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# Silica Fume and Steel Fibers - the Breakthrough for Norwegian Shotcreting in the Early 1980's

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## SILICAFUME UND STAHLFASERN - DER DURCHBRUCH FÜR DEN NORWEGISCHEN SPRITZBETON IN DEN FRÜHEN 80IGERN

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In den 70er Jahren wurden in Norwegen umfangreiche Untersuchungen über die Verwendung von Silicafume und die Entwicklung von hochfestem Beton durchgeführt. Ebenfalls in den 70er Jahren kam es zu nennenswerten Fortschritten und Verbesserungen im Gebirgstunnelbau, doch aufwendige und zeitraubende Ausbauarbeiten erwiesen sich in weiterer Folge als kritischer und einschränkender Faktor in bezug auf die Ausbruchsleistung. 1980 wurde deshalb ein umfangreiches Forschungsprogramm ins Leben gerufen, um die Effizienz der Ausbauarbeiten im Felshohlraumbau durch die Verwendung von Spritzbeton zu erhöhen. Fünf Jahre später verhalfen die vorliegenden Ergebnisse und Erfahrungen über die gemeinsame Verwendung von Silicafume und Stahlfasern der Spritzbetontechnik in Norwegen zum Durchbruch. Der vorliegende Artikel faßt einige Ergebnisse dieser Forschungsarbeit in Form eines kurzen Rückblicks zusammen.

*During the 1970's, extensive research on utilization of silica fume and development of high-strength concrete took place in Norway. During the 1970's, much progress and improvements in rock tunneling were also made, but detailed and time consuming support work successively became a critical and limiting factor to the capacity of excavation. In 1980, therefore, an extensive research program was started in order to improve the efficiency of the support work in rock tunneling by use of shotcreting. Five years later, results and experience had been obtained on the combined utilization of silica fume and steel fibers that represented a breakthrough for the Norwegian shotcreting. In the present paper, some results of this research work are summarized in the form of a brief looking back.*

### 1. Introduction

After the Second World War, extensive hydropower construction programs were started in Norway. Thus, by the end of the 1970's, more than 150 power stations in deep rock caverns and more than 2500 km of rock tunneling had been completed. In addition, more than 630 km of highway and rail-

way rock tunneling had also been driven. Thus, rock tunneling had become a very important technology for the Norwegian construction industry.

During the 1970's, much progress and great improvements in the efficiency of rock tunneling had been made. However, a detailed and time consuming support work had become a critical and limiting

factor to the capacity of excavation. Therefore, increased attention was given to the various support systems including shotcreting. Since the wet-process type of shotcreting was introduced in Norway in the early 1960's, this technique had rapidly gained favor due to higher production capacity, lower rebound and better working conditions compared to that of the dry-process shotcreting. In addition, a more controlled water-cement ratio was also obtained. When the hand-operated shotcreting equipment was replaced by robot-operated equipment in the late 1970's, the wet-process shotcreting became even more efficient. However, due to the strict requirement of high pumpability in narrow hoses, a high water-cement ratio of typically 0,60-0,70 was used, and hence, a low concrete quality obtained. In addition, placement of the traditional wire mesh reinforcement was a slow and time consuming process that also represented a certain risk from a safety point of view.

Based on the rapid development in concrete technology that took place during the 1970's, extensive research in order to improve the wet-process technique was started at the Norwegian University of Science and Technology in Trondheim. Both silica fume and new efficient admixtures had become available [1]. Much experience from the development of high-strength concrete for the first offshore concrete platforms had also been gained [2].

Since the Norwegian construction company Astrup-Høyer A/S had recently developed advanced robot operated equipment for the wet-process technique (the Robocon Shotcreting System), a joint research program with this company was established in 1980.

Five years later, results had been obtained [3], that represented a breakthrough for the Norwegian shotcreting technology. In the following, some results of this research are summarized in the form of a brief looking back.

## 2. Organization and extent of investigation

The test program was partly based on specially designed test series and partly on extensive and systematic quality control from a number of construction sites both in Norway and abroad. In order to obtain more information about the basic equipment parameters, a number of additional tests were also carried out. An overall view of the test program is shown in Fig. 1.

In the various test series, a number of variables were included, such as:

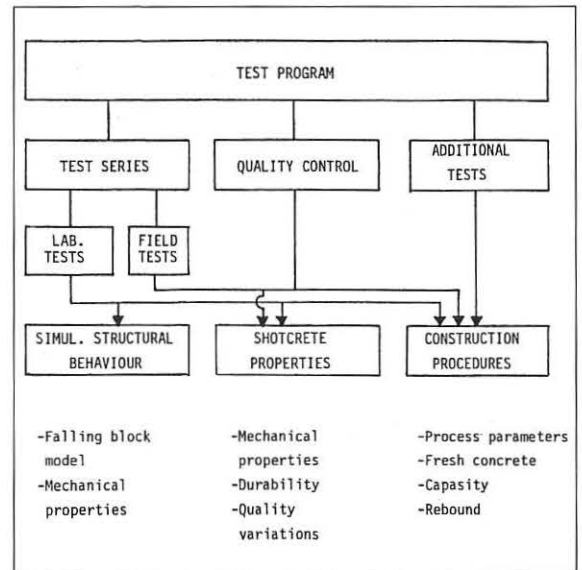


Fig. 1: Overall view of test program

- Type and amount of cement and silica fume
- Type and amount of various admixtures
  - Water-reducing admixtures
  - Shotcreting accelerators
  - Set-retarding admixtures
  - Defoamers
- W[C + SF]-ratio
- Type and amount of fibers
  - Steel fibers
  - Synthetic fibers

