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ANALYSIS OF REAL TIME TECHNICAL DATA OBTAINED WHILE SHOTCRETING: AN APPROACH TOWARDS AUTOMATION.

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Abstract: *Automation of shotcreting process is a key factor in both improving the working conditions and increasing productivity; as well as in increasing the quality of shotcrete. The confidence in the quality of the automation process itself and shotcrete linings can be improved by real time monitoring of pumping as well as other shotcreting machine related parameters. Prediction of how the different technical parameters of application are governing the whole process is being a subject of increasing interest.*

In present communication a study is made on how to approach their analysis by using some novel sensing technologies for ensuring both to fit the required layer characteristics as well as a less dispersions on the results. The main advantage is that sensors directly installed on the shotcreting machine as well as Ladar systems are relatively inexpensive non destructive measuring means that can be used also for routine quality control.

Sensors on the sprayed machine can be used for detecting the pumping needs for a given mix and therefore to regulate pumping (concrete flow) accordingly. Regarding sensing techniques based on Ladar technology, they can be used for a precise measurement of layer thickness that it is of utmost importance not only for technical but for economical reasons as well but also for governing shotcrete machine arm in order to obtain a layer with good compactness and minimise rebound.

1 INTRODUCTION

The goal of the shotcreting or concrete spraying operation is to build a compact and homogeneous layer of shotcrete over a given surface [1][2][3]. Shotcreting is essential in some tunneling methods, like NATM, where the application of a shotcrete shell is the first and perhaps most important step in providing structural support [4]. Shotcrete should comply with a predefined quality and thickness, while keeping rebound losses at a minimum [5].

The application of wet-mix sprayed concrete as compared to dry-mix sprayed concrete is dominating, with a clear trend for further increase mainly for structural tunnel lining [3]. Double piston pump base machines and accelerator dosing units are commonly used also for that case [6].

Regarding base concrete and type of equipment, general provisions are included on different standards and technical papers [6][7][8][9] such as:

a) The base concrete materials: cement type and proportions, water-cement ratio, aggregate types, grain size distribution of aggregates, special admixtures, concrete mix proportions,
b) The rheological mix parameters: relative yield stress and relative plastic viscosity, consistency, pumpability,
c) Mixing and batching techniques, transport and pumping, d) the different equipments depending on type of process consider (wet or dry), type of work and output need, etc,
e) The recommended cover thicknesses in function of mix as well as technical parameters of application and layer structural needs, and last but not least,
f) The main factors that affect the so called operational parameters and its relation on a qualitative basis (see Figure 1): speed of shotcrete when leaving the nozzle, angle nozzle-surface, accelerator dosage, distance nozzle-surface, direction of shotcreting (Up-crown, Down-floor, Side-vertical surface).

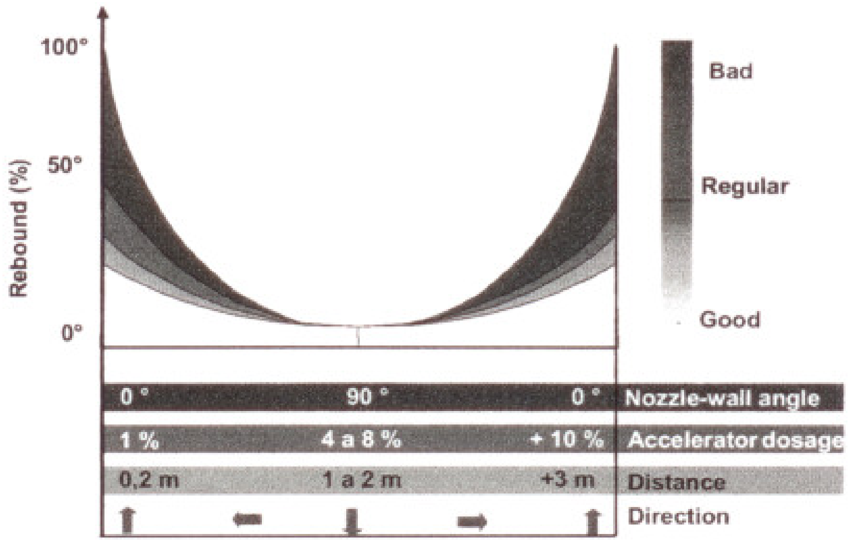

Figure 1: Effect of operational parameters on rebound and quality ([10], adapted from [2])

Moreover, there is an increasing demand of dealing with more advanced concepts related to mix design [11][12][13][14] as well as to analysing operational parameters, due the need of better tools to assess that its expected -or design- mechanical properties are a priori reached or to have a better control of the layer thickness or to reduce rebound losses. Furthermore, the lack of homogeneity on the shotcrete layer properties is also a very important gap.

