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Fully Automated Shotcrete Robot

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Summary

The situation of the shotcrete application was unsatisfactory. With the development of the "Fully Automated Shotcrete Robot" the user will have a very effective manipulator at his disposal to spray concrete (fully automated) with the best combination of the important parameters with regard to rebound and time of spraying.

Quality control (layer thickness, compaction and homogeneous) is implemented in the application process. That means that it have to be taken only some cores to investigate strength, density and impermeability of water, to verify that the archived meets at least the specified quality.

With the registration of the connection between air consumption, pressure of the compressed air, concrete volume conveying and accelerator the control is effected direct via user panel by the nozzle man. Because of this progress the application process can be handled by the nozzle man and the concrete haul driver.

Today any spraying can be done in two different modes: manual spraying and semi automated spraying. This facilitates higher performance with less damaging the workman health.

1 Introduction

Shotcrete is used worldwide as temporary or definite lining in tunnels or in building pits. The application of shotcrete is strenuous and because of that tiring if it is done by a nozzle man. This holds especially for the use of wet shotcrete. Shotcrete application as first measure of rock fuse has often to be done in an area of danger.

Having applied shotcrete, the sprayed layer thickness can't be checked without any partial destruction by drilling cores.

2 State of the art

2.1 Technical Aspects (hand spraying)

Shotcrete is in the most cases still applied by the nozzle men wielding tube and nozzle. The strain of the workman limits the quantity of concrete that can be handled. The technique of application has to be trained and needs a lot of experience. Even for a experienced nozzle man the work demands high concentration.

To get an optimum of quality and a minimum of rebound the nozzle men have to keep the right distance and angle to the surface. If the spraying angle differs from 90° the rebound increases up to 50 %. The right spraying distance depends on the velocity of the shotcrete at the nozzle. Typical nozzle distances are between 1 to 2 meters. Keeping the air pressure at the nozzle constantly you can say that the rebound increases with increasing spraying distance (wet shotcrete, dense conveying). Absolute rebound is reduced with increasing thickness of the shotcrete layer as it lasts completely on the wall.

The experience on the sites shows that it is not possible to keep all the considerably parameters in the best possible combination, especially not in large tunnel profiles or high cut linings.

In Germany, Austria and Switzerland many research on shotcrete was done the last 15 years. Especially in Germany and Austria the investigation was mainly oriented on the dry shotcrete method. Most dependency can't be transformed on the wet shotcrete method. Experiments that have been made at the Ruhr University Bochum, Germany show that absolute rebound (wet shotcrete, dense conveying) is about less than 10% for common layer thickness with the best combination of the important parameters at laboratory conditions. This statement is valid for vertical applications. For spraying overhead the rebound has to be expected up to 15% (estimated value).*

2.2 Manipulator

The unsatisfactory situation can be improved by using a manipulator. The available manipulators are operated with radio-, or cable remote control with 2 to 4 joysticks to move the distinctive joints and several switches for the control of shotcrete and dosing pump. To reduce the complexity of the system some manipulators give the possibility to operate one or two joints automatically.

The workman steers the different hinges to let the nozzle do the movements. It is still difficult to hold the quality on a steady level because of the dust of

* Uwe von Diecken: Possibility to reduce rebound of shotcrete. Ruhr University Bochum Germany. Technical Report 89-2. 1989

spraying, the distance to the spray jet as well as the unfavorable angle of sight

Based on this problem a new manipulator was constructed by modifying the well known and proven MEYCO-Robojet. The new machine owns 8 degrees of freedom. The manipulator is fit with rugged absolute encoders, whereas 7 are working on angular and one on linear measuring principle. These sensors detect the position of each joint to is next simultaneously. Therefore the position of any joint with regard to the base position (carrier) is known.

The calculation of the kinematics is done by the control system.

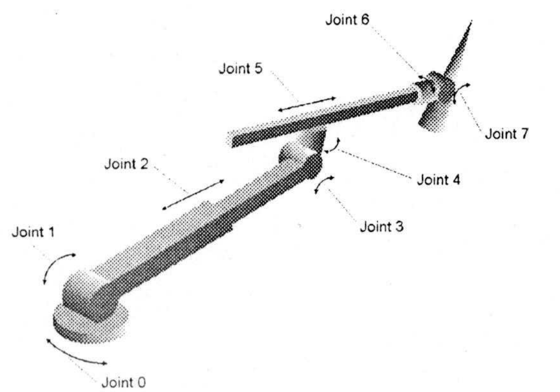


Fig. 1: Kinematics System

The movements are controlled with standard control valves that are equipped with emergency manual control in case of brake down.

