RELATIONSHIP BETWEEN CRACKING AND ELECTRICAL RESISTANCE IN REINFORCED AND UNREINFORCED CONCRETE.

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Abstract

Electrical resistivity of concrete is a material dependent property that has been used to assess transport properties. Ions contained in the pore solution are responsible of carrying electrical current through concrete’s pore network. Pore size and connectivity have an influence on the transport properties of concrete. When concrete is subjected to environmental and/or mechanical action, cracking of concrete cover is a serious threat for its durability. Cracks represent fast routes for chloride ingress that lead to corrosion of reinforcement. In concrete, cracks can be considered as spatial discontinuities between aggregates and concrete hardened matrix. For concrete infrastructure, cracks are important for assessing the remaining service life. Tensile cracks in bending have a tapered geometry, i.e. the widest crack occurs at concrete’s surface with a decreasing opening as crack propagates towards the reinforcement. This type of crack is critical for assessing the condition of a concrete structure. In this paper, real-time measurements of concrete resistance during cracking of reinforced concrete specimens were performed under laboratory conditions. A Modified Wedge Splitting Test (MWST) was used in order to create controlled cracks in the specimens. Results show that the load-displacement curves can be linked to the relationship between displacement and resistance of concrete.

1. INTRODUCTION

Reinforced concrete is the most widely used construction material in the world. Because of its cost-efficiency and capacity for withstanding severe environmental conditions, concrete infrastructure is required. However, concrete durability is not permanent. Concrete is a porous material that allows transport of matter through its pore structure. The connectivity and size of pores have a significant influence on transport properties in concrete. Ions contained in the pore solution are transported by the action of some mechanisms like diffusion, capillary suction or convection. Also, these ions can carry electrical current through concrete’s pore network. Electrical resistivity of concrete is a material dependent property that has been used
to assess transport properties of concrete. Measured values are usually between $10^1$ to $10^5 \, \Omega \, \text{m}$ and are dependent on concrete composition, age and environmental conditions [1]. The chemical composition of concrete’s pore solution depends on the cement type and composition and the presence of other binders like GGBFS or fly ash. Usually, the variation of measured values of resistivity from different concretes is high. The influence of both mix design parameters and/or environmental conditions are the cause of such variation. High values of water-to-binder ratio are related to wider and more connected pores. In this sense, it is reasonable to assume that resistivity and durability are strongly related. A higher resistance to chloride or CO$_2$ penetration; and slower deterioration (i.e. corrosion rate) should be expected when high values of resistivity are found. This relationship between resistivity and durability performance has been investigated extensively but remains still under debate [2-4]. Measurements of on-site resistivity have been used to assess the in-situ resistance to chloride penetration [5] or as a quality control assessment [6] show other applications of concrete resistivity.

One of the most inherent deterioration aspects of concrete is the presence of cracks. The causes for concrete cracking are numerous during service of concrete infrastructure. When concrete is subjected to environmental and/or mechanical action, cracking of concrete cover can occur. Cracks represent fast routes for chloride ingress that leads to corrosion of reinforcement. In concrete, cracks can be considered as spatial discontinuities of the ITZ (Interface Transition Zone) between aggregates and concrete hardened matrix. Research focused on the transport properties of cracks has revealed their strong influence on concrete durability. A review on cracking methods in laboratory, the influence of cracks on chloride penetration [7] and its influence on reinforcement corrosion [8] has been published recently. Corrosion of reinforcement is also affected by cracking of concrete cover. For concrete infrastructure, cracks are important for assessing the remaining service life. Tensile cracks in bending have a tapered geometry, i.e. the largest displacement occurs at concrete’s surface with a decreasing opening as crack propagates towards the reinforcement. This type of crack is critical for assessing the condition of a concrete structure.

Schießl and Raupach [9] showed that transverse cracks induce a macro-cell on corrosion of reinforcement, in which reinforcement intersected by cracks acts as anode. These findings were later investigated [10,11] with similar results. A study carried out by Boulay et al. [12], showed that the electrical resistance of concrete decreased as cracks occurred in disks subject to Brazilian splitting. Each disk was placed between two reservoirs that released a solution into the crack opening as cracking occurred. Measurements of resistance, and its inverse conductance, showed a linear dependence on COD (Crack Opening Displacement). As the crack became wider, more solution was allowed to fill the void, thus increasing the current flow. A study focused on the permeability of cracks found a distinction between parallel-wall cracks obtained from Brazilian splitting and V-shaped cracks from bending [13].