Different proposals exist to approach the required demands, based on the improvement of the process by means of its automation [1][2][3][15]. Nevertheless, it seems that nor available information neither actual data exist on the literature proving its actual feasibility as well as its influence on the different parameters (quantitative values) [2][16].

With the focus on the automation of the process, and applying a holistic approach, the authors are performing a comprehensive quantitative study of the influence of the most relevant technical and operational parameters on both the process and end result.

In the present paper, the first stages of this study are presented, paying special attention to the main pumping and spraying parameters, as example of the possibilities of the methodology under development. Other factors, like mix design or admixture dosing are out of its scope. In the experimental work, only "pumpable" mixes were considered.

2 MONITORING THE SHOTCRETING PROCESS

2.1 Mix dependant variables. Pumping variables

Pumping variables depend on the type of pump being used. In the case of double piston or reciprocating pumps, the main factors influencing pumping technical parameters are the tribological and rheological properties of the mix [17][16][18][19], which in turn have effect mainly on the flow-pressure relationship in the pump.

Once the mixture proportions are defined, only little changes from batch-to-batch can be expected. Therefore, noticeable variations in any of the above variables might indicate some issues in the preparation and/or transport of the mix, which can be detected analyzing the pressure-flow ratios.

Establishing the relationship between concrete flow (*q*) and pressure in the outlet of the pump (*p*) is not straightforward, due mainly to the variability in time of the pressure in the outlet of the pump -measured by concrete pressure sensors developed by AITEMIN- (see Figure 2); and requires the implementation of a fast real-time signal processing algorithm for its determination.

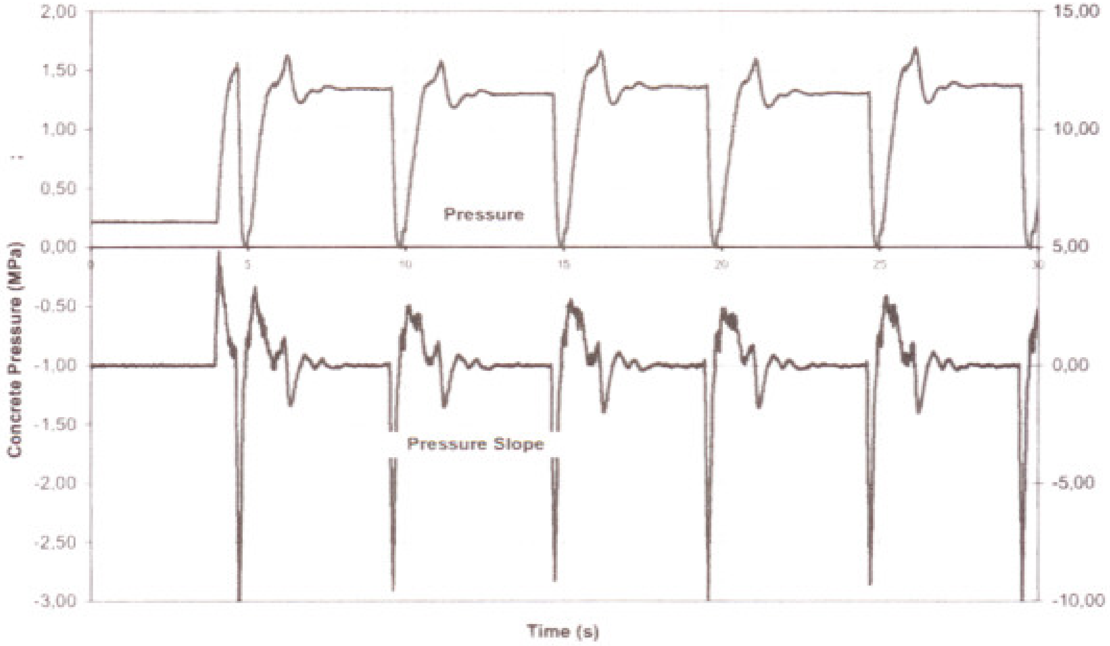

Figure 2: Actual pressure p (up, left y axis) and its slope (down, right y axis) at the outlet of a double piston pump

