CHARACTERIZATION OF DEPOSITION IN TUNNEL DRAINAGE

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Abstract - In water pressure-relieved tunnels, calcium carbonate scaling occurs in tunnel drainage systems. Mostly the drains have to be cleaned to prevent an increase of the water pressure on the tunnel lining, which can cause damage to the tunnel structure or water ingress. In order to organize the cleaning procedures efficiently, a measurement of the thickness and zones of the calcite scaling is required. This contribution lists various measurement methods and discusses electrical impedance tomography (EIT) as a representative in detail. EIT is based on measuring the impedances of all combinations between two electrodes and subsequent reconstruction of the material distribution. The basics of this measurement principle are explained and a characterization of the electrical properties of calcite is presented.

Keywords - Calcitescaling, Capacitive Coupled Electrical Resistance Tomography (CCERT), Electrical Tomography (ET),Tunnel Drainage

I. INTRODUCTION

Drainage systems in tunnels are used to reduce groundwater pressure on the tunnel lining and to drain off water. Due to the use of shotcrete and other cementeous support elements and the chemical composition of the groundwater, drainage water contains many dissolved components. The precipitation of dissolved components in drainage systems, triggered by changes in chemical equlibria, are called scaled deposits, encrustations or sinter formation. These scalings, as shown in Fig. 1, can cause significant and expensive maintenance and serviceability problems
Essentially, more than 80 % of the dissolved substancesin water in a calcareous environment can beexplainedbythe carbonate balance. In detail,the solution, hydration and dissociation of CO_2 as wellas the dissolutionof $CaCO_3$ play the most importantrole.



Figure 1: Sedimentation in a drainage pipe [1]

The reasons for changes in the carbonate balance are found in a very complex system and are affected by

- interaction of the mountain water with the surrounding geology
- hydrochemical influence of the proppants such as concrete and cement,
- flow properties within the drainage pipe.

In order to detect and monitor the scalings inthe tunnel drainage systems at the moment the growth of scale in tunnel drainage can only be monitored by camera surveys. This requires closure of the track or the whole tunnel and causes a massive operational restriction and to high financial efforts.
The goal of the research project is to find remote monitoring systems, which are suitable for use intunnel drainage and thus capture the sedimentation directly in the system to allow a corresponding optimization of the cleaning effort.

II. POTENTIAL MEASUREMENT METHODS

The requirements for a measuring method are explained in [2]. Based on this, the possible measurement methods listed below were identified:

- X-ray Tomography
- Ultrasonic Layer Thickness Measurement
- Acoustic Analysis
- Shell Vibration Analysis
- Electrical Resistance Tomography (ERT)
- Electrical Capacitance Tomography (ECT).

The following chapters describe thelast two methods, ECT and ERT; in more detail. In addition to the layer thickness of the calcite scaling, these methods also offer the possibility ofmeasuring its porosityas well as measuring the water level in the pipe.Future investigations will show whether the porosity canalso be used to deduce mechanical properties of the calcite layer, which would be helpful in terms of the choiceof cleaning method and frequency.

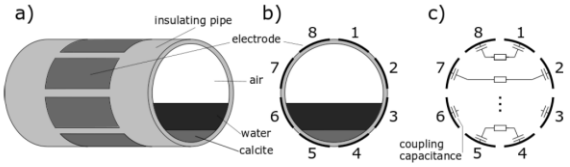


Figure 2: CCERT sensor withN_"elec" = 8 electrodes, a) electrodes arrangement, b) cross-sectional view, and c) equivalent circuit of the CCERT sensor

III. ELECTRICAL IMPEDANCE TOMOGRAPHY (EIT)

Both ECT and ERT can be generalized as EIT. The electrical impedance $\underline{Z}$ described in (1) is a complex number. Itsreal part, which is the resistance R ,is dependent on the conductivity σ. The imaginary part is the reactance X, determined by the angular frequency ωand the capacitance C, which in turn depends on the permittivity ε

$$\underline{Z} = R + j\,X = R(\sigma) + \frac{1}{j\,\omega\,C(\varepsilon)}. \qquad (1)$$

The electrical behaviour is determined by both, conductivity and permittivity. If the resistance betweenall electrodes at the circumferenceis measured and the spatial distribution of the conductivity is reconstructed, one would call this ERT. With this measurement principle the electrodes would contact the medium within the pipe and are therefore located at the inside of the pipe.
In opposite, if the capacitance is measured and the spatial distribution of the permittivity is determined, this would be called ECT. The electrodes are placed at the outside of the pipe and due to the nonconducting pipe they are insulated from the medium inside.