In this paper, real-time measurements of concrete resistance of reinforced concrete specimens were performed under laboratory conditions. A Modified Wedge Splitting Test (MWST) was used in order to control the crack opening in the specimens. By means of this test, a V-shaped crack that is representative of those found in structures was obtained. Results show that the load-displacement curves can be linked to the relationship between displacement and resistance of concrete.
2. EXPERIMENTAL DESIGN

2.1 Concrete mix design and specimen fabrication

Reinforced concrete specimens were fabricated in standard cubic moulds of 150x150x150 mm³. Table 1 shows the materials and mix design for the concrete cubes. In total, 6 specimens were tested: four with reinforcement and two without. Two reinforcing bars of 120 mm in length were placed at the bottom of the mould as shown in Figure 1. Prior to casting the specimens, a steel profile with a cross section of 40x40 mm² is mounted on the mould, with two resistance electrodes attached to the sides to obtain the target geometry. The electrodes were made from a strip of titanium mesh covered with non-conductive coating, leaving the tip (2 mm in length) uncoated. Electrodes RA were placed at the level of the notch in all 6 specimens, while electrodes RB were only placed in unreinforced specimens, at the same position as the reinforcement in the reinforced specimens. The horizontal distance between the electrodes was 40 mm. After around 5 hours, the steel profile is removed.

Table 1. Concrete mix composition.

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity, kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland Cement CEM I 52.5 R</td>
<td>368</td>
</tr>
<tr>
<td>Water</td>
<td>165.5</td>
</tr>
<tr>
<td>Fine aggregate (&lt;4mm)</td>
<td>840</td>
</tr>
<tr>
<td>Coarse aggregate (4-16mm)</td>
<td>1027.5</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>5.1</td>
</tr>
</tbody>
</table>

After 24 hours, the specimens were stored in a curing (fog) room (20C, >90% RH) for 27 days. At the end of the curing period, a notch (5 mm thick, 15 mm in depth) was sawn in the specimen using a water-cooled diamond saw. The purpose of the notch is to guide the fracture
process; namely, the crack should typically start from the notch. The depth of this notch can also be adjusted in order to achieve certain concrete cover depth.

### 2.2 Cracking and resistance measurements

At the age of 36 days, cracking procedure was performed. In order to control the obtained crack width, LVDTs are placed on both sides of the specimen at the bottom of the notch, where the crack is expected to initiate. Their average is used as a feedback signal for the machine, and controls the whole loading process. In this way, a stable cracking procedure is performed. The COD (Crack Opening Displacement) is the measurement of the horizontal displacement by the LVDT, which is related to the opening of the crack itself.

When the desired crack width has been achieved, hard plastic wedges are placed inside the notch, in order to reduce the crack closing (recovery) after unloading. That way, the final crack width after unloading, i.e. the crack width used as an input in the durability study, is closer to the final crack width obtained in the test. This is important since, even though the crack somewhat closes upon unloading, the area around the tip of the crack contains some microcracks which do not vanish when the specimen is unloaded, and are more permeable than sound concrete. These plastic wedges were able to reduce the crack recovery, but not fully: the ideal solution would be to sustain the load during the subsequent durability investigation, which is not possible due to the expected duration of the test.

Measurements of electrical resistance were carried out at the same time as the loading. For this, a LCR meter was used and the electrical resistance (120 Hz AC) was stored with a scan rate of 1 measurement per second. For the reinforced specimens, resistance measurements were performed over the electrodes RA: both at the level of the notch. For the unreinforced specimens RA and RB electrodes were measured.