The new machine gives the possibility to choose out of three different modes of spraying: full automated, semi automated or manual. Except of the full automated mode the workman uses a 6-D joystick (the Space mouse) to steer directly the movement of the nozzle. The spacemouse is a large handle with integrated "dead mans switch" and guarantees the water- and dust- firmness. The heart of the space mouse is modified piece of equipment that is used as ma standard in industrial robotics.

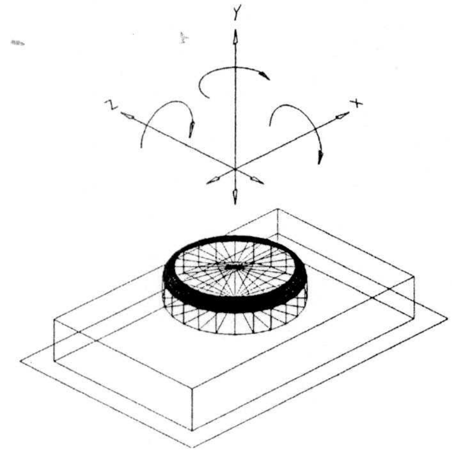


Fig. 2: Coordinates of Spacemouse

2.3 Measurement

The measuring is effected by a measuring raster the user defines on the basis of the unevenness of the surface. The measurement principle is a reflector less transit-time measurement in the infrared range. The standard deviation is ± 7-10 mm at 0.8 sec. measuring time. Faulty measurement is eliminated by an integrated filter function.

The measurement has to be carried out before and after the shotcrete application. Because they are done with the same measuring raster, defined before first time measuring, you get the layer thickness out of the difference of the distance data.

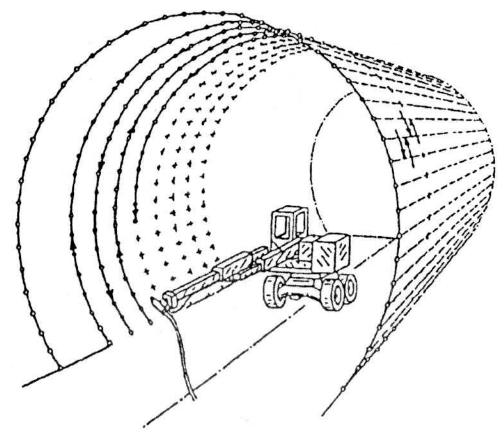


Fig. 3: measure of the raster (from down upward)

Different to the usual practice the two measurements give an interruption in the securing cycle. Therefore the security of the workman is much better because the measurement generally is done with the laser device that is launched on the manipulator. A big progress is that the data are saved in the system in which one the computation of the movement regulation is effected. With the connection to the global tunnel coordinates the final profile control is done with the spraying of the last shotcrete layer. With that a big saving of time is guaranteed.

2.4 Control

The computation of any movement is based on inverse kinematics what means that for a given path of the spray jet on the rock surface a regulation for the different hinges is definite. With a clever link of the hinges the redundancy can be avoided.

To arrange the handling as simple as possible the remote control takes the user clearly through the selected operation mode. The guidance is realized by twin bright buttons, green lightened buttons are to be used, red ones indicate function in operation, not lit buttons are not active.

All input to the system is done either by touch screen or by external computer. The parameters that are changeable are spraying distance, velocity of spraying beam along the surface and the distance between bordering rows.

2.4.1 Manual spraying

After the machine having set and stabilized the user is operating with the spacemouse. He has not to care about the hinges but he concentrates on the endpoint of the hit of the spray jet on the rock surface.

With the space mouse are steered:

- Angle
- Position
- Distance nozzle point - Tunnel wall

This mode is thought for difficult conditions (big local over profile) where it isn't possible to use one of the others.