Based on separately shotcreted test panels from the various construction sites (Fig. 2), a number of shotcrete properties were tested, such as:

- Adiabatic heat development and penetration resistance
- Flexural strength
- Compressive strength
- Uniaxial tensile strength and modulus of elasticity
- Compressive modulus of elasticity
- Free shrinkage
- Density and porosity
- Water permeability
- Frost resistance
- Microstructure

Based on concrete - rock cores, a number of further tests on in-situ properties were also carried out such as:

- Compressive strength
- Splitting tensile strength
- Bond strength
- Density and porosity
- Fiber content and orientation
- Permeability
- Microstructure

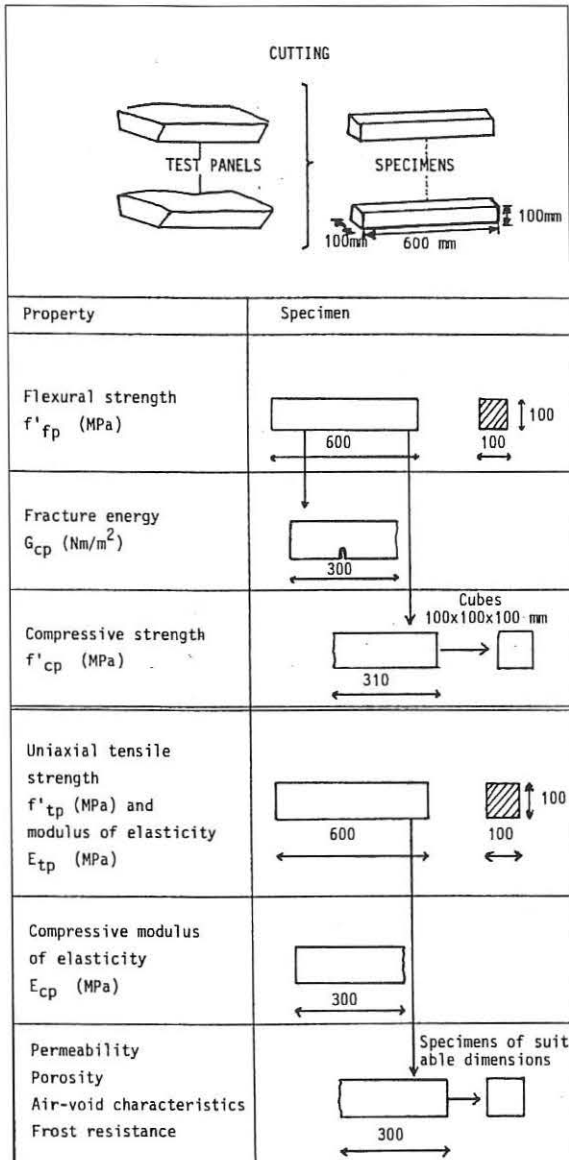


Fig. 2. Testing of shotcreted test panels

On the construction site, measurements of exit nozzle velocity and application velocity were carried out by use of test procedures as shown in Figs. 3 and 4.

In order to carry out a more systematic study of the load-bearing capacity and ductility of the shotcreting system, a specially designed test rig was constructed (Fig. 5). In a vertical position, test panels 3700 x 1300 x 120 mm, were shot on three freely movable rock or concrete blocks hinged to the test rig. Then, the shotcreting system was moved up to a horizontal position and subjected to a three point loading simulating a falling block. In addition to the load bearing capacity, extensive deformation measurements were carried out during testing.

### 3. Results and conclusions

Since most of the tests were carried out under realistic field conditions, it was more difficult to avoid variations in the testing conditions compared to that under more controlled conditions in a laboratory. Some variations in both mix design and curing conditions had to be accepted. Also variations in the shotcreting equipment and the shotcreting process did affect the results. In addition, most of the testing was carried out on drilled out or cut samples, which

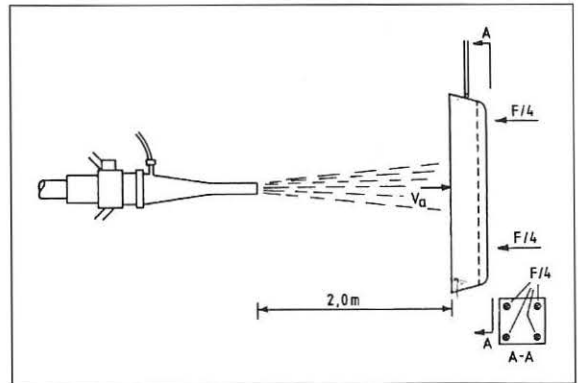


Fig. 3: Experimental set-up for determination of application velocity by measuring the change in linear momentum.

