support and maintenance that the need of fiber reinforced shotcrete as a support medium quickly becomes apparent.

II. MESH REINFORCED CONCRETE VS STEEL FIBRE REINFORCED CONCRETE (SFRS)

Concrete being a brittle material and having inherent tensile weakness, is highly prone to cracks and this, it is reinforced with wire mesh or steel fibres.

Wire mesh is available in rolls and this is cut to pieces suiting to the site requirements and length of pull. Fixing of wire mesh is a time consuming and laborious process and is the main sub-activity responsible for the extended overall cycle time.

Though the blasting operations are carried out with utmost precautions with controlled technique, blasted profile obtained is not smooth and regular. On an irregular surface, the mesh is pinned mostly at spots that project from the surface. It is pinned back inside depressions but it is draped over most small ones.

Another advantage is that SFRS can follow the exact contour of the rock. Improper shooting technique can result in voids behind reinforcing mesh. The wires of the mesh cause a much higher rebound of the bigger aggregate.

In 1979, Morgan and Mowatt under to detailed compared evaluation of plain mesh and steel fibre reinforced shotcrete. They demonstrated in load/deformation tests on large panels that SFRS can provide superior residual load carrying capacity to wire mesh reinforced shotcrete small deformations after first crack and equivalent deformations (Vandewalle 1996).

The primary advantage of the wire mesh reinforcement is in its more effective action as a net of catenary wires at extensive deflections, once the shotcrete is substantially crack, whereas the steel fibre pull out of the shotcrete under these conditions. SFRS has proved to be more economical due to faster job progress, which has a positive influence on the overall cost comparison

III. TYPES OF FIBRES

Plain unreinforced shotcrete like unreinforced concrete, it is a relatively brittle material, with little capacity to resist tensile load or strain without cracking and disruption. Reinforcement of shotcrete is required to increase its ductility and toughness characteristics. The common reinforcing elements in shotcrete are wire mesh and fibre. It was not until the early 70's that the first experimental work was undertaken with the steel fibre reinforced shotcrete.

The use of fibres has reinforcement in shotcrete is well established in many countries, including the U.S.A. Canada, South Africa, Germany, Sweden, Norway, Austria, Australia, Finland and more recently in India.

American Standard for Testing Materials (ASTM) - A820 classifies fibre reinforcement in three categories
- Steel fibre reinforced shotcrete
- Glass fibre reinforced shotcrete
- Synthetic fibre reinforced shot Crete

However, we are restricting to the study of steel fibre reinforced shotcrete only in this report.

A. Steel Fibres

The critical parameters of the steel fibres are its length, length/thickness or dia. ratio (l/d) and the shape of the steel fibre (Melbye 1994). A longer steel fibre, permits better overlapping of the same in the mass of concrete. However the diameter of the spraying nozzle make the use of fibres more than 35mm in length impossible. The diameter of the steel fibre if small compared to the length, the number of steel fibres can be increased in the distribution will be effective, the higher l/d ratio (around 100) will have greater effectiveness on the mechanical characteristics of the
shotcrete. The shape of the fibre influence the ability to bond with the cement and its resistance to on threading are essential characteristics of a good fibre. The types of steel fibres and their characteristics are as shown in the table 1 and 2.