### 3. RESULTS AND DISCUSSION

Figure 2 shows the results of the load-displacement curves obtained from the MWST and the behaviour of resistance during the measurement of a reinforced specimen (Specimen 1). With regard to the load-displacement curve Fig 2.a, results show that a maximum load of nearly 2 kN is reached during the test. At this loading condition, the average displacement of the LVDT is about 50 µm. Some variations in resistance were found during the initial loading part of the curve (COD < 50 µm), which can be attributed to the formation of microcracks. As the load is reaching the maximum level, these variations are more evident. This behaviour corresponds then to the propagation of the crack towards the reinforcement. After reaching its maximum point (the softening part of the curve), a combination of changes in both resistance and applied load are observed. The behaviour in this part of the curve may be attributed to the development of secondary cracks (debonding at the reinforcement interface). Finally, the part between 150 µm and 300 µm is believed to only increase the width of cracks, but not their depth. After the maximum displacement has been reached, the unloading of the specimen is carried out. After recovery the crack width at the notch tip was about 180 µm.

In the same figure, the relationship between COD and electrical resistance is shown. When cracking occurs, the current flow is disturbed by the presence of a non-conductive medium (crack void). In the period below the maximum load (COD ~ 50 µm), there is almost no variation in resistance. However, after the maximum load is reached, there is a sudden
increase in resistance that corresponds to the appearance of the first crack. This sudden alteration on resistance is more evident in Figure 2.b. After this, a gradual increase in resistance is observed (COD 50 to 110 µm), followed by another sudden increment. This behaviour is repeated until the maximum resistance is obtained. This behaviour was also found in Figure 2.b: sudden increments of resistance followed by gradual ones. It seems that two distinct processes are occurring: gradual increase in resistance corresponding to crack opening (increase in width); whereas sudden increase to crack propagation (debonding). Since cracks obtained from the MWST had a V-shape (see Figure 1.b), the electrical resistance increases as the cracked zone increases. Overall, it’s clear that there is a linear relationship between cracking and the resistance. The equation that describes this relationship has the form of:

\[ y = ax + b \]  

where \( y \) is the measured electrical resistance (kΩ), \( a \) is a parameter that describes the size and connectivity of the pore structure, \( x \) is the disruption of the pore network (cracks) and \( b \) is the initial resistance (kΩ). There is a good correlation factor (R²) between load and resistance in this curve. This linear relationship corresponds to that found by Boulay [12].

Figure 2. Load-COD-Resistance (a) and Load-Resistance (b) curves of reinforced concrete.

Results of load-displacement and resistance for the four reinforced specimens are shown in Table 2. In all four cases, the maximum load is on the range between 1.9 and 2.3 kN. The COD at the maximum load was found in the range between 20 and 50 µm. It seems that there is no direct correlation between the maximum load and the COD: the maximum COD was found at the lowest load and the maximum load had a narrow COD. For cracks below 300 µm, the recovery after unloading was found to be above 40% or more. It seems logical that wider cracks correspond to permanent damage that cannot be recovered during unloading (Specimen 3, 20% of recovery). As for resistance increase, in three cases it was found to be below 10%. Only in Specimen 3 the increase was above this level (15%). It seems to be that as the damage becomes permanent, the increase in resistance will be higher.
Table 2. Results of load-displacement and resistance of reinforced specimens.

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Max. Load (kN)</th>
<th>COD Max load (µm)</th>
<th>Final COD (µm)</th>
<th>Recovery (%)</th>
<th>Initial Resistance (kΩ)</th>
<th>Final Resistance (kΩ)</th>
<th>Increase (%)</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.93</td>
<td>50</td>
<td>300</td>
<td>180</td>
<td>40</td>
<td>6.4</td>
<td>7.0</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>2.02</td>
<td>30</td>
<td>200</td>
<td>120</td>
<td>40</td>
<td>7.1</td>
<td>7.4</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>2.26</td>
<td>27</td>
<td>500</td>
<td>400</td>
<td>20</td>
<td>6.2</td>
<td>7.1</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>2.04</td>
<td>23</td>
<td>150</td>
<td>80</td>
<td>47</td>
<td>5.7</td>
<td>6.2</td>
<td>8</td>
</tr>
</tbody>
</table>

Figure 3 shows the results of the load-displacement and resistance curves of an unreinforced specimen. Figure 3.a shows that the maximum load is similar to those found on reinforced specimens. However, it seems that for unreinforced specimens variations in the load during the loading period (COD < 50 µm) are absent. A reason for this behaviour is that there are no grip disturbances between reinforcement and concrete. After the maximum load has been reached, the softening part of the curve is similar as in Specimen 1. Also, the recovery had roughly the same behaviour as in the reinforced case.

