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INDUSTRIAL APPLICATION

Fully Automated Shotcrete Robot for Rock Support

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Abstract: *Optimized shotcrete application techniques are required in particular tunneling projects. Today, any spraying can be done by hand or by manipulator. With the development in the material technologies, the range of possible operation was enlarged. With automation of the application, an important contribution to improve performance and quality and to reduce rebound may be achieved. At the Swiss Federal Institute of Technology, Zurich, systematic research is done to develop the fully automated process control, focusing on the wet shotcrete method. With the development of the fully automated shotcrete robot, the user will have a very effective tool at his or her disposal to spray concrete shells (fully automated). With the new robot, the user may choose from three different modes: manual, semiautomated, and fully automated spraying. Especially the fully automated mode facilitates higher performance with less danger to the worker's health. Quality control is inherent in the application process in regard to layer thickness, compaction, and homogeneity.*

1 INTRODUCTION

1.1 Shotcrete application on site

Shotcrete is used worldwide as temporary or final lining in tunnels or in building pits. The application of shotcrete is strenuous and, because of this, tiring if it is done manually by a nozzle operator. This holds especially for the use of wet shotcrete. The capacity that may be handled is less than 5 to 8 m^3/h when spraying manually and normally up to 20 m^3/h by using manipulators (30 m^3/h were already applied).

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Shotcrete application as the first step of rock support often has to be done in a zone of danger (rock fall). With use of the robot, the safety of the worker can be improved. The handling of the robot is easier and less strenuous than steering a manipulator. A basic difference between common manipulators and the new robot is that the user steers the movements of the nozzle directly. He or she does not have to take care of the different boom joints. In the manual and semi-automated mode, the nozzle operator judges the surface himself or herself to get the required application. In the fully automated mode, total control is by the robot.

1.2 Delimitation from industrial fabrication robots

The handling of the robot tool, the spraying nozzle, is robotized according to industrial fabrication.[21] Different are the positioning of the carrier vehicle and the recording of the geometric dimensions. In a spraying cell, the manufacturing area is fenced off clearly. The carrier drives in corridors and always repeats the same pattern of motion. The dimension data are transmitted out of CAD drawings.

Blasted tunnel excavation means varying sections that are not constant not even in a round. The theoretical tunnel section is given, and the excavated sections have to be measured every round. While measuring a round, the self-positioning of the robot carrier is effected (these data are stored and available at any time). Any shotcrete application with a specified layer thickness (effective, theoretical) is a prototype. The path planning of the vehicle is no topic for the automation for safety reasons.

2 STATE OF THE ART

Worldwide, much research on shotcrete and application machines was done in the last 15 years. The new devel-

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opments involve the chemical products—water-reducing admixtures and pumping aids, plasticizers, set accelerators, hydration control, and concrete improver and curing agents[14]—and the equipment as well—shotcreting machines, dosage units, and new nozzle systems—but not many application techniques. In Germany[4,6,8,9,19,26] and Austria,[28] investigation mainly is oriented toward the dry shotcrete method. In Switzerland, the research is focused on the wet shotcrete method.[3,24,25]

2.1 Spraying by hand

Shotcrete is in most cases still applied by nozzle operators wielding tube and nozzle. The strain on the worker limits the quantity of concrete that can be handled. The technique of application has to be learned and requires a lot of experience. The work demands high concentration even from experienced nozzle operators. To get optimal quality and a minimum of rebound, the nozzle operator has to keep the right distance from and angle to the rock surface. In large tunneling sections, the nozzle operator must apply the shotcrete from a lifting platform to maintain an optimal spraying position. If the spraying angle is not perpendicular to the rock surface, the rebound and losses increase greatly. The right spraying distance depends on the velocity of the shotcrete at the nozzle. Typical nozzle distances are between 1 and 2 m. Experience on the sites shows that, due to human influence, it is not possible to keep all the main parameters in the best possible combination, especially in large tunnel sections or high-cut linings.

2.2 Spraying by manipulator

Performance can be improved by using a manipulator (Figure 1). Because the strain on the worker does not limit the spraying capacity, it may be much improved by using a conveying pump with a larger capacity and a larger conveyor hose that reduces the pulsation effects and improves the surface uniformity of applied shotcrete.

Fig. 1. MEYCO Robojet manipulator.

The worker steers the different joints with several joysticks to let the nozzle do the movements. The operation of the joints makes it difficult to keep the nozzle perpendicular to the surface and at the recommended distance. Even with remote control, it is still difficult to hold the quality on a steady level due to the poor visibility caused by the dust of spraying, the large distance between the nozzle operators and the spray jet, as well as the unfavorable angle of sight.[15, 20, 23, 27]

2.3 Spraying by robot

To improve the shotcrete quality and simplify the application technique, a robot was developed and constructed on the mechanical basic concept of the well-proven MEYCO Robojet Manipulator.[2, 16, 17] The spraying robot is mounted on a vehicle that does not move during the spraying process.

The location of the nozzle is therefore always described with reference to the vehicle. The spraying robot consists of three parts, the boom (joints 1, 2, 3, 4, and 5), the lance (joint 6), and the nozzle (joints 7 and 8). The new robot has 8 degrees of freedom (Figure 2).

The electrohydraulic manipulator is fitted with robust sensors, of which six work on angular and two on linear (joints 3 and 6) measuring principles. These sensors detect the position of each joint to the next one simultaneously. In addition to the eight joints, one joint is used for rotational motion of the nozzle tip (opening angle $\varphi_{\mathrm{Rot}} = 4°$) for a better distribution of the sprayed concrete. It has no effect on the kinematic model of the boom. The movements are controlled with standard control valves that are equipped with emergency manual control in case of breakdown.

The vector φ is the joint vector that defines the workspace of the robot. The transversal and rotational vec-

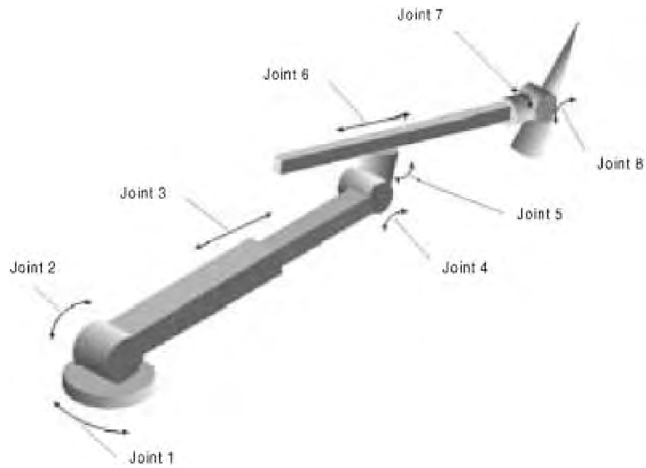

Fig. 2. Boom system: degrees of freedom.

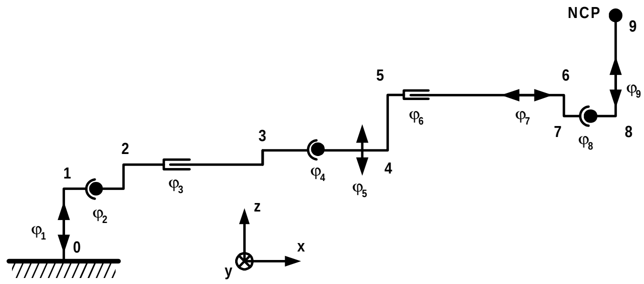

Fig. 3. Definition of the angles of calculation.

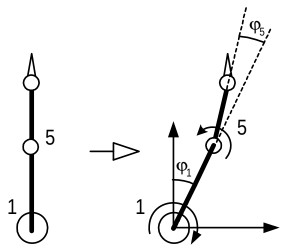

Fig. 4. Illustration constraint 1.

tors at the joints involved in the calculation are

$$\varphi^T = [\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5, \varphi_6, \varphi_7, \varphi_8]^T$$

The task requires the control of 5 degrees of freedom of the spraying robot, i.e., the position of the nozzle center point NCP (x, y, z) and two angles for the orientation of the nozzle (φ_7, φ_8). To solve the problem of redundancy, three constraints are required:

1.
$$\varphi_5 = -\frac{\varphi_1}{3}$$
This condition limits the angle at the nozzle so that perpendicularity of the nozzle to the rock surface is possible at any time (Figure 4).

