OVERVIEW
- 2 x 10 km long headrace tunnels excavated by TBM
- Permanent support was typically a shotcrete (sprayed concrete) lining applied over initial support elements
- Areas of extremely poor ground conditions required a concrete lining
- Conventional reinforcement originally used, but time constraints led to steel fibre reinforced concrete (SFRC) lining being investigated.

PROJECT LAYOUT

GEOLOGY ENCOUNTERED BY TBM
Sandstones (21%)
- Strongest members of the Murree sequence are usually grey with sharply defined contacts, with UCS’s in the 130 to 230 MPa range
- Siltsilts (79%)
- A suite of siltsilts that grade to silty sandstones with UCS’s in the 30 to 70 MPa range
Mudstones (9%)
- Represent the weakest rocks in the Murree sequence, with UCS’s in the 30 to 40 MPa range
- 16% of the mudstones encountered were sheared

Sandstones (21%)
- Sandstones (21%) and Siltsilts (79%) reinforcement bars were specified at centres of 175 mm in the circumferential and longitudinal directions respectively
- The reinforcement configuration satisfied the following requirements:
  - Minimum reinforcement
  - Requirements for flexural crack control
  - Requirements for temperature and shrinkage reinforcement

DESIGN - SERVICEABILITY LIMIT STATE (SLS) DESIGN FOR CONVENTIONALLY REINFORCED LINING
- The minimum required cover according to the applicable standards was 75 mm for the structure
- #8 (25 mm diameter) and #6 (19 mm diameter) reinforcement bars were specified at centres of 175 mm in the circumferential and longitudinal directions respectively
- The reinforcement configuration satisfied the following requirements:
  - Minimum reinforcement
  - Requirements for flexural crack control
  - Requirements for temperature and shrinkage reinforcement

DESIGN - SERVICEABILITY LIMIT STATE (SLS) DESIGN FOR STEEL FIBRE REINFORCED LINING
- Crack control is one of the main benefits provided by steel fibres to structural elements
- The most significant effect of fibre addition to the brittle cementitious matrix is the enhancement of toughness
- SFRC in a tunnel lining offers:
  - Excellent ductility
  - Good durability
  - Reduction in the shrinkage of concrete
  - Elimination of micro-cracks in conventional reinforcing
  - Shallower construction joints compared to traditional ones
- Increased toughness and flexural strengths that are equal in all directions
- Easy crack control and high absorbed energy after matrix failure

The distance between steel fibres is much smaller than typical spacing within traditional bars

DESIGN - ULTIMATE LIMIT STATUS (ULS) DESIGN

COMPARISON OF TIME AND COST

<table>
<thead>
<tr>
<th>No.</th>
<th>Reason for Lining</th>
<th>Length (m)</th>
<th>Cover (m)</th>
<th>Time per Linear Metre (min)</th>
<th>Placement Delays</th>
<th>Cost per cm (NOK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Partially lining</td>
<td>108</td>
<td>1.25</td>
<td>96</td>
<td>11</td>
<td>0.32</td>
</tr>
<tr>
<td>2</td>
<td>Linings (u/s)</td>
<td>24</td>
<td>1.25</td>
<td>96</td>
<td>11</td>
<td>0.32</td>
</tr>
<tr>
<td>3</td>
<td>Delaminated</td>
<td>24</td>
<td>1.75</td>
<td>62</td>
<td>2%</td>
<td>0.36</td>
</tr>
<tr>
<td>4</td>
<td>Section 1</td>
<td>24</td>
<td>1.25</td>
<td>96</td>
<td>11</td>
<td>0.32</td>
</tr>
</tbody>
</table>

*Values have been adjusted to account for the fact that the values of concrete placed per linear metre for these sections were found to be significantly lower than the other sections due to the inclusion of a limit that reduced the effective placement time for the concrete.*

COMPARISON OF TIME
- Lining installation using conventional reinforced concrete typically ranged from 134 to 175 minutes per linear metre, on an average of 161 minutes per linear metre
- The associated time delays when using the conventionally reinforced concrete typically varied from 26% to 35%
- The time taken to install the SFRC lining typically ranged from 62 to 98 minutes per linear metre (excluding outlier – section No. 8), or an average of 77.5 minutes per linear metre, offering a significant time saving over conventionally reinforced lining installations
- The associated typical placement delays using the SFRC lining type typically ranged from 0% – 9%

COMPARISON OF COST
- The first section of concrete lining to be completed was section 3 (Major Fault in left tunnel). This has been taken as the benchmark for the costs analysis. i.e. this cost is expressed as 100% and all other costs are compared to this.
- The lining installed using conventional reinforced concrete ranged from 82 to 100% of the benchmark cost
- The data from the Table shows that the lining installed using fibre reinforced concrete ranged from 33 to 48% of the benchmark cost, a very significant saving.

CONCLUSIONS
- In summary, the adoption of SFRC over conventional reinforcement proved to be a notable success.
- As well as meeting the same design criteria as a conventionally reinforced lining, SFRC offered the following advantages:
  - Saving money over the actual quantity of steel employed
  - Saving time by being quicker to install
  - Producing a lining with smaller crack widths and improved durability over the life of the structure