Figure 3: Used calcite samples, labelled 1-7 from left to right

A. Sensor Design

A sketch of the used sensor is presented in Fig. 2. In Fig. 2a) the arrangement of the electrodes around the circumference outside the pipe is shown. Fig. 2b) shows the cross-sectional view and Fig. 2c) depicts the equivalent circuit of the sensor. According to the description in the section above, the arrangement would suggest the sensor to be an ECT sensor. In fact we are measuring the conductivity of the water and calcite inside the pipe. So the sensor is a capacitive coupled electrical resistance tomography (CCERT) system.
The big advantage of this technique is that it is neither intrusive nor invasive and therefore no interaction between the water or calcite and the electrodes can effect the measurement. Another benefit is the mechanical stability of this arrangement,needed for the cleaning process inside the pipe. One major drawback is that the measured impedance is a series combination of impedance of the medium inside the pipe $\underline{Z}_x$ and the two coupling capacitances at each pipe wall, as described in (2).The additional series impedances affect the resolution of the measurement

$$\underline{Z} = \underline{Z}_{pipe,1} + \underline{Z}_x + \underline{Z}_{pipe,2} = \underline{Z}_{pipe} + R_x + j\,X_x = \frac{1}{j\,\omega\,C_{pipe}} + R_x + \frac{1}{j\,\omega\,C_x}. \qquad (2)$$

To overcome the problems resulting from the capacitive term, an inductorwhich has a positive imaginary impedance can be connected in series to compensate all imaginary parts thus mainly the resistance $R_x$is measured [3]. This may be evaluated in future work.

B. The Principle of EIT

The distribution of the electrical potential V inside the drainage pipe is given by the partial equation

$$-\nabla \cdot \left(\left(\sigma(x,y) + j\,\omega\,\varepsilon(x,y) \right) \nabla V \right) = 0. \qquad (3)$$

Solving (3), including and meeting the boundary conditions, is called the forward problem.
$\sigma(x,y)$ denotes the electrical conductivity and $\varepsilon(x,y)$ the electrical permittivity at any point (x,y) inside the pipe. As mentioned above, both quantities determine the spatial distribution of the potential within the considered volume. By taking them in ratio in (4) one gets the factor

$$r_{\sigma,\omega\varepsilon} = \frac{\sigma}{\omega\,\varepsilon}. \qquad (4)$$

This coefficient describes which one of those two material properties affects the potential distribution more at a certain angular frequency ω [4].

If $r_{\sigma,\omega\varepsilon} \ll 1$the potential distribution is more heavily affected by the dielectric properties and thus ECT is to be preferred. In contrast, ERT should be used if $r_{\sigma,\omega\varepsilon} \gg 1$, sincein this case the electrical conductivity significantly influences the potential distribution.Furthermore, the coefficient$r_{\sigma,\omega\varepsilon}$ can still be influenced by a suitable choice of the measurement frequency.In our case, the electrical conductivity predominates, which is why subsequently the dielectric properties can be neglected.

The inverse problem is the reversal of the forward problem and determines the spatial distribution of electrical conductivity within the drainage pipe. The impedances $\underline{Z}_{ij}$ of all combinations between all possible pairings of electrodes i and j are measured, resulting in independent measurements.

$$M = \frac{N_{elec} \cdot (N_{elec} - 1)}{2} \qquad (5)$$

Fromthose measurements the spatial distribution of the electrical conductivity is determined. The inverse problem according to [5] is an ill-posed problem.

IV. CHARACTERIZATION OF CALCITE DEPOSIT

Due to the difficulty of obtaining useful samples of calcite scaling, it is expedient to model the real deposit with another material. For this purpose, a characterization of calcite in terms of its electrical properties is necessary. In addition, the porosity of various calcite samples is determined to establish a connection with the conductivity.

A. Porosity



Figure 4: Bottom (left) and top (right) of the measuring cell

The porosity Φ is defined in (6), where ρ denotes the bulk density, ρ_0 the particle density, V_V is the volume of the void-space and V_T is the bulk volume of the material. The porosity

$$\Phi = 1 - \frac{\rho}{\rho_0} = \frac{V_V}{V_T} \qquad (6)$$

sampe #	Φ_{Air}	Φ_{Water}	$\overline{\Phi}$
1	0,20	0,24	0,22
2	0,45	0,47	0,46
3	0,23	0,21	0,22
4	0,16	0,14	0,15
5	0,17	0,17	0,17
6	0,14	0,14	0,14
7	0,41	0,37	0,39

Table I: Porosity of the calcite samples

of the samples in Fig. 3 were calculated in two different ways. The first variant is based on the former part of the definition. The geometrical dimensions of the samples were determined, their dry mass was measured and then the bulk density was calculated. This was divided then by the particle density and used to calculate the porosity Φ_{Air}. The second option used the latter definition of porosity. From the mass of fully water-saturated calcite samples, the dry mass is subtracted, from which the total pore volume can be calculated using the density of water. The result is divided by the bulk volume and leads to the porosity Φ_{Water}.