2.
$$\varphi_4 = \frac{1 + \varphi_2}{6}$$
This condition rules out the possibility of a collision of parts 3 and 6 (Figure 5).

3.
$$\varphi_3 = \frac{1.85}{3}\varphi_6$$
This condition optimizes the workspace of the robot.

These equations guarantee a large workspace and minimize the consumption of oil. The computing is based on the inverse kinematics principle, which means that for a given movement of the nozzle, a pattern of motion for each individual joint is computed by the mechanical process control. Due to the complicated kinematic structure of the robot, no closed-form solution for the inverse kinematic model exists.

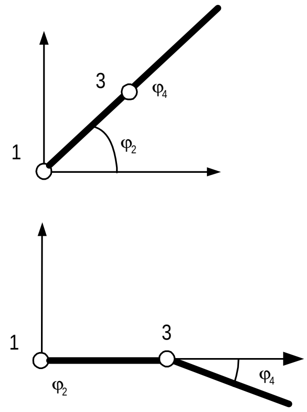

Fig. 5. Illustration constraint 2.

Fig. 6. Remote control (twin bright buttons) with a 6D-joystick.

The joint angles are thus calculated numerically with the Newton-Raphson method.

The nozzle operator uses a remote control with a six-dimensional (6D) joystick (Figure 6) to steer directly the movement of the nozzle, due to the inverse kinematic mechanical process control, which gives a much higher performance than using common manipulators. The 6D joystick is a large handle with integrated "dead man switch" and guarantees water and dust resistance. The heart of the 6D joystick is a modified piece of equipment that is used as a standard in industrial robotics.[13, 29, 30]

The new robot provides the possibility to choose three different modes of spraying: fully automated, semiautomated, or manual. The advantages are as follows:

- Very easy, ergonomic control
- Reduced training time

- Shotcrete quality and performance that are independent of the nozzle operator's qualification (semiautomatic and fully automated mode)
- Tunnel profile measuring and shotcrete application with one machine
- Possibility to measure sprayed layer thickness
- Saving of time for setup, spraying, and profile control process

Manual spraying. The worker uses the robot as a manipulator to apply shotcrete manually. Application control is not supported by application process control, but the movements of the manipulator (boom, lance, nozzle) are controlled by the mechanical control system. This mode is thought to be appropriate for irregular conditions, where a description of every movement is too difficult to be implemented into an operational program due to its complexity or for economic reasons. Such conditions typically could include

- Extreme irregular local overprofile
- Local covering of drainage half-shells and anchor plates
- Fast repair work with limited extension
- Filling of holes caused by rock fall

After the machine has been positioned, the user operates the application with the 6D joystick. He or she does not have to take care of the individual boom joints but guides only the movement of the nozzle (Figure 7). All joint movements are process controlled by the mechanical control system.

The 6D joystick steers

- Angle of the nozzle to the rock surface
- Path line and velocity of the nozzle v_n
- Distance d_{vp} from the nozzle tip to the tunnel wall

Semiautomated spraying. The user has the freedom to choose the path line; all other process functions of the application are controlled by application process control and internal mechanical process control. The semiautomated mode is an optional mode that can be used in areas where neither manual application nor fully automated mode is economically or technically useful. The distinguishing difference from manual application mode is that application process control is generating, in addition to process control of the mechanical system, a virtual plane congruent to the scanned wall surface out of laser-controlled measurements. On this plane, nozzle movement is computer-controlled with regard to wall distance as well as to the perpendicularity of the nozzle to the scanned wall surface. The path of motion is on this virtual plane; it is, however, manually controlled via the 6D joystick by the nozzle operator.

The sequence of the application process is as follows: To give the necessary data to the robot application system, the tunnel profile has to be measured. Therefore, the user first marks the required spraying range with a laser device. The program calculates, out of the automatically measured data, a virtual plane congruent to the scanned surface in the distance d_{vp}, and the nozzle tip is automatically guided perpendicularly to the virtual plane. The spraying distance d_{vp} (distance from the virtual plane to the rock surface) has to be specified by the user. In the generated congruent plane, the driving of the nozzle tip is done by the user manually with the 6D joystick (Figure 8).

The 6D joystick steers

- The path line of the nozzle on the virtual plane
- The velocity of the nozzle v_n

The semiautomated mode avoids increasing rebound, particularly in ranges that are poorly visible or overhead and far away from the user, due to optimized nozzle control with respect to the wall surface. This mode allows full manual application freedom with regard to layer thickness or shape of any surface, but the nozzle operator has to judge the surface by sight to check the layers applied.

Fully automated spraying. In comparison with the other two modes, the system has to take over the nozzle operator's experience and supervision functions with the resulting actions. The robot assumes full control of the shotcrete application process. This mode is in development for the following conditions:

- Smooth blasted excavations
- Drilled profiles by TBM

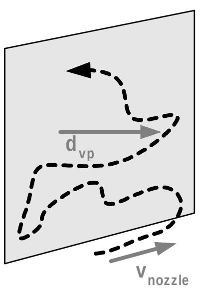

Fig. 7. Manual spraying mode.

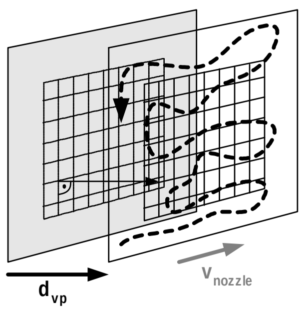

Fig. 8. Semiautomated mode.

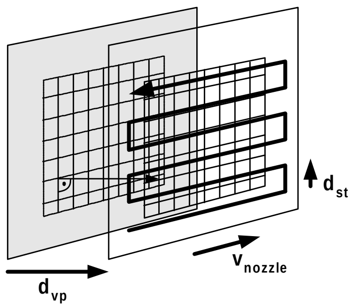

Fig. 9. Fully automated mode.

Measurement is done in the same way as in the semiautomated mode by defining the points where the automated spraying starts and ends. Depending on the input given by the user (spraying distance d_{vp}, layer thickness, sprayed concrete capacity per time unit) the application process control program calculates the necessary application control data based on the measured tunnel section data and the final profile required. The movements are controlled by the application process control that drives the nozzle automatically in the path line, with the velocity and path line distance to achieve the required layers or the final profile by always keeping the nozzle perpendicular to the surface (Figure 9).

The user only has to specify the requested layer thickness as well as the capacity of spraying. The path motion of the nozzle is described in the computer program of application process control. The distance between the path lines, to achieve the required layer thickness, is calculated on the basis of the results of the experiments described later on. The 6D joystick is locked; but for safety reasons, though, the user still has to press the dead-man's switch. This mode enables the highest average performance over time.

2.4 Control components

Using bus cables, all electrical components of the robot are connected with the control box. Based on the data from any single sensor, the computer calculates, depending on the application task, the appropriate pattern of motion. The joints are controlled in such a way that none of them are operated at the limit of their range of movement or extension and that a minimum of oil volume in the pistons is used for joint movements to ensure a fast interactive reaction between steering action and process-controlled boom reaction.

The robot system contains the following main components:

- *Mechanical structure.* Boom, lance, nozzle, and sensors for movement control
- *Mechanical process control.* Computer (following industrial standards) with flash-EPROM memory and necessary interfaces to connect the system with ethernet to Internet for remote diagnostics and service, remote control with 6D joystick, and touch screen with input possibilities and visualization function
- *Application process control.* Laser measurement system, application process control program

2.5 Profile measurement in the semiautomated and fully automated modes

Except when using the manual mode, the rock section under consideration has to be measured as a first step. The measurement is done by a laser measurement system. The laser device is located at the head of the lance of the manipulator (inbetween joints 6 and 7). The range of measurement along the tunnel axis is limited to 3.00 m by the mechanical structure of the boom and lance. The measuring principle is a reflector-less transit-time measurement in the infrared range. The computer program eliminates faulty measurements by an integrated filter function. The measuring grid is defined by the user. As more measuring points are taken, the real condition is recorded more exactly. The criteria for choosing the distances of the grid notches depend on the evenness of the rock surface.

