1. INTRODUCTION
Modern construction engineering could not exist without sprayed concrete ("shotcrete") – whether in tunneling, mining or road construction. Underground construction is a vast engineering field and will be of strategic importance in the future. On one hand, many tunnels are in need of repair, while, on the other, there is always demand for new ones to be constructed. However, these are both expensive and time-consuming. In tunneling, time and material consumption are particularly critical. Yet both can be reduced by modifying the shotcrete with polymers. Such polymer-modified shotcrete lends itself to both wet and dry spraying.

A combination of inorganic and polymer binders in dry-mix mortars is essential to modern construction techniques, which demand high quality and safety. The concrete must meet stringent requirements in respect of strength, stability and impermeability. However, spray-application of concrete suffers from the problem of rebound, which becomes a time and cost factor because of the loss of material and the changes in the concrete’s properties. Polymer additives have therefore been designed specifically to tackle this problem. Large-scale tests have confirmed that adhesion to wet substrates, permeability and cracking can all be improved. The extra costs incurred are more than offset by the reductions gained in working time. Initially, the concrete mix can be designed in the laboratory, but ultimately the complex interaction of dosage, mixing, transport and nozzle systems, together with the method of application, can only be properly evaluated through large-scale application.

2. STEPS IN DEVELOPING THE SHOTCRETE
Inspired from the long years of experience using polymers in building chemicals, that chemistry was tested in a new segment - the sprayed concrete [1].
- The development tests were carried out in the Hagerbach Test Gallery (CH) after intensive laboratory tests. The climatic conditions remained constant in this test area and the whole mixing, application and testing could be done at the same location.
- Wacker Chemie owns a salt mine in Stetten (south-western Germany) which has been producing rock salt for more than 150 years. When digging a new tunnel, ground water ingressed in the middle of the total tunnel length. By modification of the regular concrete formulation with polymers, the quality of the sprayed concrete could be improved significantly and assured the finalization.
- Those positive effects inspired the owners of a water power plant. At the pressure water tunnel in Huntermuhr (A), the logistics was critical for project realization and the reduction of rebound supported positively the project progress. The polymer modification of dry sprayed concrete could reduce the water penetration and in addition the rebound reduction can shorten the time until the work has to be finished. Important given requirement was: having no significant influence on the quality of the sprayed concrete.
- Repairs to a canal near Munich, Germany, entailed the use of polymer-modified dry-shotcrete to strengthen the flanks against elevated water pressure.

3. GAINING KNOWLEDGE AT HAGERBACH TEST GALLERY
Can wet sprayed application be improved by using polymer binders, was the question to answer. In general the advantage of this method lies in using the economical, ready-mix concrete technology for standard commercial transport systems. The quality can be checked before
addition of the accelerator and can be adjusted to a faster cement setting time for optimal processing. The first development tests determined the proportion of additive that would reduce rebound of shotcrete without impairing the desired concrete properties. Various concrete formulations were applied to standardized test areas in order that their effects on the properties could be studied. Design of experiments (DoE) methodology was employed to determine the parameters needed for planning the next level of tests.

The study was divided into two parts: 1. Tests of the principal behavior of the raw materials and selection of the best formulations for further testing. 2. In situ testing of the best formulations on the tunnel surface [2].

3.1. Concrete-mix design

The purpose of this series of tests was to compare the effects of polymer modification on the properties of the concrete with those of a commercially similar, arbitrarily selected reference mixture under realistic conditions. The following formulations for cement, admixtures and polymers were used for the tests. Behavior with the various polymers was studied in additional tests involving different plasticizer and accelerator contents, with the percentage value for the additive being expressed in terms of the quantity of cement. The same machines, materials, methods and personnel were used in the production and spray-application of the concrete. After preparing the concrete, the mixture was applied by machine to a standardized concrete plate.

Cement: 450 kg/m³
Sand 0-1: 7%
Sand 1-4: 58%
Rock 4-8: 35%
W/c: 0.48
Polymer liquid: 2.5 to 10% (solids content 50%); expressed in terms of cement
Polymer powder: 1.7 to 5%; expressed in terms of cement
Plasticizer for liquid polymer: 0.33 to 1.0%; expressed in terms of cement
Plasticizer for powder polymer: 0.83 to 1.55%; expressed in terms of cement
Accelerator: Between 5 and 8%; expressed in terms of cement

The focus of these studies was to compare the development of strength and the amount of rebound with those of a reference mixture containing no added polymer. The concrete was sprayed onto the panels, which were then weighed. The weight of concrete applied was thus the difference between the new weight and the original weight of the panel.