2.4.2 Semi automated spraying

To give the necessary data to the robot the tunnel profile has to be measured. Therefore the user first marks the required work area by a laser device. The program calculates, out of the measured data, a movement regulation that holds the nozzle in the scanned range permanent perpendicularly in the fed nozzle distance. The spraying angle and the distance nozzle point - tunnel wall are consequently coordinated automatic.

With the space mouse are steered:

- Position
- Velocity

This mode gives the highest flexibility for the user without increasing the rebound particularly in ranges which are badly observably or over head far away from the user. The risk for the nozzle men is reduced and the capacity of the shotcrete application much increased. But to get the requested layer thickness the nozzle men still have to judge the surface by sight.

2.4.3 Full automated spraying

The measurement is effected similar. The user defines a starting point of where the robot leaves in meander shaped stripes. The control computer holds the nozzle perpendicular with the given spraying distance to the surface with the specified velocity.

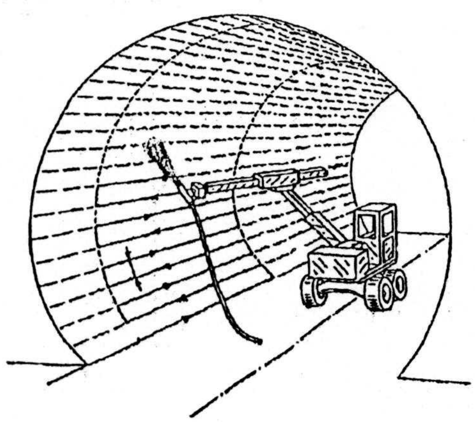


Fig. 4: shotcrete application in strips

In comparison with the other two modes the system has to overtake the experience, the supervision and the judgement of the nozzle men with the resulting actions. This aspect is something very new hasn't been examined up to now. This is the point where the further research starts.

2.5 Computer

Using bus cables, all electrical components of the robot are connected with the control box. Out of the data of any single module the computer calculates, depending on the task, the according pattern of motion. The hinges are controlled among other things in such a way that none of them are at the stop and a minimum of oil is needed. The moduls of the system are:

- Computer following industrial standards with flash, EEPROM memory and the necessary interfaces.
- Robot mechanical structure with sensors / actors.
- Laser scanner.
- Remote control with spacemouse.
- Touch-screen panel with visualization and input Possibilities.
- Interface to connect system with Ethernet to Internet for remote diagnostics and service.

3 System Intelligence (automated spraying)

The gravity is very important for the automated shotcrete application. Depending on spraying horizontal or over head or in any other angle the influence is different. Spraying horizontal the partition curve of the shotcrete distribution by the spray jet is sloped against the ground, spraying over head the rebound is increasing. In between the two effects go fluidly from one to the other. This effects have not been quantified yet.

3.1 Objectives

The knowledge of the nozzle men and the judging of the surface by sight have to be transformed from the workman to the system. Therefore we have to provide the system with artificial „construction engineering" intelligence.

The shotcrete application has to be carried out fast, in a constant layer thickness that was defined before, in high quality, with a even surface and a minimum of rebound. With holding this demands the costs can be reduced pertinent.

The connection between concrete conveying, compressed air to get an optimum of rebound, strength and water permeability must be described so that it can be controlled via the user panel by the system. Today the adjustment is done trying on site. That way you could save one working man.

3.2 Method

The research isn't done as exact as possible but as exact as required, and this is very important, by site conditions (in a factory yard). Because so many facts can't be influenced on site the data shell not be valid in general than show the regularities regarding material and application technical parameters. The test arrangement is protected by a control system which guarantees that all experiments are repeatable. Only this demands guarantee that the results are useful to be implemented into the system .

For the full automated application of shotcrete the structure of the surface is very important. It has to be differentiated between three types of surfaces: smooth surfaces, rough surfaces (blasted excavation) and steel girder and reinforcement installation. The research at the Swiss Federal Institute of Technology Zurich concentrated in a first step on smooth surfaces. The five phases are:

1. preliminary tests
2. Hypothesis for full surface shotcrete application and confirmation with Experiments
3. Extension of the range of application by varying the application parameters
4. Hypothesis of the regularity for common use, creation of a series of calibration tests
5. Validation

The other mentioned types of surface are an adaptation of the treatment of the transition regions and of the systematic of spraying. This tests will be done by phases 2 to 5.