In the fully automated mode, measurement is carried out twice with the same grid pattern, before and after shotcreting. The computer calculates the layer thickness achieved at any point on the scanned surface by comparing the zero measurement of the excavation line with the surface of the applied shotcrete lining. Joining the profile measurement with the global tunnel coordinates (allocation of the stationing with the corresponding theoretical profile to the profile measurement of the robot), the final profile control in the future will be completed as follows:

- Measurement of the excavated tunnel profile by the laser measurement system
- Feeding of the theoretical profiles into the application control computer
- Calculation of the necessary shotcrete layer thickness out of the difference between the excavated and theoretical profiles of every grid field by the application process control program
- Calculation of the application velocity between each grid point out of the interpolated thickness along the grid path by the application process program (the velocity is a function of the conveying capacity and the shotcrete layer thickness).

The layer thickness of each shotcrete application is limited by the adhesiveness of the concrete and the accelerator dosage. If the calculated layer thickness exceeds the limit, the robot decides to apply shotcrete in several layers.

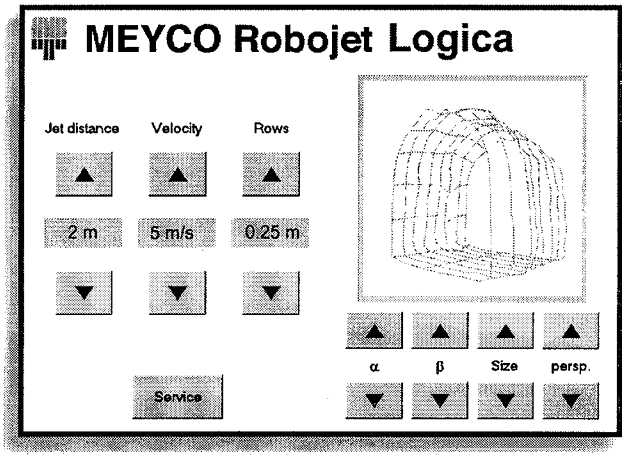

Fig. 10. Touch screen.

In the other two modes, the thickness must be controlled manually. The system does not support the computer-controlled application thickness.

2.6 Application control in the semiautomated and fully automated modes

The computation of any movement is based on inverse kinematics, which means that for a given path of the spray jet on the rock surface a regulation for the different joints is defined. By defining constraints for selected joints, the redundancies of the kinematic degrees of freedom are eliminated.[11, 12]

To arrange the handling as simply as possible, the remote control alerts the user by twin brightly lighted buttons (green buttons are used; red ones indicate function in operation, and unlit buttons are not active) clearly to the selected operation mode (see Figure 6).

The basic principle of automation is the computation of a virtual polygonal 3D plane parallel in distance d_{vp} to the rock surface measured previously. Depending on the mode chosen for the spraying process, some parameters have to be given to the system as manual input by touch screen (Figure 10).

The specified functions are taken over by application process control while reducing the nozzle operator's freedom of action: full robot control in the fully automated mode and no application process control in the manual mode.[10, 19] The unspecified functions are steered manually by the 6D joystick. The 6D joystick enables a user-friendly handling.

3 SYSTEM INTELLIGENCE FOR AUTOMATED SPRAYING

If knowledge of the independent relations of some spraying parameters is sufficient for spraying by hand or manipulator, it is not for fully automated spraying by the robot. The different influences have to be quantified to be put into the relation. All these dependent and independent factors have to be programmed in the application process computer program (application process control).

Important for the research is the adaptability of any experiments to site conditions because only this demand ensures that the results can be implemented usefully in the robot application system (application program). Because so many facts cannot be influenced on site, the experimental data shall not be taken to the last two digits after the decimal point. Much more important is consideration of the interaction of the material and the application parameters.

3.1 Objectives

Two main fields have to be investigated: the application and the conveying systems. Application technique, done by a nozzle operator, includes judging of the profile by sight and knowledge of the systematic spraying. For fully automated applications, the operational skills have to be transformed into "artificial application intelligence." This means that all important parameters of the application process have to be analyzed and optimized in their interrelation, and then they must be described in an operational application process control program. This will allow high-performance shotcrete application in a defined constant layer thickness or in layers to equalize irregularly blasted profiles (hole filling) to achieve the theoretical final lining profile with high quality, an even surface, and minimal rebound. By adhering to these demands, the costs can be reduced effectively. The basis for reaching this goal is quantification of the distribution of the spray jet as a single shotcrete strip and the overlap.

The rebound and the surface evenness of spraying depend on the acceleration of the concrete by the compressed air at the nozzle, i.e., from the exit velocity of the concrete, as well as the nozzle distance to the wall. The relation between the quantity of concrete conveyed and the pressure of the compressed air must be described in such a way that in the future the control of concrete capacity and air pressure will be effected automatically by the system.[31]

3.2 Research method

For the fully automated application of shotcrete, the texture uniformity of the surface is very important with regard to appearance, strength, and water permeability. For the application process system of the robot, three types of initial surfaces have been defined: smooth surfaces (drilled profiles by TBM, smooth-blasted regular profiles), rough surfaces (blasted excavation with overprofile), and surfaces with steel girder and reinforcement installations. To gain the process knowledge for each type of surface, the research at the

Swiss Federal Institute of Technology Zurich is structured in five phases:

1. Preliminary tests (only on smooth surfaces)
2. Basic experiments
3. Specific application experiments
4. Creation of calibration tests
5. Validation of the laboratory experiments by site conditions

With the preliminary tests, the suitability of the developed robot was checked as well as the recording of the basic data. Consequently, some adaptation for further research was done, on the one hand, by modifying the robot (manipulator, software, laser device) and, on the other hand, by adaptation of the test program. The basic experiments collected data on the distribution of single-spray-jet strips. By assessing the results, a hypothesis about the full range of applications was drawn up. By varying the most relevant parameters of the basic experiments, the boundary conditions for useful field employment of the robot (fully automated mode) were determined in phase 3. With a simulation, the hypothesis about the full range of applications was confirmed. The stage of laboratory tests is completed and supplemented by ongoing experiments on site. In phase 4, specific calibration tests (status of work) will be developed to transfer the results from the basic and specific experiments to potential material properties of the specific mix design as well as the required application technique. In the last phase, the functionality of the fully automated mode will be checked on site.

For the complexity of rough surfaces and surfaces with steel girder and reinforcement installations, the definition of different zones is necessary. The conditions in each zone can be treated similarly, e.g., the transition region between adjoining ranges or the backfilling of girder installations (pretending the shadowing effect). The systematical shotcrete application of these zones will be examined by the research phases 3 to 5.

The test arrangement must ensure the repeatability of any experiment. This is achieved by

- Controlling the adhesiveness of the fresh concrete
- Using the robot in the semiautomated mode for constant spraying distance, perpendicular nozzle, constant nozzle velocity, and constant nozzle rotation
- Measuring from a fixed point for identical measurement in any experiment[1]

The first step of the specific application experiments is to quantify the distribution of the shotcrete by the spray jet in one layer along the path line. The research has to optimize a variety of parameter combinations that include distance of the nozzle to the surface, nozzle moving velocity, nozzle motion, quantity of concrete per hour, and quantity and pressure of air. Different from spraying by hand or by manipulator, only some system adjustments can be done while spraying automatically. The reason for this is that once having left the finished part of the spraying range that cannot be reached by the spray jet in the same spraying pass, the evenness of the sprayed surface has to be final. The quantified distribution curve rectangular to the path of the spray strip is the basis for the full-range application. To spray a homogeneous range, the nozzle path has to be developed out of the distribution curve of one path. Depending on the layer thickness required, the spray layers (distribution curves) have to be overlapped. For this reason, the distance between nozzle path lines has to be calculated by an evaluation program.