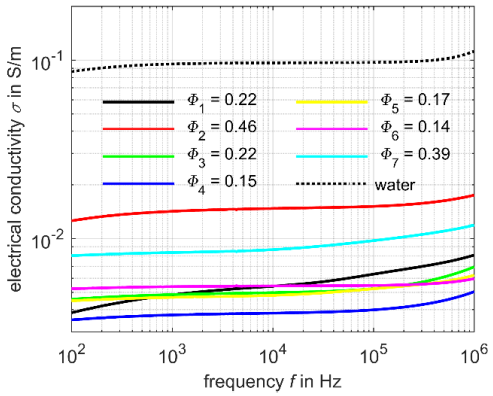


Figure 5: Electrical conductivity of water saturated calcite samples 1 to 7

A comparison of the results of both methods as well as the averaged porosity$\overline{\Phi}$ is summarized in Table I. It can be seen that both methods agree well for all samples. The small deviations can be attributed above all to the variation of the samples from the ideal cylindrical shape which was assumed for the calculation.

B. Electrical Conductivity

In order to determine the electrical conductivity of the calcite samples, the measuring cell shown in Figure 4 was built. It consistsof a cylindrical container 100 mm in inner diameter and a sort of a lid being lowered to touch the sample form top. Both parts comprise of a copper plate as electrode.

To reproduce the conditions in the tunnel drainage as accurately as possible, wastewater from cement production is used to measure the conductivity of the water-saturated calcite samples. Like the mountain water of a typical drainage system this wastewater has a much higher conductivity than tap water.

The water-saturated calcite samples are placed in the lower part and contacted from above with the counter electrode. By means of the impedance analyzer HP4194A, the impedance spectra of all samples were recorded. Using the real part, the electrical conductivity is calculated for each sample. The results are shown in Fig. 5.The equivalent electrical circuit diagram for this configuration is usually a combination of series and parallel connection of resistors and capacitors. Due to the comparatively high conductivity of the calcite samples and the large electrode area, the parasitic capacitances can be neglected with a good approximation and the electrical behaviour can be regarded as purely resistive.

The conductivity of the water-saturated calcite samples is constant over a wide frequency range. It turns out that the conductivity of calcite increases with increasing porosity, since calcite is a non-conductor when dry. The higher the concentration of water due to the greater porosity, the better the conductivity.

Therefore, the above-mentioned determination of the porosity by measuring the conductivity is possible.

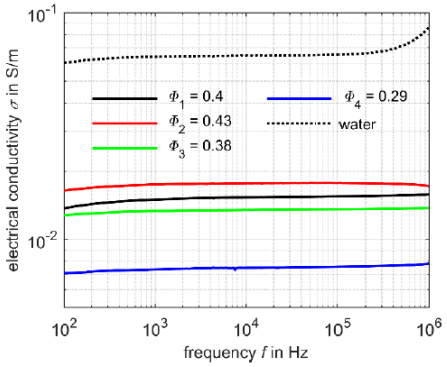


Figure 6: Electrical conductivity of water saturated sand

For comparative purposes, the conductivity of water was also determined and indicated in Fig. 5 as well. It was measured with both, the developed measuring cell and the conductivity measuring cell 6.0912.110 from Metrohm. Both measurements gave the same result, confirming the correctness of the former method.

In order to model the electrical properties of calcite as accurately as possible, quartz sand was used. This was also measured as already described and the conductivity spectra are depicted in Fig. 6. Again, the conductivity is constant over a wide frequency range and increases with increasing porosity. For comparison, the conductivity of water was measured and indicated in Fig. 6. It can be observed that the conductivity of water-saturated sand at a porosity of about $\Phi = 0.4$ is about one-tenth the conductivity of pure water. For calcite, this also is true, too, to within the same order of magnitude.Thus, it is shown that quartz sand is suitable for modelling the electrical properties in a real measuring setup.

V. SUMMARY AND OUTLOOK

In this paper the problem of detecting the layer thickness of a calcite layer using CCERT is described. The future work will be directed to obtain measurements from the experimental setup and choosing a suitable reconstruction algorithm to reconstruct the material distribution inside the drainage pipe.

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