With the preliminary tests the suitability of the developed manipulator is checked beside the recording of the basis data. Consequently, some adaptation for the further research must be done, on the one hand side by modifying the manipulator, on the other by the adaptation of the test program.

3.3 Experiments

The research concentrates on the application with a standard spraying nozzle (meyco) on the manipulator with dense conveying transport of a stabilized standard concrete adding the accelerator at the nozzle. The spraying capacity is varying between 10 and 20 m^3/h. The proportioning of the accelerator is limited by the necessity of scraping of the hardened concrete of the experimental wall. Therefore, and because the optical assessment doesn't show a meaning modification up to 8%, the dosage was committed with 4%. That the behavior of the incident shotcrete at the wall doesn't depend on the variation of the dosage of accelerator, in the mentioned range, has to be checked in phase 5. The expectation is that the influence is limited on rebound and final strength (not concern because of the required early strength as a rule).

The first step of automation is to quantify the distribution of the shotcrete by the spray jet. The manner of the application makes demands to the proportion of the shotcrete distribution of every sprayed strip to their distance. The research has to include the variety of parameter combination (distance nozzle to surface, nozzle moving velocity, nozzle motion) to make a statement that is valid in general.

Different to spraying by hand only some system adjustments are useful by spraying automatic because of the very important evenness of the sprayed surface. With this knowledge a description for full range spraying can be defined.

The preliminary test have been carried out on a vertical wall with smooth surface. The shotcrete was sprayed in single strips on two different levels. The distribution was measured on both levels in five parallel cuts in two passages.

To get a constant flow of the concrete (pulsation) and

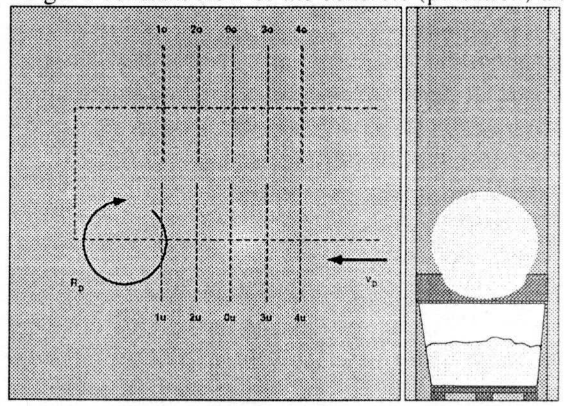


Fig. 5: Experimental assembly

in consequence a homogenous application with a constant nozzle moving velocity to be measured it was sprayed into a box at the beginning as well as in the end phase. Beside the measurement of the distribution and the maximum layer thickness the rebound was registered in the same time, by comparing the weight of the rebound and .the adhesive shotcrete.

Three groups of series of nine experiments have been planed: distance nozzle to the surface (1.0 m, 1.5 m, 2.0 m), nozzle moving velocity (10 cm/s, 15 cm/s, 20 cm/s) and the nozzle rotation (fix, 1 Hz, 2 Hz) were varying in all possible combinations. The concrete conveying was constantly by 10.6 m^3/h. After the first experiment with the fix nozzle without any rotation this adjustment was fliped out of the experimental concept because of very bad spraying structure.

The measurement was done, for all experiments, from the same survey point. The laser device took five parallel profiles. For the statistical safeguard every experimental adjusting was carried out twice in two independent strips.

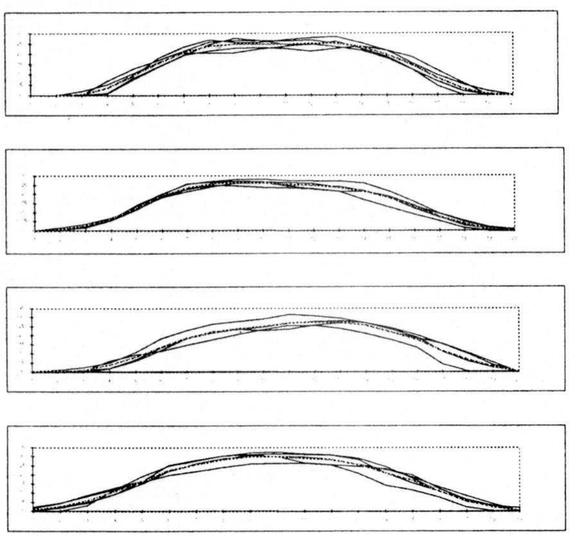
The course of every experiment was: positioning of the laser device, quality control of the wet concrete, application with constant conveying, measuring of the sprayed strips, weight of rebound and the adhesive shotcrete, remove of any concrete and preparation for the next application.