In a closer analysis of the pulses (Figure 3), four stages can be observed (a) Pre-compression, at the beginning of a stroke (b) Transient, with great oscillations in pressure (c) steady state, with more or less constant pressure and (d) abrupt fall at the end of stroke. There are three characteristic pressures in the pulse: *Peak* (p_p), *Valley* (p_v) and *Steady State* or *Constant Speed* (p_{vk}) pressure.

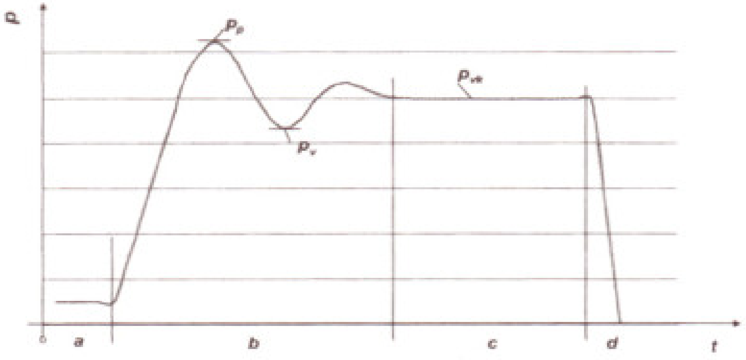

Figure 3: Shape of a pressure pulse. Characteristic stages and values.

During stages a, b, and d, there are great changes in pressure and concrete speed in the pipe, and therefore it is very difficult to establish any correlation between flow and pressure. Then, it seems reasonable to use the average pressure in stage *c* for establishing the aforesaid flow-pressure relationship.

Finding the limits of stage *c* requires some signal processing. It has been found that in practice *a* and *b* stages have quite variable lengths, while *d* stage has a fixed and short duration. Therefore, the better approach for establishing the limits of *c* stage consists of start detecting the limits of stage *d*. This stage is characterized by i) high negative slope and ii) pressure decreasing almost to 0 (Figure 2). After the start of *d* is found, finding the beginning of *c* is quite straightforward, for in *c* the slope of the pressure curve is null or very low.

Therefore, going back (right to left) on the signal until slope rises, will allow determining *b-c* border, and then the average value of *p* in *c* interval (p_{vk}).

Application of the above method in real time requires recording and storing data of at least a couple of pressure cycles, and some signal processing, including the application of a convolution (FIR) filter [20] to the raw data in order to eliminate signal noise. Slope in a sampling instant *i* (s_i) is determined as usual as quotient of increments:

$$s_i = \frac{p_{i+k} - p_i}{t_{i+k} - t_i} \tag{1}$$

Where p_i and p_{i+k} are the pressures read at sampling instants i and i+k (at times t_i and t_{i+k}) and *k* is an integer factor whose value is chosen in order to get a smoother variation of *s*.

In consequence, the algorithm for determining the limits of *c* stage consists of the following steps:

1. Record pressure data at fixed intervals in a buffer of suitable size.
2. Search for a local minimum value, whose absolute value is below certain threshold
3. When a minimum is found, go back in the record while the slope is lower than a second threshold. This is the start of *d* stage and the end of *c* one.
4. Finish the process when slope increases again. This is the beginning of *c* stage.

5. p_{vk} is the average value of p in c interval, which can be correlated with q

Different experimental results on the subject show that there is always a small difference between the values of t_S and p_{vk} when measured in consecutive strokes, fact that can also be observed in the example of Figure 2.