The operation program with the generated application intelligence (input is only the layer thickness) calculates the necessary concrete capacity and compressed air as well as the pressure and movement parameters of the nozzle path line, distance, rotation, and velocity.

3.3 Experiments

The following concrete conveying and application system was used in the experiments:

- Meyco Robojet shotcreting machine, Meyco Suprema 0–20 m^3/h, standard spraying nozzle
- Twin air supply, dense conveying, adding accelerator at the nozzle

Further, the following concrete was used for the experiments:

- *Mix design*: CEM I 42.5 450 kg/m^3 (Normo 4),[22] aggregates 0/8 mm 1736 kg/m^3, Delvo stabilizer 1.1 percent, Rheobuild T3 plasticizer 1.1 percent
- *Characteristics*: water-cement ratio $\approx$ 0.47, spread $\approx$ 50 cm[5, 18]

Several series of experiments have been executed with the following parameters:

- Distance from the nozzle point to the surface d_{vp}: 1.0, 1.5, 2.0 m
- Nozzle moving velocity v_n: 10, 15, 20 cm/s
- Nozzle rotation R_n: fix, 1, 2 rps

The parameters were varied in all possible combinations. The concrete conveyance was kept constantly at 10 m^3/h. The experiments without nozzle rotation have been excluded from further tests because of the insufficiently uniform structure of the sprayed surface.

Basic experiments. The basic experiments were carried out on a vertical wall with a smooth surface. The shotcrete was sprayed in single strips on two different and independent paths that were repeated for statistical reasons. The distribution was measured by laser device on both independent paths in five parallel profiles. Measurement was done, for all experiments, from the same survey point. To eliminate the pulsation of concrete flow at the beginning and end of each experiment, the concrete was sprayed into a box until a homogeneous application was possible. Besides measurement of the distribution perpendicular to the path and the maximum layer thickness, rebound was registered at the same time.

The distribution curve of shotcrete dosing at the wall (design profile) did not vary over the accelerator range of 4 to 8 percent of cement content. For practical experimental reasons, the dosage was fixed at 4 percent.

Specific application experiments. In phase 3, two test series with the appropriate parameter sets out of phase 2 that had the highest evaluation scores with regard to the specified quality requirements have been selected for further testing with a conveyed concrete capacity of 15 and 20 m^3/h. With the enlarged capacity, a higher dose of cement was necessary to prevent plugging of the conveyor hose and closing of the nozzle (CEM I 42.5 500 kg/m^3).

The sequence of every experiment was as follows: positioning of the laser device, quality control of the fresh concrete, application with constant conveyance, measurement of the sprayed strips, weighing of rebound and the totally sprayed shotcrete, removal of any concrete, and preparation for the next application.

Besides recording data on shotcrete distribution analogous to the basic experiments, the theoretical full-range application was confirmed by laboratory and site experiments.

3.4 Results of the basic experiments

To give an idea of the results of a single experiment (concrete conveyance = 10 m^3/h, distance of nozzle from surface $d_{vp} = 1.5$ m; nozzle velocity $v_n = 15$ cm/s; nozzle rotation $R_n = 2$ rps), the superelevated representation of four path lines, each measured by five profiles that are taken along the path lines, is shown in Figure 11 (on the y axis, every mark means 10 mm; on the x axis, 50 mm). The maximum thickness of this sprayed strip (single layer) is between 3.5 and 4.0 cm. The width of the spray strip (cross-distribution) at the wall is about 1.10 m.

The concrete maximum grain size is 8 mm, which gives a roughness of the shotcrete at the wall of about 10 mm. By increasing the dosage of the accelerator, the roughness may be improved.

The design profile (Figure 12), which is implemented as a standard strip-distribution profile in the application process control program, is determined from the family of distribution profiles of one path line. It shows that gravity has a very limited influence even if the spraying is done against a vertical wall.

The basic requirement for a layer-wise application is the need for a constant cross-distribution along a path line. For this reason, the spraying distance d_{vp} for robotic application has to be kept between 1.50 and 2.00 m. Using a spraying distance of 2.00 m, nozzle velocities v_n between 10 and 20 cm/s and nozzle rotations R_n of 1 or 2 rounds per second (rps) are possible. Using a spraying distance of 1.50 m, a nozzle velocity of 10 cm/s and a nozzle rotation of 2 rps have to be maintained. These parameter combinations result in a very small standard deviation in design profile.

3.5 Design of the system intelligence

Investigation of the meander-wise path planning of nozzle motion revealed that the orientation (horizontal, vertical, or any other orientation in between) of the path lines did not influence concrete quality with regard to homogeneity and compressive strength. Rebound of the applied shotcrete did not vary significantly. These investigations are based on the dry shotcrete method. The shotcrete is applied with a modified industrial robot.[8]

To prevent sagging of the applied shotcrete layers, the application has to be carried out from the bottom to the top. Path planning (vertical or horizontal) is technically determined by the kinematics of the boom and the lance. Because of the orientation of the lance, application in horizontal meander-wise path lines is predominant.

3.5.1 Hypothesis. Based on the design profile (Figure 12), which serves as a basis for systematic shotcrete application, the best application parameter will be filtered with an algorithmic simulation of full-range application, as described later. Application on a smooth vertical experimental wall is quite different from application on a rock surface on site because holes and peaks influence the distribution of the shotcrete. In a first step, the application is optimized for smooth surfaces.

The application is executed from the bottom to the top of the side wall in parallel horizontal path lines. The setup of every parameter combination remains constant for the whole spraying process. The design profile is overlapped in parallel horizontal path lines to build up the final layer thickness, as shown in Figure 13. The basic design profile has an extension of 95 cm and a maximum thickness of 0.05 m. With a spraying path line distance of $d = 15$ cm, the required total lining thickness of 22 cm is achieved.

The precision of boom, lance, and nozzle movements limits the path line distance to 0.05 m, with a resulting maximum theoretical layer thickness of 0.80 m (concrete capacity 20 m^3/h). In practice, the thickness of the sprayed shotcrete layers will be less than 0.40 m due to insufficient bond strength. To achieve a uniform distribution along the path line, the upper limit of the path line distance is equal to the cone diameter of the nozzle rotation angle. With a nozzle rotation angle φ_{Rot} of 4 degrees, a path line distance lower than 21 cm for a spraying distance of 1.50 m and 28 cm for 2.00 m results.

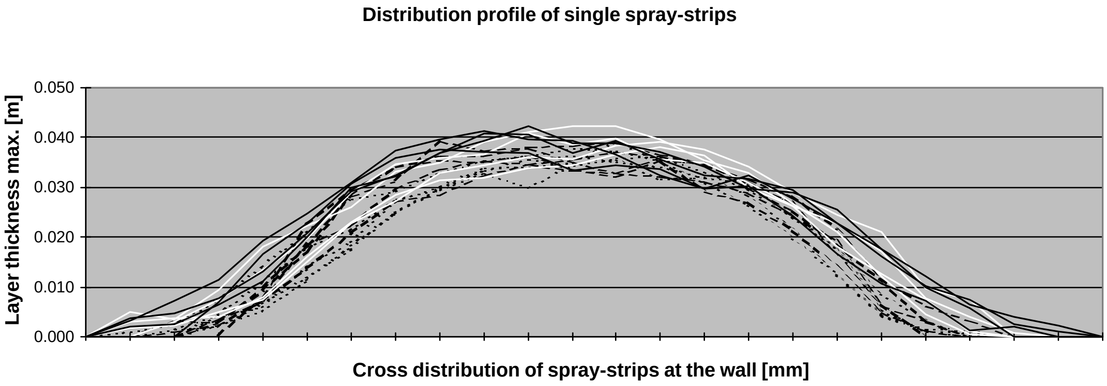

Fig. 11. Concrete cross-distribution curves sprayed in single strips.