3.4 Results

For the quality and the informative value of the experiments it was very important to have the mean axis of the spray jet parallel to the ray of the laser device. Even little differences caused unambiguous changes in the spraying figure. This requirement was not easy to keep what it is showed in a few experiments.

Because no surface is as smooth as the experimental wall this effect will be more than overlapped by the irregularity of the natural surfaces. Nevertheless this recognition went into the construction changes of the new machine.

To give an idea of the results some super elevated representation of a single experiment (concrete conveying 10.6 m^3/h, distance nozzle surface $a_D = 1.5$ m; nozzle velocity $v_D = 15$ cm/s; nozzle rotation $R_D = 2$ Hz) show that the results of the measured distributions are very close together. The first four diagram show the families of curves per stripe (on the y-axis every mark means 5 mm, on the x-axis 50 mm).



It is obvious that the distribution is not symmetric, that was expected.

The maximum thickness of the in a single layer spread strips is between 2.5 and 3.0 cm. The expansion of the covered face is about 0.85 m.

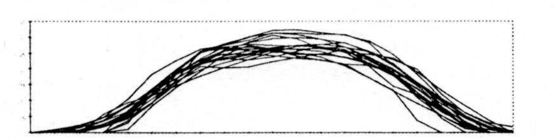


Fig. 6: Families of curves

All curves together give a better overview and show that the asymmetry is not as distinct.

A better visibility give the families of the mean curves or the resulting decisive curve of this special combination of the parameters (nozzle velocity, distance nozzle-surface, nozzle rotation).

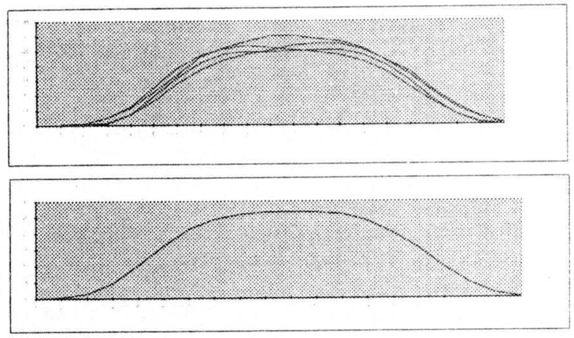
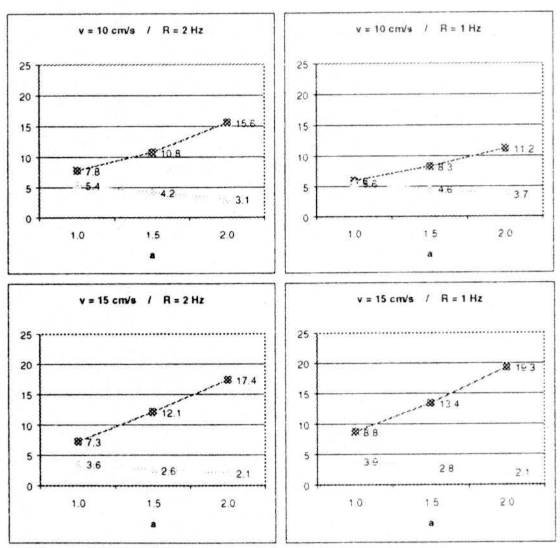


Fig. 7: Decisive curve of the according adjustment

The percent mean variation is quite high. The reason is meanly the little layer thickness of the sprayed strips but the discontinuous conveying of the shotcrete and the clearance in the joints of the manipulator too. As better the homogeneity of the sprayed strips is as lower is the mean variation.

Because of the necessity of a even surface a long the strips only about 40% of the checked experimental regulations can be used for further studies.

The diagram below show the dependence between the maximum of the layer thickness of a single sprayed strip to the rebound. The difference between the right and left side is the different frequency of the nozzle rotation. The nozzle moving velocity is increasing from the top to the bottom. The upper line gives the rebound in %, the lower line the thickness of the layer in cm.