On the other hand, it is necessary assigning a value to flow (q). As the speed of pistons during each stroke is pretty constant, it seems reasonable using the average flow rate $\overline{q}_i$ as defined in equation (2), where Vs is the volume displaced in each stroke and t_S the stroke time.

$$\overline{q}_i = \frac{V_S}{t_S} \tag{2}$$

Moreover, there is a linear relationship between pressure p and flow rate q [16][19].

$$p_{vk} = k_1 q + k_2 \tag{3}$$

Therefore, if p_{vk} is measured for two different values of q, and for each q in at least two consecutive strokes, both parameters k_1 and k_2 can be estimated. Experimental work carried out by the authors with different pumpable mixes (see Figure 4 as example) show that k_1 is pretty constant as far as there are no variations on the mix composition. In other words if no variation from batch to batch exist, no changes in k_1 will happen. On the other hand results shown that also for the same mix k_2 varies along the time. Complementary studies have done correlating this parameter with concrete slump flow. Measurements show that a close relation exists between both. As a consequence it is possible to estimate change on the mix properties along time by computing k_2.

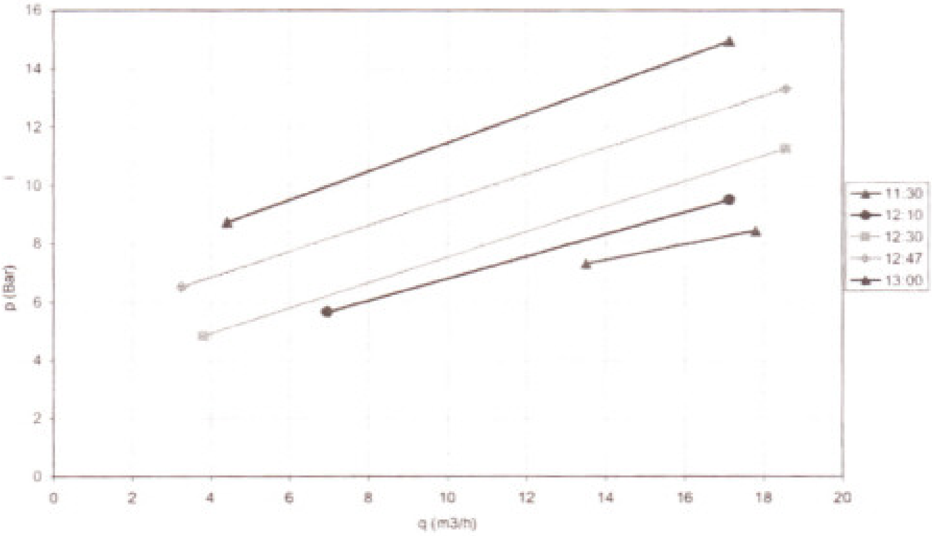

Figure 4: Evolution of p_{vk} / q relationship with mix age

Thus, the actual value of k_1 and k_2 can be used for both detecting differences in the mix provided, and therefore be used as quality control parameters but also for adjusting automatically flow rate for a given mix in order to not overload the concrete pump hydraulic system among other ends.

2.2 Spraying variables

Among the main factors governing the spraying part of the process (See Figure 1), only the position and attitude of nozzle will be considered in this section; where a brief description of the issues to be addressed, and the methods proposed for solving the problem, will be made.

a) Absolute position and attitude of the nozzle

Absolute attitude of the nozzle (angle with the vertical) can be calculated quite easily using a two step method, consisting of:

- **i)** Finding the relative position between the nozzle and the chassis of the machine and
- **ii)** Combining this info with data on the attitude (actually only inclinations are relevant) of the chassis of the machine.

The calculation of nozzle position with regard to the chassis requires having a good model of the boom that holds it (usually in terms of its Denavit-Hartenberg -or D-H- description [21][22]) and the knowledge of the value of all joint angles and displacements contained in the aforesaid description (see Figure 5 where a SIKA-PM 407 is described by using the Denavit-Hartenberg Model).

