Empirical experience with shotcrete in deep underground mines

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Photos from multiple mines over last ~15 years
Deep Mining implies stress fracturing around openings, and significant stress change / deformation near stoping.
X-Ray vision looking around a deep hard rock tunnel
Profile of a Deep mining tunnel

Hard rock

Geological structure

Stress cracking

Surface also impacted by blasting
- Good perimeter control (drill accuracy)
  - Lighter charge
  - Tighter hole spacing
  - Half barrels good indicator of smooth blasting

BradCad version of what a hard rock tunnel profile might look like, local geology and stress conditions will dictate what it actually looks like...
Ground Support required
For deep mining

Wedges + gravity = ouch

We sometimes turn off brain with pattern bolting
- It is ok to add some extra bolts to tag wedges

Bolting required to hold up
Bigger blocks/wedges

Sliding, so not full dead weight
as is case in the back
Ground Support required
For deep mining

Bolts tag wedges
-Knit together fractured rock
-Laminated beam

Bolting Pattern - 5.0m x 5.3m Drift
Flat Back
Bolts not enough, especially in deep mining context – need to hold in the stuff around the bolts - Shotcrete and/or screen required
How does a thin layer 50mm (2 inches) of sprayed concrete help stabilize a 5x5.5m opening? The shotcrete isn’t as strong as the rock...
But the shotcrete is a hell of a lot stronger than the weaknesses in the rock....
If shotcrete holds block “1” in place, then harder for block “2” to fall out, and so on

-A little can go a long way to help the rock stabilize itself

-Key block theory, hold the key one in place = much harder for the rest to come out
Assumption – Shotcrete can always add value to any support system

But it is relatively expensive, so cost / benefits sometimes tough to quantify
For shaft access mines, cumbersome logistics

Dry process 1 tonne bags

Wet process
Slickline or borehole
To transmixer
QA QC is both material properties plus how it is applied.....
There are many factors that impact shotcrete performance such as: QA QC; mix design; wet versus dry process; fiber addition (1E10 different fibres on the market); additives (need Ph.D. in chemistry especially for wet mix); **skill of nozzle man**; temperature; surface preparation; natural geology its sprayed on; etc etc

But empirically mines have had good experience using it
Although shotcrete generally works well – it has deformation limits – bursting and/or squeezing ground can exceed those limits...

102 t sulphides
12 t fibrecrete
severe squeezing ground – shotcrete might be necessary to allow bolting (mechanized drill can = mining for poor rock) – but it doesn’t stop squeezing ground
For deep hard rock mines, the loading mechanics can get complicated, stress fracturing, bulking, shearing, seismic and blast vibrations (repeated), plus gravity and geological structure.
Key is to understand how things hold up over time

1. S/C ok for driving overcut
2. S/C ok after blasting stope
3. S/C getting tired after blasting nearby panel
4. S/C on the floor after blasting another nearby panel
Shotcrete
- Remotely sprayed
- Rigid
- Resists deformation right away
- Limits dilation
- keeps key blocks in place
- Dental work
- Flaw fixer upper
- resilient for equipment and blast damage
- corrosion resistant, seals the ground/fill

**But limited deformation capacity**

Screen
- soft, lots of movement before it resists load
- Safety net approach
- can stretch and retain
- prone to equipment and blast damage
- corrosion
- **high deformation capacity** (although watch for weak links like poor overlaps, square edged plates guillotining...)
30 tonne jack with pull plate designed to pull through screen, shotcrete or thin spray on liner

Left - #6 gauge weld mesh test

Right – pull plate yanked through fibcrete
Fibrecrete ~13t load but total failure after 18mm movement

~1.5 kJ

Screen over 0.5m movement to get 4.5 t
Only broke wire strands around the bolt plates

~5.2 kJ

Screen is good safety net but very passive, it takes a lot of movement before it builds up load
Shotcrete is very stiff, it resists movement right away, keeps rock tight, but can’t take large movement
Screen is very passive, allows a lot of rockmass dilation. Low confinement around skin of opening, most bolts rely on friction.
Bolt is ok
Not much friction around it
For this level of deformation:
- Shotcrete keeps ground tight.
- Screen can hold the loose but blastholes poking through,
  equipment scraping along it, fly rock, corrosion...
  can create a hazard (wear and tear)
fibrecrete brows usually hold up reasonably well
But can only take
Limited movement
Bolt and screen brows can get ugly.
Mesh reinforced S/C
Example of blow out where the screen Reinforcement stopped
Bolt and screen over shotcrete = keep ground tight, but have safety net if lots of movement

But lose advantage of blast resilience, screen peels back
00 gauge mesh strap embedded in shotcrete
8mm diameter strands

!@#$@#$@% ground control guys – never give a clean answer – shades of grey rather than black or white – shotcrete protects screen from corrosion, blast & equipment damage – but it also stiffens it up.....
enhanced support: 2.4m rebar (1.2x1.2m pattern) No. 6 weld mesh + 00 gauge 30x30cm plates, shotcrete and back cablebolts