3.2. Concrete base - Effect of polymer on strength and rebound

No matter which variant is chosen, adding solid (FSZ) or liquid (FLZ) polymer reduces rebound (Figure 1), while different kind of plastisizeres where used, FM (Melaminsulfonat) and FMVZ (Naphtalinesulfonate with Retarder). Rebound for the liquid polymer tends to rise again if the dosage exceeds 10%. The smallest relative rebound, at 29% compared to the 0- mixture, is achieved with 7.5% liquid polymer.

![Figure 1: Relative rebound versus polymer content.](image-url)
The development of the strength of polymer-modified concrete and the reference concrete is shown in Figure 2. In the case of the reference mixture, the strength develops at a constant rate over the entire period, and is associated with early strength. The J1, J2 and the J3 areas are shown for guidance [3]. The code for the units of the figures are the dosage of additive in percent calculated on cement, e.g. FLZ –FM-5-1.5 first No. gives the polymer dosage second No. stand for the plastisizer. The mixture containing cement with 5% liquid polymer content exhibits develops more strength than the reference mixture. For the first hour, strength development of all mixtures remains below that of the reference mixture. After one hour, the strength of some mixtures jumps above the strength of the reference mixture. After two hours, the strength of the remaining mixtures rose dramatically, far above the level of the reference mixture. After six hours, the strength of all of the above mixtures exceeds that of the reference mixture, almost reaching J3. The 28 d results in Figure 3 show values much higher than 50N/mm².

**Figure 2:** Comparison of early strength development with J-areas.

**Figure 3:** 28 day drill core compressive strength as a function of rebound.
3.3. Approval tests at the tunnel surface

A further objective was to highlight any non-conformity of the polymer-modified shotcrete. For this series of tests, "standard cement" from the Swiss market was used. The results of this test series are expressed in terms of the values achieved for the 0-mixture in the development tests. This formulation was used to prepare 3 m³ batches of concrete from CEM I 52.5 R (CEM A) and from CEM 42.5 N (CEM B). The solid polymer made up 5% of the cement while the liquid polymer accounted for 7.5%.

As in the development tests, it proved possible to lower the rebound significantly. The potential for this is illustrated in Figure 4, which compares the rebound to the actual rebound of the standard 0-mixture.

![Figure 4: Relative rebound compared to rebound of the 0-mixture, data abstract.](image)

The change in strengths of the mixtures based on CEM I 52.5 R corresponds to the results of the development tests. The concrete based on CEM I 42.5 N demonstrates continuous strength development, as would be expected of this concrete. Examination of the change in early strength for CEM I 52.5 R confirms the expectation that mixtures having higher cement contents exhibit higher strength. It can thus be predicted that high-strength specifications could be met by a polymer-modified concrete.

3.4. Results - Hagerbach test Gallery

The development trials demonstrate that polymer modification significantly reduces rebound. Examination of the rebound values shows that some mixtures met the goal of halving the rebound compared to that for the reference mixture. It even proved possible to reduce rebound by up to 71%, compared to the value for the 0-mixture. The application tests demonstrated that the use of polymer reduces rebound for both CEM I 52.5 R and CEM I 42.5 N concrete by around 73.5%.

The application tests also showed that the strength specifications could be achieved with a conventional accelerator in conjunction with both CEM I 52.5 R and CEM I 42.5 N concrete. Strength development of CEM I 52.5 R concrete containing cement with 5% liquid polymer was the same in the application tests as it was in the development tests. In the application tests, it was found that a combination of commercially available cement met a specification for development of high early strength.