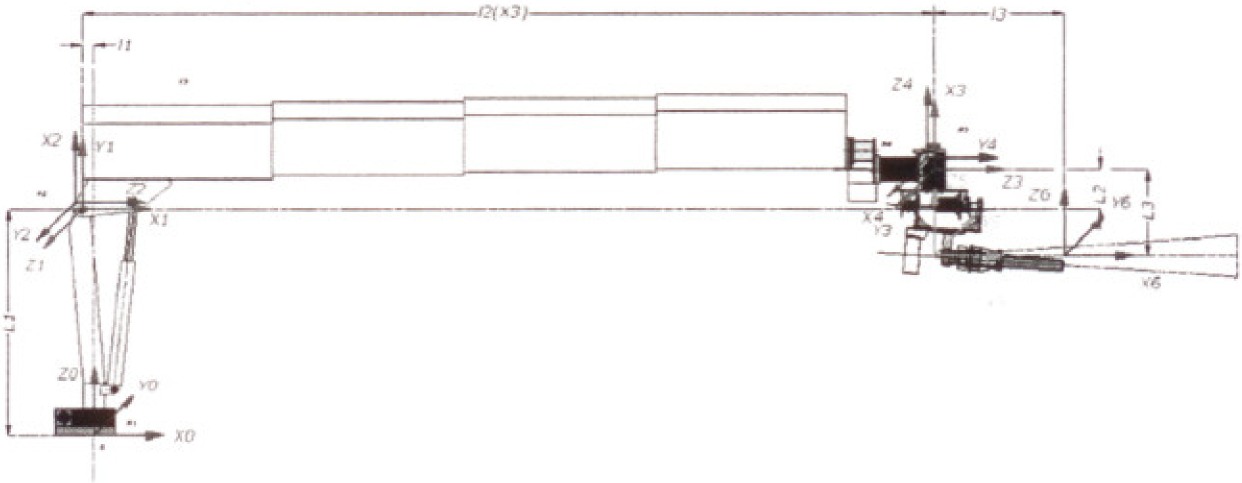

Figure 5: Denavit-Hartenberg model of a SIKA-PM 407

After operating -intermediate steps are not shown- a final transformation matrix like the one shown in equation (4) is obtained. This matrix relates D-H coordinates of the nozzle in the coordinates system of the machine with its coordinates in the local-nozzle reference system. Matrix elements are functions of the values of the remaining D-H coordinates (in this matrix the simplified notation C_x and $S_x$is used for representing the functions $\cos(\varphi_x)$ and $\sin(\varphi_x)$) Therefore, it is essential to measure and record all joint variables (see table 1) of the nozzle manipulator in order to compute the nozzle coordinates as a function of the joint variables.

Joint	*alpha*	*a*	θ	*d*	*Parking*
1	*90°*	$-l_1$	φ_1	L_1	*0*
2	*90°*	*0*	φ_2	*0*	*90°*
3	*0*	L_2	*0*	$L_2(X_3)$	*0*
4	*90°*	*0*	φ_4	*0*	*90°*
5	*0*	*0*	φ_5	$-L_3$	*90°*
6	*0*	*l3*	*0*	*0*	*0*

Table 1: Denavit-Hartenberg parameters of a small nozzle manipulator.

$$[T] = \begin{bmatrix} C_1C_2C_4C_5 + S_1S_4C_5 + C_1S_2S_5 & -C_1C_2C_4S_5 - S_1S_4S_5 + C_1S_2C_5 & C_1C_2S_4 - S_1C_4 & -C_1C_2S_4L_5 + C_1C_2L_3 + S_1C_4L_5 + C_1S_2l_3 - C_1l_2 + l_6(C_1C_2C_4C_5 + S_1S_4C_5 + C_1S_2S_5) \\ S_1C_2C_4C_5 - C_1S_4C_5 + S_1S_2S_5 & -S_1C_2C_4S_5 + C_1S_4S_5 + S_1S_2C_5 & S_1C_2S_4 + C_1C_4 & -S_1C_2S_4L_5 + S_1C_2L_3 - C_1C_4L_5 + S_1S_2l_3 - S_1l_2 + l_6(S_1C_2C_4C_5 - C_1S_4C_5 + S_1S_2S_5) \\ S_2C_4C_5 - C_2S_5 & -S_2C_4S_5 - C_2C_5 & S_2S_4 & -S_2S_4L_5 + S_2L_3 - C_2l_3 + L_1 + l_6(S_2C_4C_5 - C_2S_5) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

Assuming that the values of the above joint variables are known, it is straightforward to calculate the position and attitude of the nozzle with regard to the machine local coordinates system. Finally, angles of the machine chassis with the vertical can be easily measured using a two-axis inclinometer.