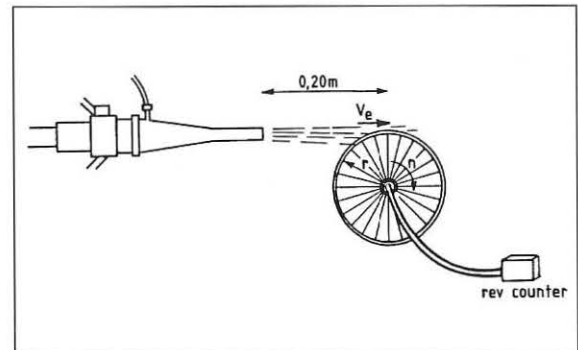


Fig. 4: Experimental set-up for determination of exit nozzle velocity

showed a greater variation than testing of traditionally cast concrete specimens. Hence, the scatter of test results was relatively high.

However, since the most important parameters were repeated in a number of test series and quality control programs, the following results and conclusions could be outlined:

- By proper combinations of silica fume, water reducing and defoaming admixtures, it was possible to reduce the water-binder ratio from the typical range of 0,60 to 0,70 down to 0,35. As a result, the in-situ compressive strength was increased from typically 20-30 MPa to more than 100 MPa.

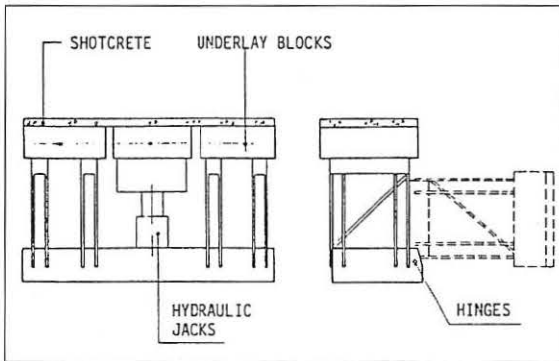


Fig. 5: Experimental setup for testing load-bearing capacity and ductility of the shotcreting system

- The incorporation of silica fume also distinctly improved the bond strength. For underlays of rock or concrete, typical bond strengths of 0,6 - 1,2 MPa and 0,4 - 2,2 MPa were obtained, respectively. At the same time, a distinct reduced permeability and increased frost resistance were also obtained. However, proper curing conditions became more important
- For the given characteristics of the shotcreting equipment, the shotcrete quality appeared to be controlled mainly by the water-cement ratio, the amount of shotcreting accelerator and the curing conditions.
- The incorporation of silica fume made it possible to substantially reduce the amount of shotcreting accelerator. Thus, 10 % silica fume by wt. of cement typically reduced the amount of shotcreting accelerator from 10-12 % to 1-2 % by wt. of cement.
- The traditional amount of shotcreting accelerator did typically reduce the compressive strength by up to 50 %. This strength reduction was partly due to the formation of inhomogenities in the cement paste and partly due to increased water-cement ratio from the water in the accelerator.
- For the equipment used, nominal production capacities of up to 12 m<sup>3</sup>/hour were obtained. Depending on job site conditions, however, the actual long-time capacity was much lower and typically less than 50 % by that of the nominal capacity.
- The incorporation of silica fume did also distinctly reduce the rebound loss to a range of 3-14 %, and no significant change in the material composition of the rebound was observed compared to that of the applied shotcrete.
- The presence of silica fume did further reduce

the amount of dust, where measurements showed that none of the threshold limits for total dust (10 mg/m<sup>3</sup>), respirable dust (5mg/m<sup>3</sup>) or respirable quartz dust (0,1 mg/m<sup>3</sup>) were exceeded, provided normal ventilation.

- The introduction of silica fume also made it easier to incorporate steel fibers, and as a result, increased ductility was obtained. Thus, the addition of 1,0 - 2,0 vol. % of steel fibers with a high aspect ratio increased the fracture energy by up to 60-80 times compared to that of the plain shotcrete.
- The flexural strength was also improved by the incorporation of steel fibers. Thus, the addition of 1 vol. % steel fibers increased the flexural strength by 10-70% compared to that of the plain shotcrete. The effect of steel fibers on both tensile and flexural strength was much dependent on the curing conditions.
- Due to their crack-arresting and stress-distributing effects, the incorporation of steel fibers reduced both cracking and bonding failure due to shrinkage. This effect was higher under the more adverse curing conditions.
- As rock support, shotcrete with 1 vol. % of steel fibers typically showed a higher load-bearing capacity compared to that of shotcrete with the traditional wire mesh reinforcement in the same concrete matrix. Similar ductilities were also obtained. As a result, the time consuming process of placing the wire mesh could be omitted.

#### 4. References

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