4. REALISATION OF POLYMER-MODIFIED SHOTCRETE AT MINING

At Wacker’s salt mine in Stetten, the two existing entrances cannot be accessed by typical vehicles due to the roadway arrangement. Consequently, construction of a new entrance that would allow standard trucks to pass through the tunnel was begun in 2007. It was decided to drill and blast both the 905-meter access tunnel and ten-percent incline [4]. Tunneling ran smoothly for the first few months, but then groundwater began to seep in after about the first 450 meters.
This slowed the advance rate from 140 meters per month (m/m) first to 50 m/m and finally to only 10 m/m in January 2008. At this point, in order to avoid stopping the work, it was decided to use the improved polymer-modified sprayed concrete at the concerned stretch of about 100 m. The original wet-mix formulation of the sprayed concrete satisfied safety criteria under dry conditions, but showed weaknesses in adhesion when applied to a damp substrate. The aqueous polymer variant was used for this large-scale application because of its greater ease of handling in the mixing plant.

4.1. Shotcrete pilot trails, to prepare the application trails for Stetten salt mine.

The laboratory tests revealed good strength development, which proved to be either almost on a par with or greater than the very early 6-hour strength, and exceeding 15 N/mm² (Table 1), which is a requirement for shotcrete [5]. The aqueous polymer was used for this large-scale application because it was easy to work with in the mixing plant. The additive was metered into the concrete to yield a final concentration of 40 liters per cubic meter of concrete.

<table>
<thead>
<tr>
<th>Polymer type</th>
<th>Reference concrete</th>
<th>Polymer-modified concrete</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Polymer, rel. to CEM</td>
<td>Without</td>
<td>Aqueous</td>
<td>Powder</td>
</tr>
<tr>
<td>Sand 0/4</td>
<td>1046</td>
<td>1046</td>
<td>1046</td>
</tr>
<tr>
<td>Gravel 4/8</td>
<td>814</td>
<td>814</td>
<td>814</td>
</tr>
<tr>
<td>CEM II B-T 52,2 N</td>
<td>400</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Fly ash</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>accelerator</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>$f_{\text{prism}}$: 6h N/mm²</td>
<td>1,51</td>
<td>1,44</td>
<td>2,12</td>
</tr>
<tr>
<td>$f_{\text{prism}}$: 24h N/mm²</td>
<td>27,2</td>
<td>22,6</td>
<td>22,3</td>
</tr>
</tbody>
</table>

*Table 1: Mix design of shotcrete and early compressive strength development (measured at 40x40x160mm³ prisma).*

4.2. Application trails of shotcrete at Stetten salt mine

The purpose of using modified shotcrete in the mine was to investigate its properties and benefits. The newly developed polymer-modified shotcrete was used for the first time under realistic conditions. These trials revealed some further interesting properties of additional benefit, such as adhesion and imperviousness, and facilitated more extensive use in the tunnel at the start of 2008. The fundamental insights were corroborated by laboratory tests, followed by practical applications of this shotcrete technology (Table 2).

<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>Polymer, rel. to CEM</td>
<td>Without</td>
<td>Aqueous</td>
<td>Powder</td>
</tr>
<tr>
<td>$f_{\text{cyl}}$: 1 d N/mm²</td>
<td>16,6</td>
<td>10,5</td>
<td>15,3</td>
</tr>
<tr>
<td>$f_{\text{cyl}}$: 27 d N/mm²</td>
<td>36,9</td>
<td>39,8</td>
<td>35,6</td>
</tr>
</tbody>
</table>

*Table 2: Modification of application tests and compressive strength, measured at core (2:1); 200x100mm.*

It was possible to produce and deliver the wet mix of polymer-modified concrete to the construction site without any deterioration in properties. The originally selected wet shotcrete fulfilled its function as support under dry conditions, but exhibited adhesive failure on wet substrates. Damage due to wetness and water pressure hampered the application of shotcrete and led to localized weakening. Consequently, localized spraying of additional concrete was needed. Inspection of the test surfaces in the side wall revealed a large number of wet patches in the case of the standard shotcrete (Figure 5), whereas the polymer-modified shotcrete (Figure 6) exhibited much better adhesion to the wet substrate, greater impermeability, and a lower probability of crack formation.
5. HINTERMUHR / AUSTRIA - A PRESSURE WATER TUNNEL

The canal was built between 1988 and 1992, but inspections showed a high level of undesirable escape of water into the mountain. Various sealing techniques were used, especially different types of injection, but these proved inadequate for the most critical area, and so a 15cm in-liner ring was installed. In total, 59 m was installed in April 2009. This time slot was chosen because it would guarantee safe working before the snow started melting in the higher mountains and because economics dictated that the melted snow is used to fill the supply lake. Nevertheless an avalanche and additional avalanche risks prevented work from starting on schedule. Reduced rebound then became a major concern as less rebound would mean less spraying time and especially less time would be needed for manually removing the rebound from the tunnel. The small diameter of about 3.9 m and especially the circular shape were the two reasons why a machine could not be used for removal. (Figure 7).