<table>
<thead>
<tr>
<th>Make</th>
<th>Shape</th>
<th>Type</th>
<th>Package</th>
<th>Method of production</th>
<th>Length mm</th>
<th>Dia mm</th>
<th>L/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bekaert</td>
<td>ZP 30/80</td>
<td>Soluble glue</td>
<td>Steel wire C10导演</td>
<td>Cold drawn</td>
<td>30</td>
<td>0.80</td>
<td>37.5</td>
</tr>
<tr>
<td>ILM</td>
<td>25/90</td>
<td>Loose</td>
<td>Steel wire C10导演</td>
<td>Cold drawn</td>
<td>25</td>
<td>0.90</td>
<td>27.8</td>
</tr>
<tr>
<td>Fibrocev</td>
<td>30</td>
<td>Loose</td>
<td>Lamina</td>
<td></td>
<td>30</td>
<td>0.63</td>
<td>47.6</td>
</tr>
<tr>
<td>Harex</td>
<td>1-32</td>
<td>Loose</td>
<td>Milled from steel</td>
<td></td>
<td>32</td>
<td>1.12</td>
<td>28.6</td>
</tr>
<tr>
<td>Draco</td>
<td>30/80</td>
<td>Loose</td>
<td>Drawn steel wire</td>
<td></td>
<td>30</td>
<td>0.80</td>
<td>37.5</td>
</tr>
<tr>
<td>Edilikem</td>
<td>30</td>
<td>Loose</td>
<td>Lamina</td>
<td></td>
<td>30</td>
<td>0.73</td>
<td>41.1</td>
</tr>
</tbody>
</table>

Table 1: Showing the Different Shapes and Sizes of Commercial Steel Fibres (Tesio, et.al., 1991)

For fibres with a rectangular or deformed circular section the equivalent diameter was calculated using the formula Dia = 2(√A÷√π)

Table 2: Recommendations for Steel Fibre Reinforced Shotcrete ASTM - 820

The main reason for incorporating steel fibres in shotcrete is to impart ductility, to other wise brittle material. Steel fibre reinforcement improves the energy absorption, impact resistance and crack resistance of shotcrete. The various properties of Steel fibre reinforced shotcrete are as follows.

1) Flexural Strength & Toughness Index

As per the USA standard ASTM C – 1018 - 89, a test beam cut from a shotcrete test panel is subjected to third point loading in flexure and a load Vs deformation curve is plotted. Flexure strength is defined at the first crack and subsequently the various toughness indices I.

The first crack is defined as the point at which the load – deflection curve deviates from the straight line. A toughness index is the ratio of absorbed energy up to a given deflection to a absorbed energy up to the first crack. The area below the load – deflection curve is a measure of the absorbed energy.

In the standard toughness indices I, I<sub>10</sub> and I<sub>30</sub> are defines for a deflection 3δ, 5.5 δ and 15.5δ where δ is the deflection of the first crack for elastic and fully elastic – plastic behavior have been shown in the table 3

A plain shotcrete would fall upon apart after reaching first crack and thus by definition have a toughness index I = 1.0.As per Morgan the table 3 shows the values of toughness index with SFRS on the basis of result of tests have been indicated as follows.

Table 3: Showing Values of Toughness Index

<table>
<thead>
<tr>
<th>Category</th>
<th>Rating</th>
<th>I&lt;sub&gt;10&lt;/sub&gt;</th>
<th>I&lt;sub&gt;30&lt;/sub&gt;</th>
<th>R&lt;sub&gt;50/10&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Marginal</td>
<td>&lt;4</td>
<td>&lt;12</td>
<td>&lt;40</td>
</tr>
<tr>
<td>II</td>
<td>Fair</td>
<td>6</td>
<td>12</td>
<td>40</td>
</tr>
<tr>
<td>III</td>
<td>Good</td>
<td>6</td>
<td>18</td>
<td>60</td>
</tr>
<tr>
<td>IV</td>
<td>Excellent</td>
<td>8</td>
<td>24</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 4: Showing the Shotcrete Classes According To Finnish Guide Lines

If the material concerned were perfectly elastic, the value of R<sub>30/10</sub> obtained would be 100. Flexural strength increases with increase in aspect ratio and volume concentration of steel Fibres.

2) Compressive Strength

Compressive strength is little influenced by steel fibre addition. It is mainly controlled by shotcrete matrix design, if higher compressive strength is required silica fumes along with additives can be used. The test provides data as per the ASTM D – 2938 - 86 in determining the strength properties of rock specimen namely Peak compressive strength, peak shear strength at various lateral pressures, coefficient of friction and cohesion intersect.