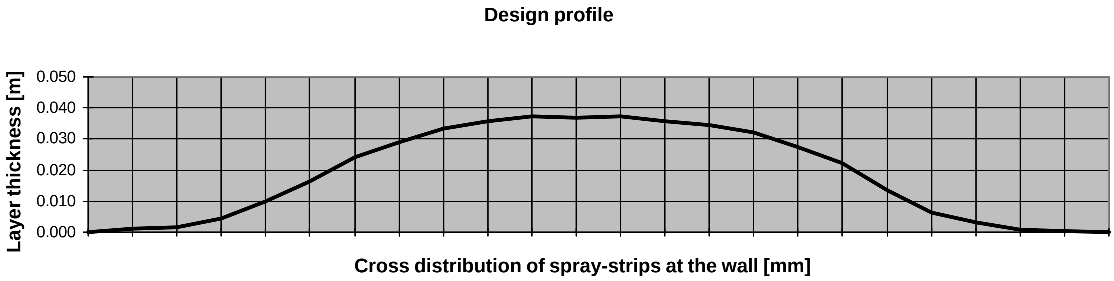

Fig. 12. Design profile.

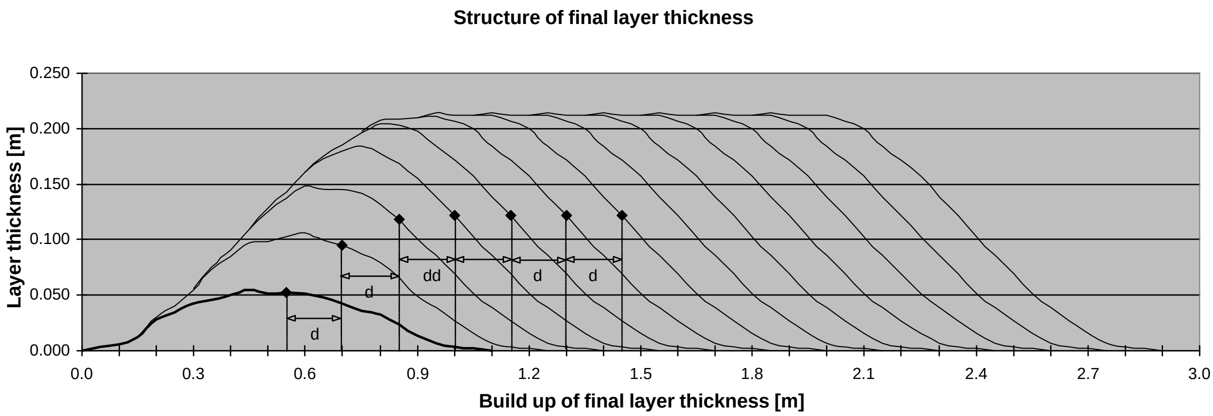

Fig. 13. Structure of final layer thickness.

3.5.2 Simulation. The experimental data (design profiles, rebound, application parameters, water permeability, compressive strength, air pressure, and concrete characteristics) are summarized in a database. A programmed algorithm runs through the database, searches for the required parameter combination, and suggests the optimized adjustment for process control.

The only quality criterion that may be specified by the user is the evenness of the final shotcrete lining. The evenness (Figure 14) specifies the difference between the maximal and reduced layer thicknesses applied to the distance d_m of two adjoining maxima:

$$\text{Evenness} = \frac{\Delta}{d_m} \qquad \Delta = \ell_m - \ell_r$$

Three types of evenness have been defined:

- Smooth: $\Delta \leq 10$ mm
- Medium: $\Delta \leq 20$ mm
- Rough: $\Delta \geq 20$ mm

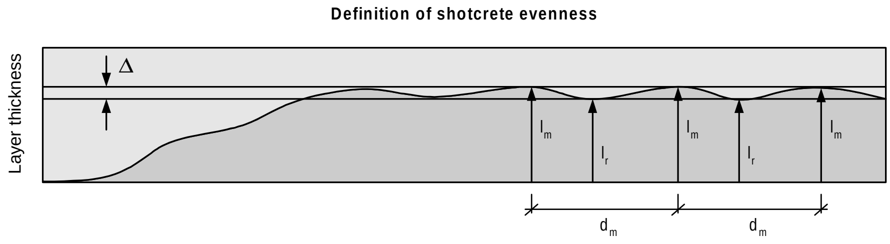

Fig. 14. Shotcrete application evenness.

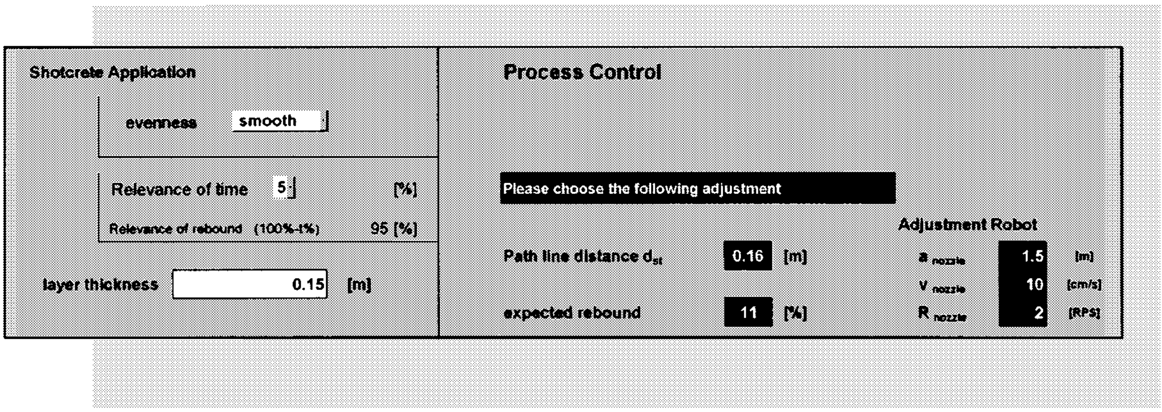

Fig. 15. Input mask: evaluation process control.

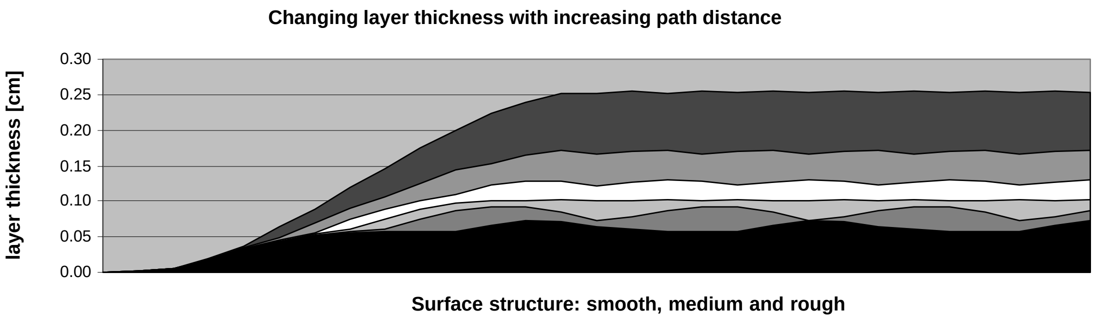

Fig. 16. Evenness of different final layer thicknesses.

With algorithmic simulation of the spraying process, the parameter sets that fit the requirements of a smooth surface structure (evenness) have been evaluated. The increase in layer thickness was realized in steps of 0.01 m.

Specifying the evenness of the surface to be sprayed—smooth, medium, or rough—and classifying the relevance of rebound to time of spraying, the best process control parameter set is evaluated automatically for the required layer thickness (Figure 15). The path line distance is assigned according to the required layer thickness. These were simulated for each parameter set out of the whole database collected from the preliminary and basic experiments.

The simulation of different lining thicknesses for one chosen parameter set (concrete conveyance = 10 m^3/h, distance nozzle surface $d_{vp} = 1.0$ m, nozzle velocity $v_n = 10$ cm/s, nozzle rotation $R_n = 1$ rps) is summarized in Figure 16.