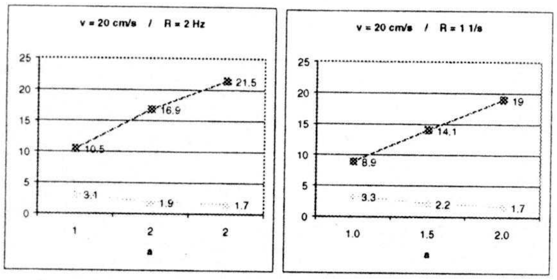


Fig. 8: Rebound

The results of the experiments show that the rebound can be divided in two sectors. Sector 1: layer thickness lower than 5 cm with a relative rebound up to 22 %, and sector 2: layer thickness about 5 cm with a relative rebound about 6 – 8 %. It is obviously that the absolute rebound is approaching approximately 6 % for layer thickness above 5 cm.

Although the experiments by U. von Diecken.* have been done with a quantity of concrete less than 6 m^3/h the tendency can be token over.

The 2 best regulations have been scrutinized with concrete conveying of 15.1 and 19.6 m^3/h in consequence. While spraying different concrete cubages with various air pressure, measured at the nozzle, it appeared that the rebound doesn't follow the same regularity. Beside the registration of rebound, the strength after 7d and 28d as well as the water impermeability have been examined. The water impermeability is an effective criteria for the interpretation of the dependence between rebound, strength, air pressure and concrete cubage.

The results can be summarized as follows:

- With increasing distance from the nozzle to the surface the spraying figure gets more homogenous, 1.0 m is not practicable
- With nozzle rotations of 1 or 2 turns per second the pulsation effects can be reduced what gives more regular results.
- With nozzle moving velocities less identical 15 cm/s the regularity of the shotcrete strip gets better.
- With larger distance the rebound increases much for amounts of concrete less than 10.6 m^3/h, increases little or stays constant for a concrete amount of 15.1 m^3/h and stays constant or reduces for a concrete amount of 19.6 m^3/h, depending on the air pressure that was deposited.
- The increase of the strength from 7d to 28d mostly is similar.

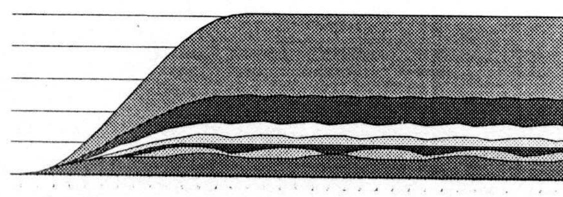
Conclusion:

It is not permissible to say in general that with increasing distance the strength increases as well but as well not that the strength reduces, the same is valid for increasing air consumption. It can only be given a statement that with a certain concrete cubage an according air pressure with the recommended distance and nozzle movement has to be taken to get the optimum of compaction (strength as well as water permeability!).

This results have been expected because of the divagation of the specification of the literature, even if the main research has been done with dry shotcrete.

The series of experiments are the basis for the development of the artificial „construction engineering" intelligence. The hypothesis is drawn up for the full range application (smooth surfaces).

The single strips, as showed above, can be overlapped to a theoretical shotcrete thickness up to 0.70 m.



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ig. 9 : Overlapping strips

Two sectors have to be distinguished: the transition region where the layer currant increases and the region with the required layer thickness. The second, constant region is as regular as more jet strips are overlapped. Dependent on the maximum thickness of the strips (depending on the combination of the above mentioned parameters) not every layer thickness may be applied with the same regulation. Therefore the concrete cubage is a quite interesting variable.

The problem is the transition between adjoining ranges. That means that in every spraying range a special area along the limit lines has to be defined and treated accordingly. This effect is very important and must be solved especially regarding profiles with steel girder installation. This research is in preparation.

4 Vision

The treatment of the transition region will be defined. The systematic of the application on different types of surfaces, especially with big local over profile, will be examined.

That the legality fit for any common concrete the characteristics have to be quantified by a series of calibration tests for site conditions.

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* Uwe von Diecken: Possibility to reduce rebound of shotcrete. Ruhr University Bochum Germany, Technical Report 89-2, 1989