<table>
<thead>
<tr>
<th>Class</th>
<th>Min. Comp Strength</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>K30</td>
<td>Sites with strict structural requirement e.g. bridges</td>
</tr>
<tr>
<td>II</td>
<td>K30</td>
<td>Rock reinforcement normal concrete structures etc.</td>
</tr>
<tr>
<td>III</td>
<td>K20</td>
<td>Temporary support during the excavation to ensure the safe continuation of the excavation process.</td>
</tr>
</tbody>
</table>

Characteristics | Test method | Minimum requirements |
|----------------|-------------|----------------------|

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The bond strength determination above by pull out test equipment more or less resembles like a tensile testing of the specimen, which gives the tensile strength at the interface rather than the bond strength. Hence the values may not reflect in actual bond strength.

4) Tensile Strength

The tensile strength of the rock specimen can be directly measured for the characterization of intact rock as per the ASTM D 2936. The tensile strength of the specimen can be calculated by dividing the maximum load applied by the original cross sectional area. The tensile strength can also be indirectly determined by the Brazilian test. The justification for the test based on the experimental fact that most rocks in biaxial stress field fail in tension at their Uniaxial tensile strength when one principle stress is tensile and the other finite principle stress is compressive with a magnitude not exceeding three times that of the tensile principle stresses.

5) Shear, Normal Stiffness & Strength

This test measures peak and residual direct shear strength as a function of stress normal to the shear plane. These results are useful for limiting equilibrium analysis with the interface between concrete and rock. The normal stress and the shear stress are computed using standard formulae.

B. Polypropylene Fibre

Polypropylene fibres are resistant and durable in concrete environment. The addition of polypropylene fibres at the rate of 1 kg/m³ enhances resistant to plastic shrinkage and provide green strength to freshly applied shotcrete i.e. resistant to falling of shotcrete during finishing operation.

IV. ADDITIVES

The three important additives in the shotcrete mix are as follows,

A. Condensed Silica Fumes (CSF)

Condensed silica fumes are the very fine particles of amorphous silica recovered from the flue gases of silicon or ferrosilicon furnaces. The material consists of fine spherical particles with an average size of 0.1µm, which is about 100
times finer than particles of ordinary Portland cement (OPC). The bulk density varies between 200 to 250 kg/m³. The surface area of the CSF varies between 15,000 to 30,000m²/kg compared to that of fly ash 400 – 700m²/kg and OPC 300 – 400m²/kg (Vandewalle 1996).

Addition of CSF in the shotcrete mix has the following advantages

Improvement in Cohesiveness and Adhesiveness, substantial reduction in rebound on both vertical and overhead surfaces and increase in compressive strength. In shotcrete application, the amount of the CSF varies from 8% to 12% of cement weight.

B. Pulverized Fuel Ash (pfa)
Pulverized fuel ash, more commonly fly ash is a finely divided powder obtained as a by-product of combustion of pulverized coal in thermal power station. In general terms, and with particular regard to its use in concrete, pfa can be divided in to two distinct categories (Dhir, 1986).

- Low lime pfa (ASTM class F) and High lime pfa (ASTM class C)
- pfa is primarily used in wet mixed shotcrete for following reasons (Morgan, 1992)
  - Improves the workability and pumpability, Reduce the heat of hydration
  - Improves sulphate resistance rate, Controls alkali aggregate reaction
  - Control resistance, Provide more economical mixtures

C. Accelerators
When a rapid gain in the early strength of shotcrete is required in order to provide immediate support to the rock, accelerating admixtures or accelerators are added to mix. The addition of accelerators can also be used, improve shooting conditions and to reduce rebound particularly working overhead (Hoek & Brown, 1980). The normal dosage for most accelerators is around 2% by weight of cement, but sometimes up to 7% is used if extra rapid hardening is required. ASTM C 1141 gives the details about the requirements of admixtures for a dry and wet shot Crete mix.