Combining the results of both steps will give directly the angle of the nozzle with the vertical.

The speed of implemented algorithm (Based on the above D-H Model) was considered also crucial as all these data must be processed in real time.

b) Relative position and attitude of nozzle

The relative position and attitude (angles) of the nozzle with regard to the walls cannot be measured easily in a direct way, and as a consequence some indirect method should be used.

Proposed one consists of four steps:

- **i)** Finding the relative position between the nozzle and the chassis of the machine
- **ii)** Obtaining a representation of the surface S_t of the tunnel walls in a coordinates system linked to the machine
- **iii)** Finding the intersection point i_p of the line representing the axis of the nozzle and S_t
- **iv)** Then it is immediate calculating the distance nozzle-wall as the distance the distance from the nozzle end and i_p; and the angle nozzle-wall as the angle between nozzle axis and the normal to on i_p (Figure 6: Calculation of nozzle-wall distance and attitudeFigure 6).

Step **i)** operations are exactly the same than in step **i)** of the previous case, and therefore will not be repeated here. The outcome of this first step will be the coordinates of the endpoint of the nozzle (i_n) and the unitary vector defining its axis (u_n)

Step **ii)** step requires the use of some kind of 3D imaging device (a 3D high speed LADAR Scanner), which obtains a numerical 3D image of the surroundings of its stationing point. Due to the scanning patterns and operating principles of these devices, the raw image is usually formed by a cloud of points defined by their polar coordinates in a reference system centred in the scanning device [23].

After the raw image is available, a polyhedral mesh can be fitted to this cloud of points, and then rendered to a continuous surface [23].

Once the cloud of points representing the surface of the tunnel is reduced to a representation of reasonable size, complexity and smoothness, it is possible proceeding to steps **iii)** and **iv)**. Finding the intersection of the line defining the attitude of the nozzle with the walls of the tunnel is straightforward, as is also the case of finding the angle φ with the walls (Figure 6).

Distance is the length of the segment $i_n\, i_p$, while $\cos(\pi/2 - \varphi) = n_t \cdot u_n$

Therefore, using a combination of position sensors installed on the shotcreting boom and a Ladar scanner mounted on the machine, it is possible determining the position and attitude of the nozzle, both absolute and relative to the walls of the tunnel. This information is useful for both the automation of the process and for quality control purposes.

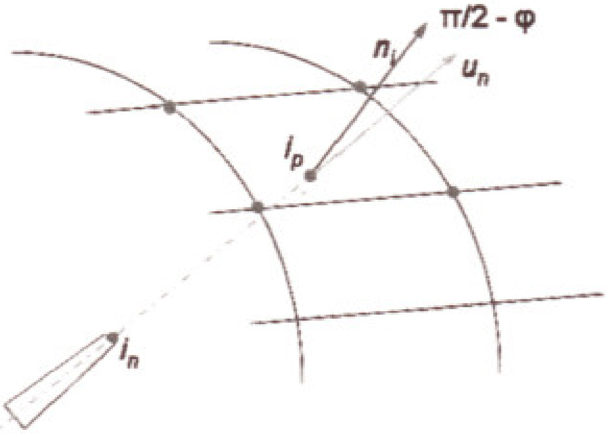

Figure 6: Calculation of nozzle-wall distance and attitude

3 CONCLUSIONS

From the above preliminary results the following conclusions can be drawn:

- Monitoring the pumping process through observation and analysis of pumping pressure might provide very useful information for automating the process. They can also be used as an onsite quality control tool, for some parameters derived from the analysis of pressure-flow relationships may constitute good indicators of fresh concrete properties.
- Pumping pressure may also be used for adjusting automatically flow rate for a given mix in order to not overload the concrete pump hydraulic system, among other ends.
- It is possible determining in real time the position and attitude of the nozzle, both absolute and relative to the walls of the tunnel, using a combination of position sensors installed on the shotcreting boom and a Ladar scanner mounted on the machine. The implemented algorithms constitute a useful for the automation of the spraying process and can also be used for quality control purposes.
- Analysis of sensor data in real time could provide "early warnings" critical for a quick reaction of involved staff, but it also constitute a first step in the automation of the process based on rational and quantitative criteria.

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