For resistance measurements, electrodes RA showed a behaviour somewhat similar to Specimen 1, while electrode RB remained undisturbed over the whole measuring period. This means that even after the maximum cracking occurs, the disturbed zone does not reach 100 mm from the top of the reinforcement. It seems that the first sudden increase in resistance did not correspond to the displacement at the maximum load, but occurred at about 45 µm. This is also observed in Figure 3.b, the increase in resistance for electrode RA occurs when the load in the specimen has already decreased. Compared to Specimen 1 the sudden changes in resistance, which were attributed to crack propagation, were not so evident in unreinforced concrete. In this case, the crack propagation and crack opening are closely related probably...
occurring simultaneously. It seems that in reinforced concrete, the crack propagates towards
the reinforcement almost immediately, whereas in unreinforced penetrates slowly. This was
also found by Pease [11]. For electrodes RA the relationship between the electrical resistance
and COD had the same linear dependency as in reinforced concrete. Table 3 shows the results
of load-displacement and resistance in unreinforced specimen.

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Max. Load (kN)</th>
<th>Max. COD (µm)</th>
<th>Max. COD (µm)</th>
<th>Final Rec.</th>
<th>Initial RA (kΩ)</th>
<th>Final RA (kΩ)</th>
<th>↑ RA (%)</th>
<th>Initial RB (kΩ)</th>
<th>Final RB (kΩ)</th>
<th>↑ RB (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.90</td>
<td>30</td>
<td>300</td>
<td>198</td>
<td>34</td>
<td>5.9</td>
<td>7.0</td>
<td>0.98</td>
<td>3.7</td>
<td>3.7</td>
</tr>
<tr>
<td>6</td>
<td>2.28</td>
<td>35</td>
<td>400</td>
<td>300</td>
<td>25</td>
<td>7.5</td>
<td>9.0</td>
<td>0.98</td>
<td>7.1</td>
<td>7.1</td>
</tr>
</tbody>
</table>

Results of unreinforced specimens show that for electrodes at the level of the notch (RA),
the increase in resistance was up to 20%. This is higher than in reinforced specimens. It seems
that unreinforced concrete is subject to higher deterioration from wide cracks (above 300 µm).
For resistance at 100 mm deep (RB) there is no influence on resistance, meaning that for a
crack width of 300 µm at the level of the notch the crack depth has not reached 100 mm from
the top of the specimen. In other words, cracking of unreinforced concrete occurs from the
combination of crack opening and propagation acting simultaneously. In the case of
reinforced specimens, this behaviour is not expected because cracks propagate first towards
the reinforcement and along it (Figure 1.b).

3.1 Forthcoming work

Future research on the relationship between concrete durability and cracks involve the
exposure and monitoring of transport properties, corrosion deterioration and different
materials (particularly CEM III/B). Research focused on studying the debonding of concrete
and steel will be included in future publications.

4. CONCLUSIONS

Reinforced and unreinforced concrete specimens were subject to loading in a Modified
(MWST) and ordinary Wedge Splitting Tests (WST). Displacement and electrical resistance
between two electrodes were monitored during loading. Results showed that resistance
variations found in reinforced concrete were attributed to crack opening and propagation,
independently. For unreinforced concrete, these two mechanisms were found to be acting at
the same time, leading to smaller variations of resistance and loading during the experiment.
The most important findings include:

1. Maximum load in reinforced and unreinforced specimens was about 2 kN. There was
   no influence of reinforcement on the load at cracking
2. Electrical resistance showed a linear relationship with COD at the level of the notch
   (electrodes RA) for reinforced and unreinforced concrete; no effect on resistance was
   found at 100 mm deep (unreinforced, electrodes RB).
3. For reinforced concrete, sudden increments of resistance are probably attributed to crack propagation towards and along the reinforcement. This will be confirmed with further experiments.

4. In unreinforced concrete, electrical resistance did not show sudden increments but a rather gradual behaviour.

5. Less recovery of COD at unloading was found in unreinforced specimens. Also, in the same specimens a higher increase in resistance was found near the crack opening.

6. Monitoring electrical resistance provides a useful way of characterising cracking in concrete.

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REFERENCES