V. SHOTCRETE MIX DESIGN
Actual mix depends upon the experience of the working people to select a first trial mix. Different trial mixes are then made and shot to select acceptable one. Based on the particular mix design the equipment design may also be different particularly the size of hosepipe and the nozzle.

<table>
<thead>
<tr>
<th>Components</th>
<th>Dry mix</th>
<th>Wet Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>419</td>
<td>419</td>
</tr>
<tr>
<td>49%</td>
<td>19.0</td>
<td>18.1</td>
</tr>
<tr>
<td>Silica fume additive</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Blended Aggregate</td>
<td>1670</td>
<td>1600</td>
</tr>
<tr>
<td>50%</td>
<td>75.5</td>
<td>68.9</td>
</tr>
<tr>
<td>Accelerator</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>0.60%</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>Super plasticizers</td>
<td>---</td>
<td>6L</td>
</tr>
<tr>
<td>0.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water reducer</td>
<td>---</td>
<td>2L</td>
</tr>
<tr>
<td>0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air entraining</td>
<td>---</td>
<td>If</td>
</tr>
<tr>
<td>1.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

VI. REBOUND
Rebound is defined as the material that ricochets off the receiving surface and fast to the ground during shotcrete operations (Morgan, 1991).

In all types of shotcrete, the material travels at high velocity to the rock surface. The lighter particles of cement, sand and steel fibres are carried towards the wall with higher velocity than the heavier coarse aggregates. First a thin layer is formed by the cement grout and sand particles less than 2mm in size. The fine material penetrates the pores and cracks and provides a foundation for the placement and compaction of total thickness. During the initial layer built up, most of the coarse aggregate rebound and fall to the floor. Finally a soft cushion of cement, sand and water is built up, and subsequent rebound drops up to 20% or less, as the new shotcrete strikes the soft cushion and adheres to it.

In welded mesh rebound is more due to the vibrations of the mesh. Thicker the shotcrete layer lesser will be the rebound of coarse aggregate and fibre. The final in place of fibre contents depends upon the following factors, including (Morgan, 1991).

- The fibre rebound is higher in thin shotcrete layers
- Higher the overall rebound the lower the in place steel fibres content
- Coarse aggregate gradations can increase fibre and overall rebound
- Fibre and overall rebound is higher in dry mix
- It depends upon the shooting technique, including air pressure, shooting distance and nozzle orientation to the receiving surface.

It was found that for the same dry shotcrete mix rebound from coal sidewalls in Moonidih Mine were about 15% and 20% in Jhanjra. This is due to the surface at the Jhanjra Mine was smoother. The rebound of coarser material by dry mix was about 20%. The fibre losses were 78% to 59%. The fibre content in the shotcrete layers were virtually independent of layer thickness. However there was decrease
in the total material rebound with increase in the layer thickness.

Some of the remedial measures can be taken to reduce rebound are as follows (Sharma, 1995)
- Reduction of air pressure: Reduction of air velocity
- Use of more fines: Use of small size aggregates
- Use of shorter and thicker steel fibres: Pre-dampening
- Shotcreting at the wettest stable consistency
- The characteristics of different mixes according to Morgan, 1992 are given below in the Table 9

<table>
<thead>
<tr>
<th>DRY MIX SHOTCRETE</th>
<th>WET MIX SHOTCRETE</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATRIX TYPE</td>
<td>PLAIN</td>
</tr>
<tr>
<td>Type</td>
<td>Nil</td>
</tr>
<tr>
<td>fibre content kg/m^3</td>
<td>0</td>
</tr>
<tr>
<td>Comp. strength Mpa 7 days</td>
<td>44.5</td>
</tr>
<tr>
<td>Flexural strength Mpa 7 days</td>
<td>--</td>
</tr>
<tr>
<td>Toughness index 1, 7 days</td>
<td>--</td>
</tr>
<tr>
<td>Rebound % Vertical Over head</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>54.6</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 9: Showing the Characteristics of Different Mixes

In past the shotcrete was manually operated. With the development of the technology the use of robot has become very common in risky area like underground. With the use of robot not only the shotcrete is done at the faster rate but safety is also maintained. The shotcrete time is also reduced when programmable spray arms are used, work can be under taken in dangerous area without the risk of human life.