Depending on the path line distance (5–30 cm) and the parameter set, described above, layer thicknesses of 25 to 5 cm were achieved. The quality of the evenness of the simulated surface is very different. Application with the represented parameter set of a layer thickness less than 10 cm, as shown in Figure 16, does not fit the requirement of a smooth structure of the surface.

A visualization of the fully automated shotcrete application (Figure 17) shows two different regions, the tran-

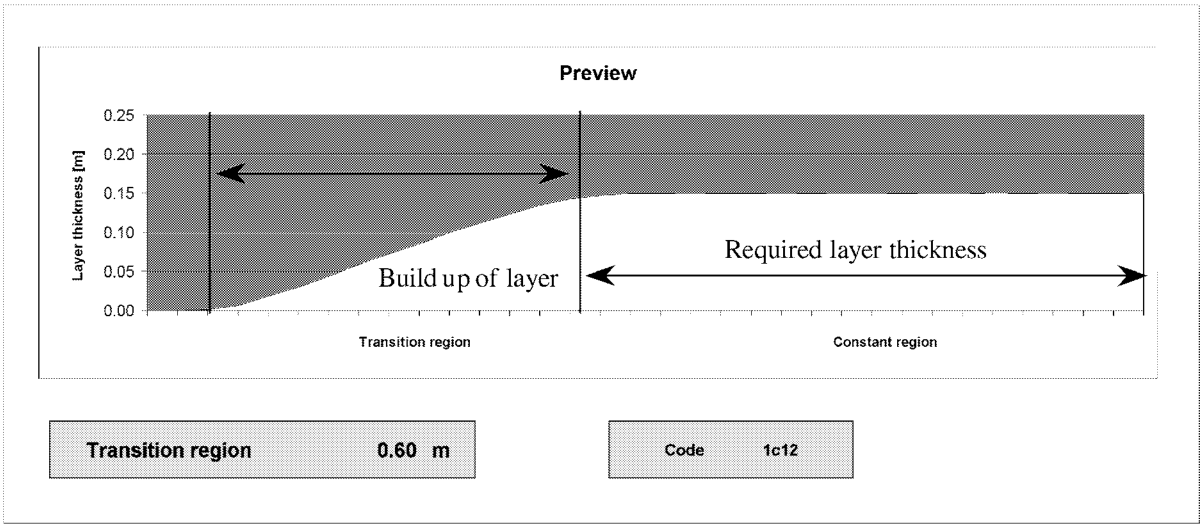

Fig. 17. Visualization of output parameter set.

sition region where the layer thickness increases and the constant region. The transition region results from the first single strip application and the following path line application until the layer thickness stays constant as required (treatment of the transition region will be analyzed in the next step of research). The stretch of the transition region depends on the layer thickness and varies between 0.50 and 1.00 m.

3.6 Results of specific application

The parameter sets that turned out to fulfill the quality requirements in the simulation were used to enlarge the spraying capacity to 15 and 20 m^3/h. The maximal design profile thickness that may be achieved varies between 0.02 and 0.07 m depending on the parameter set chosen and the concrete conveying capacity of 10, 15, or 20 m^3/h (Figures 18 and 19).

Figure 20 shows a verification test. The following findings have been made in comparison with the theoretical buildup of the layer thickness (constant region):

1. The surface appears scaly (the scaly appearance depends on the accelerator dosage; with increasing dosage up to 8 percent of cement content, homogeneity improves.
2. The layer thickness is enlarged.
3. The standard deviation of different sections is maximal and equal to 1.2 times grain size max.

The experiments showed that the layer thickness of the design profile increases with application on setting shotcrete instead on rock. Due to the overlapping of the different spray strips to achieve the theoretical layer thickness, the rebound is decreasing, and therefore, the design profile is enlarged. The value of the increase is proportional to the gradient of the design profile (application on rock). A quantified increase of 0.001 to 0.003 m is reverse proportional to the thickness of the design profile.

The practical application thickness is increased in relation to the theoretical layer thickness. This phenomenon was studied in several experiments and quantified by the following correction functions:

$$y = -0.1357x + 2.0291 \qquad (R^2 = 0.93)$$

for layer thickness up to 0.05 m and

$$y = -0.0189x + 1.4242 \qquad (R^2 = 0.98)$$

for layer thickness above 0.05 m.

The recommended parameter sets of the simulation have been verified for layer thicknesses of 0.05 to 0.11 m and 0.15 m and 0.20 m at laboratory conditions. The standard deviation of the measured shotcrete linings generally was less than ±1 cm.

3.7 Summary of laboratory experiments

All applications of the laboratory experiments were executed with the semiautomated or the fully automated mode of the Meyco Robojet. The spraying distance d_{vp}, the nozzle velocity v_n, and the perpendicularity of the nozzle to the rock surface were controlled by the application control system and at all times maintained precisely. Besides registration of surface evenness and rebound, the strength after 7 and 28 days, as well as the water permeability, has been examined. The water permeability is an effective criterion for a check of the bond between the sprayed layers and separation of the concrete texture. The water permeability correlates with the compressive strength. The increase

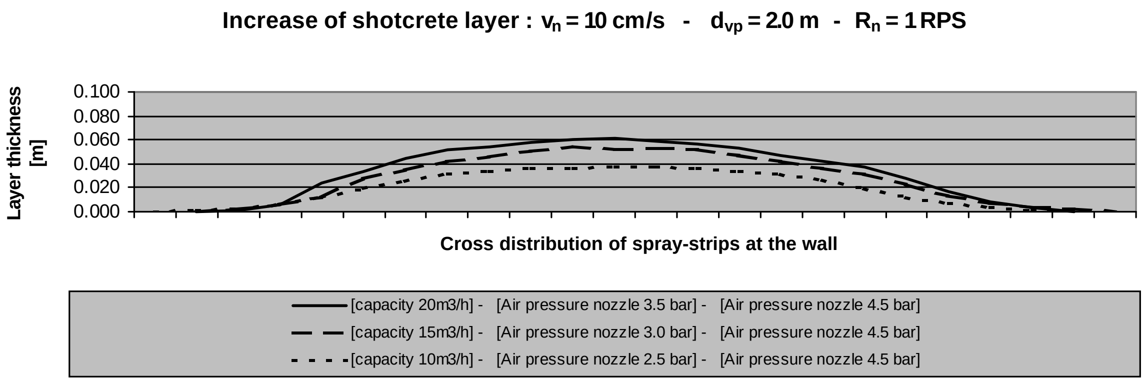

Fig. 18. Increase of design profiles from 0.04 up to 0.06 m with enlarged concrete capacity ($R_{\text{nozzle}} = 1$ rps).

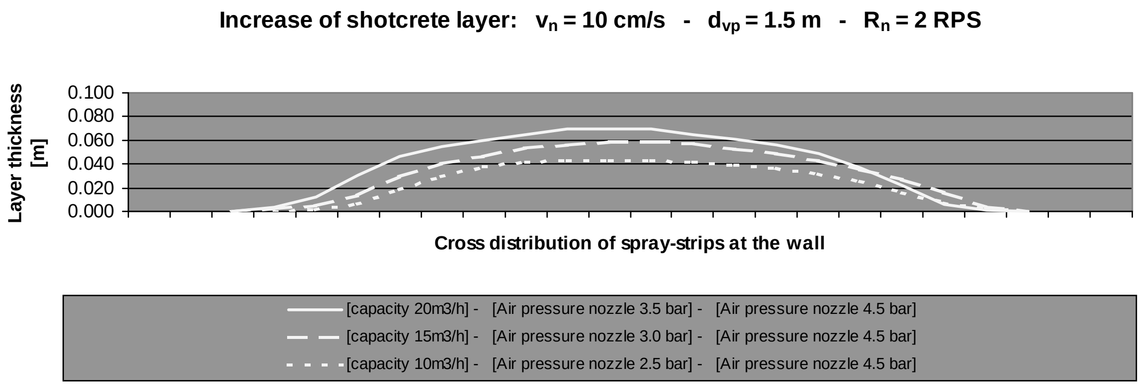

Fig. 19. Increase of design profiles from 0.04 up to 0.07 m with enlarged concrete capacity ($R_{\text{nozzle}} = 2$ rps).