It was simply too narrow to have machinery inside as well (Figure 7). Rebound was a significant factor when it came to evaluating the quality and performance of the section made with dry shotcrete. On one hand, manual pick-up of rebound took a lot of time and, on the other, the rebound modified the characteristics of the shotcrete and had to be disposed of. Thus, reduced rebound became both a technical and a commercial objective. For sprayed-concrete application, various polymer-modified systems were tested (Table 3). The polymer content used in the project itself was 7.5%, because it offered good rebound reduction, as well as the required compressive strength values shown in Table 4., proving more than 40N/mm² after 28d.
Concrete type | Standard unmodified | Polymer-modified | Polymer-modified
--- | --- | --- | ---
Polymer on cement | without | 5.0% liquid | 10.0% liquid
7d $F_{\text{cyl} 100x200\text{mm}}$ | 44.0 | 36.0 | 33.0
28d $F_{\text{cyl} 100x200\text{mm}}$ | 58.0 | 57.0 | 48.0
Rebound reduction | 0 | 23% | 46%

*Table 3:* Modification of preliminary tests and compressive strength, measured at core (2:1); 200x100mm.

Concrete type | Standard unmodified | Polymer modified
--- | --- | ---
Polymer | without | 7.5% liquid, on cement
28d $F_{\text{cyl} 100x200\text{mm}}$ | 49.2 ($\pm$ 4.9) | 53.8 ($\pm$ 5.5)

*Table 4:* Application tests at the Hintermuhr Tunnel providing the requirement of having > 40N/mm² after 28d.

While the technical requirements were being assessed, the economics of using this polymer in conjunction with shotcrete were examined. Rebound reduction was found in the full-scale trials: the empirically calculated consumption of dry-mixed concrete was reduced, and this was corroborated by the measured volume of rebound. 50% less rebound was achieved with 7.5% polymer dosage. The studies fully confirmed expectations as regards a reduced rebound, with ultimate savings of approx. 190 working hours (Table 5).

<table>
<thead>
<tr>
<th>Damage</th>
<th>Preparation</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong damage</td>
<td>Removal of old concrete or full covering</td>
<td>Application of wet concrete</td>
</tr>
<tr>
<td>Partly damaged</td>
<td>Removal of damaged areas</td>
<td>Application of polymer modified dry concrete</td>
</tr>
<tr>
<td>Cracks, but good concrete</td>
<td>Cleaning the cracks by high-pressure water</td>
<td>Application of polymer modified dry concrete</td>
</tr>
</tbody>
</table>

*Table 6:* Description and classification of damage categories at the water canal.

After the water level in the canal had been reduced or the canal emptied completely, an inspection revealed how the rehabilitation of the existing construction needed to be done. The repairs to the canal, which supplies hydro power stations, are projected to last some 30 years.
7. CONCLUSIONS
Polymer-modified concrete offers interesting potential, both technical and commercial. Present studies have shown that it is ready for the market. Further detailed studies are essential to ensure that it is exploited fully. Different projects created different expectations: Polymer modification of wet- or dry-shotcrete has many positive effects, such as less rebound, good workability e.g. pumpability, improved adhesion and cohesion, a waterproofing effect and, also important, easy installation of metering equipment. The water-proofing effect is interesting in the positive-pressure direction (onto the concrete) as well as in the negative-pressure direction (from the rear of the concrete). Besides the immediate effect of reducing costs and saving time, long-term effects can be expected. System costs for construction projects will become more important in the future and polymer modification will make a major contribution to cutting total costs. Current studies indicate that shotcrete is developing in line with the market. It is versatile, and can be applied vertically and to ceilings. It lends itself to tunneling and mining, as well as to use on slopes and in canals and conduits.

8. REFERENCES