There are two methods used for applying shotcrete, one by spraying the dry mix and the other wet mix. The equipments required for both types of mix varies depending upon the actual working place. Dry mix is preferred in moist conditions as well as for small volume of work whereas, for continuous concreting wet mix system is preferred. A comparison of dry and wet mix processes is given below in table 10 according to Suri, 1994.

<table>
<thead>
<tr>
<th>Sl no</th>
<th>Item</th>
<th>Dry Mix</th>
<th>Wet Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Equipment</td>
<td>Less investment</td>
<td>3 times the cost of dry mix</td>
</tr>
<tr>
<td>2.</td>
<td>Mixing</td>
<td>Pre-mix dry ingredients can be used</td>
<td>Can use bulk ready mix</td>
</tr>
</tbody>
</table>

Table 10: Showing Comparison of Dry and Wet Mix

VIII. SHOTCRETE SUPPORTS FOR DIFFERENT GROUND CONDITIONS

The shotcrete-lining act to prevent rock displacement by
- Stiffening and strengthening the rock mass by filling open joints and fractures.
- Resist the rock load from adjacent rock by arch action
- By cohesion and friction loads are transferred
- Acts as plate / beam element with plane loads

The shotcrete lining can be effectively provided for different types of ground conditions such as loosening ground, overstressed ground, swelling ground, slaking grounds, squeezing rocks, etc.,

IX. OBSERVATIONS

The observations are as follows
1) The shear and the normal stiffness at the shotcrete rock interface determines the displacements whereas the tensile force, cohesion and friction determines the load bearing capacity. These are the design parameters.
2) The fibre reinforce shotcrete induces higher ductility and hence it is preferred over the plain shotcrete in the areas where large deformations are situated.
3) The observation made from the report “System ductility of long fibre reinforced shotcrete” by H.A.D.Kirsten by conducting beam test on various types of fibres with different end conditions are as follows
   - The beam load for different steel fibre reinforced beam is not affected by differences in fibre contents.
   - Ultimate deflections at 3.2% fibre content are larger compared with 1.98% by mass.
   - In case of polypropylene fibres the peak loads and the ultimate deflections are not affected by differences in fibre contents.
   - The peak load is doubled and ultimate deflection tripled by considering fixed end supports for steel fibres compared with simply supported end conditions.
For polypropylene fibres the peak load and the ultimate deflection were tripled with the fix end compared to simply support.

- The dramix fibres carried higher loads beyond the peak than either the steel or Polypropylene fibre.
- The observations confirm that the fibre reinforced shotcrete-sustained load at extended deflection.

X. CONCLUSIONS

The fibre shotcrete is sprayed concrete reinforced with discrete fibres. The plain concrete is brittle and weak in tension whereas wire or welded mesh shotcrete is time consuming and causes much rebound. Fibre reinforced shotcrete can be advantageous used which has better peak load and ductility. Accelerators used for fast early gain in strength and condensed silica fume increases cohesion and adhesion thereby reducing rebound. The dry and wet mix designs of shotcrete usually based on trial process.

The strength characteristics, method of mixing and application of the shotcrete has improved a lot over past decade, many countries over the world such as South Africa, Sweden, Australia, Canada, India etc., are using shotcrete for underground mining and civil engineering applications. The shotcrete is gaining wide acceptance for underground support system due to the lower cost, less cycle time, less disturbance of ground, prop free workings and higher productivity etc.,

REFERENCES