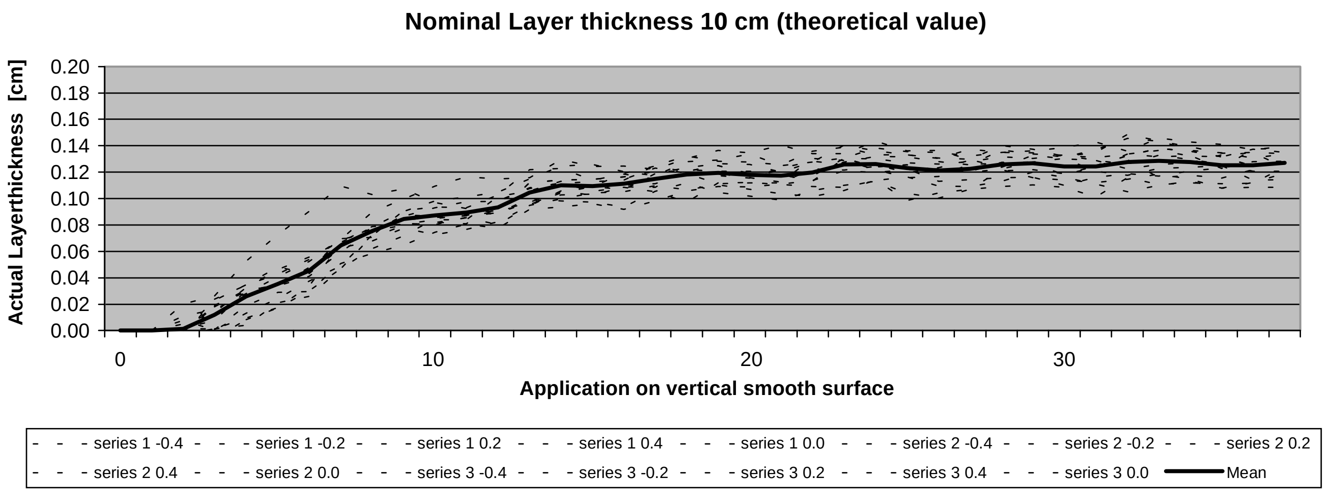

Fig. 20. Experimental layer thickness.

in compressive strength between the seventh and twenty-eighth days is, for the experimental parameter sets, very similar.

The laboratory experiments resulted in the following findings: Nozzle rotations of 1 or 2 rounds per second (rps) reduce the pulsation effect, which gives a better evenness. With nozzle velocities of less than or equal to 20 cm/s, the uniformity improves. With increasing distance (1.5–2.0 m) from the nozzle tip to the rock surface, the spraying figure gets more homogeneous. With distances between 1.5 and 2.0 m from the nozzle point to the rock surface, the rebound changes for the given concrete conveyance as follows: It increases greatly for 10 m^3/h, increases little for 15 m^3/h, and decreases for 20 m^3/h. The compressive strength for all parameter combinations (smooth surface) is higher for a spraying distance of 2.0 m than for a spraying distance of 1.5 m. These trends have become more or less apparent, depending on the air pressure at the nozzle (2.25, 2.75, or 3.5 bar). The air pressure at the compressor was constantly 4.5 bar. This indicates that not only the air consumption but also and even more the effective air pressure at the nozzle are key factors for the rebound.

3.8 Application on site

Considering the correction functions (Figures 21 and 22), the transition from laboratory experiment to application on site was achieved. Shotcrete application was carried out with an accelerator dosage of 4, 6, and 8 percent. Shotcrete was applied on presprayed rock and on blasted rock both washed previously with water.

For any application, the excavation line is evened out by the shotcreting, holes are partially filled, and peaks are covered less.[27] The overlaying of several spraying paths (design profile) has a balancing effect that optimizes the homogeneity of the final surface. With the following lower limits of accelerator dosages, sagging and falling in the crown were avoided: 4 percent for a layer thickness of 0.05 m on presprayed rock, 6 percent for a layer thickness of 0.12 m on presprayed rock and 0.08 m on blasted rock, and 8 percent for a layer thickness of 0.15 m on presprayed rock and 0.12 m on blasted rock.

The application was executed from the bottom of the side wall to the center of the crown (smooth-blasted excavation). In each of these sections, several profiles have been measured. In Figure 23, the developed length, from the side wall to the crown, is shown (three profiles measured). The required layer thickness (theoretical profile) is 0.10 m. According to reference 23, the tolerances of excavation support for shotcrete shells less than or equal to 15 cm is −0.01 m. With the simulated and corrected parameter combination, the fully automated shotcrete application achieves very easily the required shotcrete lining of 0.10 m.

The effective lining (mean) does not fall below the tolerance of 0.09 m. A few points, measured on peaks, do not achieve the limit. Measured points at holes, caused by overbreak, give a lining thickness of 0.11 to 0.12 m. While spraying shotcrete meander-wise in path lines, peaks are covered less and holes are filled. To guarantee at any point the theoretical layer thickness, too much shotcrete would be applied. The profile shown (Figure 24) represents the situation locally in detail.

The basic requirement of fully automated application (quality control is inherent in the application process) is to rule out that the sprayed layer thickness falls below tolerance. The fully automated shotcrete application guarantees the best, precise layer thickness possible, fulfilling the standard of underground work.[23]

3.9 Recommendations for shotcrete application

The smaller the layer thickness of the design profile and the smaller the path line distance, the better is the evenness of the final layer thickness. Conveying capacities of 10 to 20 m^3/h are mainly suitable for preapplication (filling of cracks and holes) or for layer thicknesses larger than 0.20 m. To prevent sagging of the fresh concrete and a scaly appearance, the shotcrete layers should be 5 to 15 cm thick. The evenness gets better with a higher dosage of accelerator; dosages lower than 5 to 6 percent should be avoided.

4 CONCLUSION

Different boundary conditions on site require different application modes. The manual mode of the robot is mainly for shotcrete application on extraordinary surface irregularities, e.g., local overbreaks. The semiautomated mode improves the quality of the shotcrete by taking over some functions from the nozzle operator. The fully automated mode guarantees high performance, quality, and a constant layer thickness at the same time. With regard to the situation on site, the user may select the most efficient mode for the application process.

A single formula that describes all parameters in general does not exist. It is not difficult to make suggestions regarding the right application technique for any single parameter (nozzle distance, nozzle velocity, concrete capacity, air pressure, rebound, etc.). Some important system parameters have to be interrelated because of their interdependence with reference to application intelligence to control the entire automated application process. The user may select some important parameters to set priorities between rebound, evenness, and performance of spraying; i.e., doing the application without the best possible evenness, the concrete conveying capacity may be enlarged, which reduces the time of spraying, or if high performance does not matter, a parameter set is chosen that minimizes

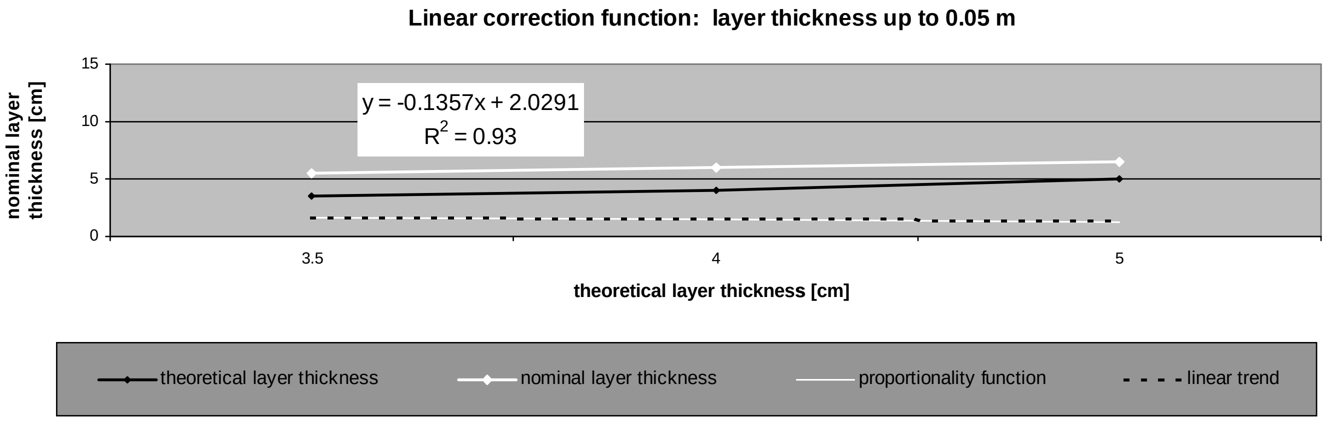

Fig. 21. Correction function theoretical-nominal layer thickness (layer thickness up to 0.05 m).