Held after burst
Mn 1.6 ~10m away
No injuries but rained shotcrete shrapnel
Mn 1.9 20m away – areas with screen over shotcrete held
- Shotcrete over screen – stiffened up the mesh and blow out occurred
Screen over shotcrete is empirically effective but two processes $$ (time and money).
Deep Mines Research Consortium (CAMIRO)

RDP tests

Round determinant panel tests
800mm diameter x 75mm thick SC sample
Supported 3 spots and ram pushed onto centre
CANMET Sudbury does nice job for these tests

Test used to compare different shotcrete reinforcement – especially fibre

test is typically small displacement (~40mm) – we pushed it further for better comparison
Same test just showing early deformations – plaincrete – cracks and then sheds load right away – reinforced shotcrete – reinforcement bridges the cracks and holds it together (TSL example is over fibrecrete...)
More fibre = higher post crack performance in RDP test, but there are practical limits that are important!!! Synthetic floats = sumps / pump issues, steel fibre has high equipment wear, too many fibres can clog the slick line or borehole for the wet process......
For deep mines – can’t afford to plug the borehole! Expensive problem
“Superliner” concept - interesting possibilities – need to look at cost benefit of screen over shotcrete versus TSL over shotcrete more carefully – but complimentary products.... And both can be remotely sprayed

Shotcrete is **RIGID, resists ground loosening, good compressive strength, LOW elongation, low tensile**

TSL’s are often **stretchy** (plastic) so **passive**, but can have **high elongation/tensile strength**

Right – From James Archibald et al work @ 2005

TSL Assessment Review (WSIB sponsored work conducted by Queens)

TSL over RDP panel 2013

“Superliners” (TSLs + thin shotcrete (5cm) or fibrecrete (3.3 cm) layers)
<table>
<thead>
<tr>
<th>rockburst resistance</th>
<th>RDP sample analogue</th>
<th>comment</th>
<th>ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>surface support</td>
<td>energy Joules@40mm</td>
<td>typical average RDP results shown, treat as index ranking</td>
<td></td>
</tr>
<tr>
<td>plain shotcrete</td>
<td>40</td>
<td>cracks at only a few mm!!!! No post crack strength</td>
<td>poor</td>
</tr>
<tr>
<td>synthetic fibrecrete</td>
<td>436</td>
<td>more fibre types than you can shake a stick at, this example is 7kg/m3 54mm plastic fibre, limited by fibre length, equipment / borehole / sump pump clogging also is practical restraint on fibre length / dosage</td>
<td>minor strainburst only</td>
</tr>
<tr>
<td>#6 gage mesh embedded in shotcrete</td>
<td>474</td>
<td>underground will depend on where mesh is within shotcrete layer, wires start snapping before the 40mm RDP deflection, screen is get what you pay for so heavier gage is better, good for 10's of mm movement, NOT for 100's of mm movement</td>
<td>strainburst ok heavy rockburst S/C stiffens up mesh!!</td>
</tr>
<tr>
<td>TSL over fibrecrete</td>
<td>1225</td>
<td>limited testing out there, didn't test TSL over plaincrete, but good potential for &quot;superliner&quot; concept</td>
<td>un-proven but could be good</td>
</tr>
<tr>
<td>mesh liner only</td>
<td>RDP is not representative test</td>
<td>passive, allows rock to loosen up, often see rock un-ravel around bolts and spill out after screen seam opens (bolt might not see the load transfer), screen is get what you pay for, heavier gage is better, straps over screen seams = very big improvement....</td>
<td>good</td>
</tr>
<tr>
<td>mesh over shotcrete</td>
<td>RDP is not representative test</td>
<td>shotcrete keeps ground tight, promotes more even load on bolts and screen, screen can take 100's of mm movement if no weak link fails (seams, plate guillotining....)</td>
<td>good / ? Best</td>
</tr>
</tbody>
</table>

Qualitative ranking for rockburst resistance of surface support, not comprehensive

e.g. chain link deforms more than weld mesh, typically smaller aperture
Cable lacing known to work well for heavy bursting...
Note timber

\[ a + b - c = 12 \text{cm} \]

For large bursts – you need 10’s of cm to survive Wave going through....

8. 1. 2001
Summary – shotcrete is not magic solution for all ground control problems
It is brittle material and does what brittle material does during dynamic loading.

It is often only as good as the nozzleman...
Failed secondary pillar
Just-in-time development

But it is an excellent component of many ground support systems

Shotcrete posts 3.19.2001

S/C arches under weak ground

Arched back paste fill tunnel

Enough pyrrhotite to cause oxidation of exposed fill, needed seal plus get structural benefits of shotcrete 1/26/2001
Plaincrete ~ mm’s of movement

Fibrecrete ~ a few cm of movement

Screen reinforced shotcrete ~ a little bit more than typical fibrecrete

If you expect 10’s of cm – need mesh on the outside
(heavy bursting or squeezing ground)

Shotcrete Pros
• remote spray
• great construction material
• high wear and tear resistance, corrosion protection
• keeps rock from loosening!!!

Shotcrete Cons
• expensive
• can’t manage high deformation