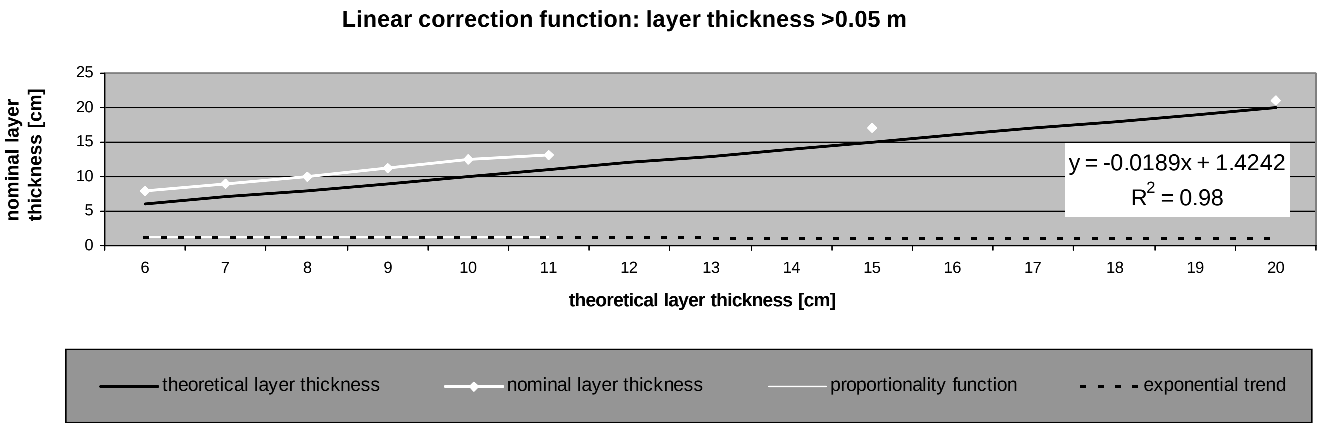

Fig. 22. Correction function theoretical-nominal layer thickness (layer thickness > 0.05 m).

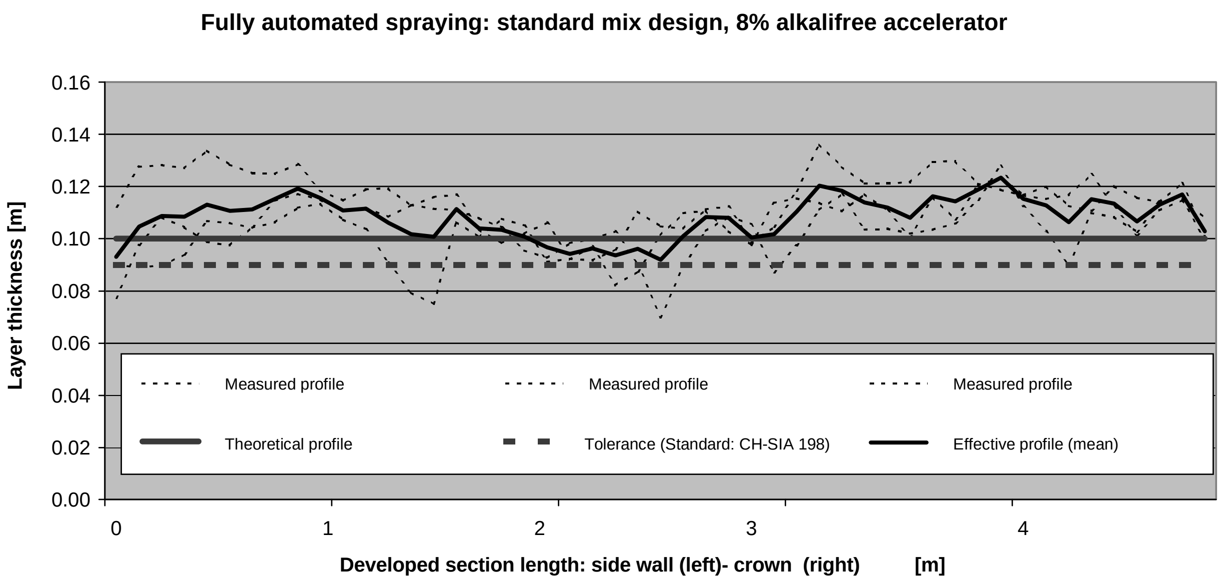

Fig. 23. Layer control of fully automated shotcrete application.

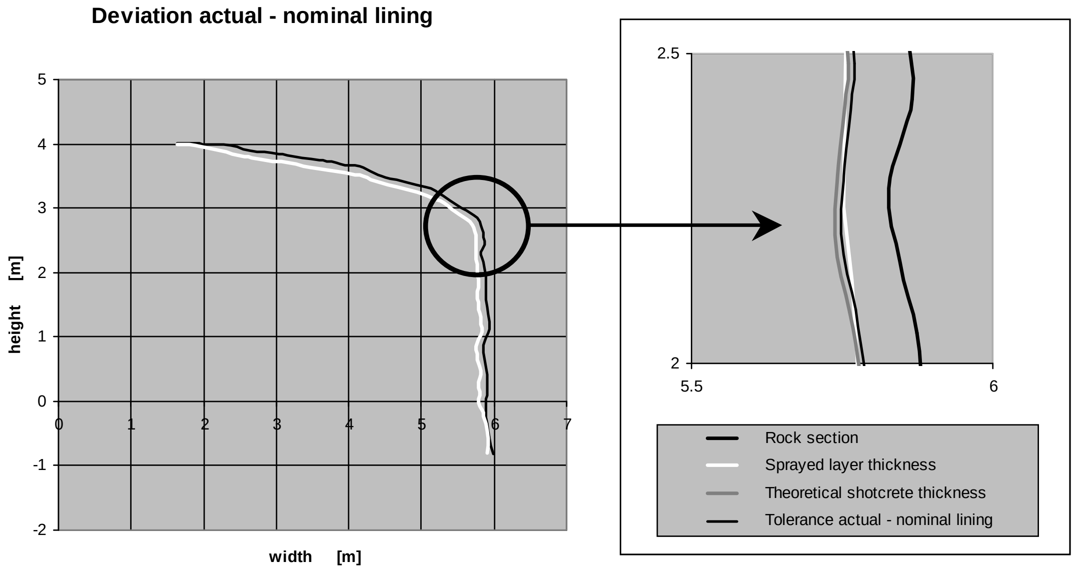

Fig. 24. Shotcrete application in a blasted tunnel section.

rebound. With calibration tests (in development), the different concrete mixes as well as the conditions on site can be adopted to transfer the basic process data (gained out of the experiments) into the adjusted requirements for any site.

The fully automated shotcrete process has high potential for application in areas with quite uniform site conditions to step up the performance and overall quality of shotcrete. In combination with other high-performance equipment in the construction process chain for drill and blast as well as TBM advancing, the shotcrete robot is one element to improve the profitability of tunnel construction.

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