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DURABILITY CHALLENGES

FOR NEW REINFORCED CONCRETE STRUCTURES MADE OF BLENDED CEMENTS WITH REDUCED CO_2 FOOTPRINT

Durability challenges for new reinforced concrete structures made of blended cements with reduced CO_2 footprint

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Concrete and reinforced/pre-stressed concrete is and will be the main construction material for civil engineering infrastructure. Much more then in the past this construction technology faces challenges both for new and existing structures due to the increasingly significant problem of reinforcement corrosion around the world. Existing infrastructure is ageing and environmental actions adversely affect the durability and safety of our infrastructure (bridges, power plants, tunnels or buildings). For new structures that will be built in industrialized and emerging countries to expand the civil engineering infrastructure, the challenge is to achieve long service life, practical, cost-effective solutions with materials having a reduced environmental footprint but with a lack of long-term experience regarding durability.

Ageing of infrastructure

The main cause of damage and premature failure of reinforced and post-tensioned concrete structures is chloride induced reinforcement corrosion caused by the ingress of chloride ions from sea-water or de-icing salts. Chloride ions destroy the protective oxide film on the reinforcement and in presence of humidity and oxygen localized corrosion attacks develop, leading to a dangerous loss of cross-section (figure 1). These localized attacks do not manifest at the surface by cracking or spalling because no rust is formed [1]. Detailed statistical information on the age of infrastructure is rare. The Swiss National Highway system has a very high network complexity: from the total length about 10% are ramps, 12% tunnels and 15% bridges (about 3350 individual objects). From the detailed distribution of the age of the bridges (Figure 2) it can be seen that a great part of bridges was built between 1965 and 1975, today their age is between 40 and 50 years. This indicates that compared to the past only few new bridges are constructed and the existing stock becomes progressively older. From the Netherlands it is known that about 10% of all the bridges need substantial repair after 50 years of service life. Thus it can be concluded that the aging infrastructure is one of the most serious problems faced by society today. Great efforts will be needed in future to maintain the infrastructure.

figure 1. Chloride induced localized corrosion of the reinforcement (bridge deck, 26 years)

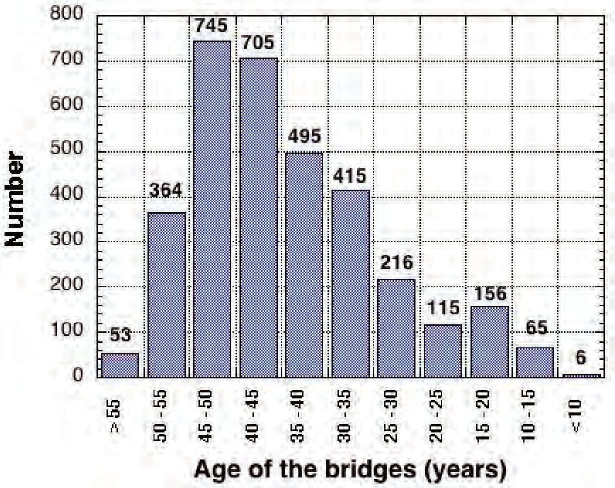

figure 2. Age distribution of the Swiss Highway Bridges

Cost of corrosion

A detailed study on the cost of corrosion in industry (figure 3) was conducted by NACE in 1998 for the US [2]. Infrastructure in the NACE study was divided into the following sectors: highway bridges, gas and liquid transmission pipelines, waterways and ports, hazardous materials storage, airports, and railroads. The total annual direct cost in the category "infrastructure" was estimated to be $22.6bn.

From the approximately 583,000 highway bridges in the US about 15% are structurally deficient because of corroded steel and steel reinforcement. Annual direct cost estimates total $8.3bn, including $3.8bn to replace deficient bridges over the next 10 years, $2bn for maintenance and capital costs for concrete bridge decks and $2bn for their concrete substructures, and $0.5bn for maintenance painting of steel bridges. Indirect costs to the user, such as traffic delays and lost productivity, were estimated to be as high as 10 times that of direct corrosion costs. Today, it is estimated that the numbers in the NACE corrosion study in 1998 approximately can be doubled [3].

In Switzerland detailed costs are reported for repair and maintenance of the national highway system (figure 4), showing an increase from 249 Mio (1995) to 768 Mio (2010) [4]. While corrosion of the reinforcing steel might not be the sole cause of all repair work, it is a significant contributor [3]. Repair costs per square meter bridge deck are reported to be 1200-1800 sFr. For other European countries the numbers might be similar.

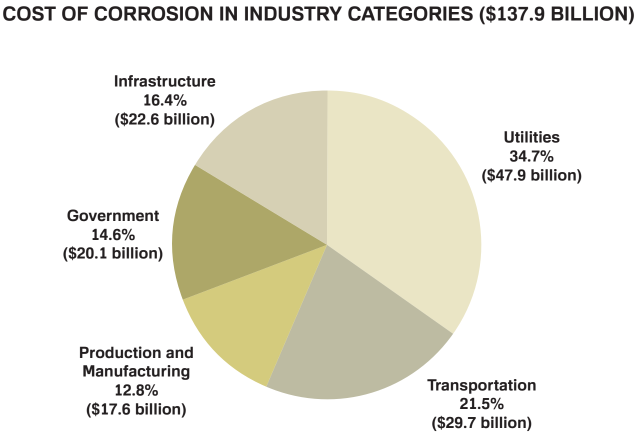

figure 3. Cost of Corrosion as evaluated by NACE

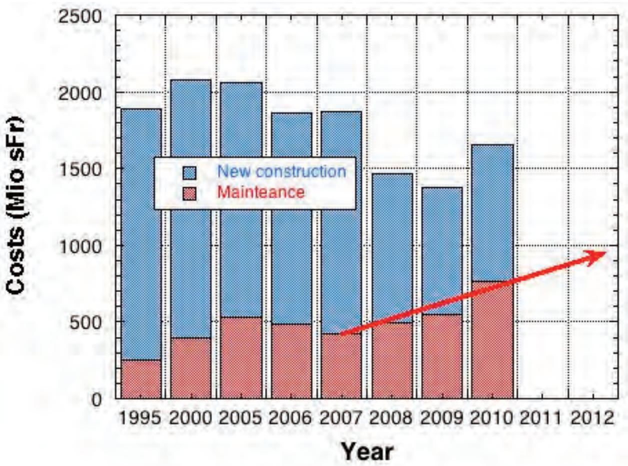

figure 4. Evolution of the costs for new constructions and repair work on the Swiss Highway System

A high speed railway bridge construction site in Guangxi province, China. The challenge is to achieve long service life, practical, cost-effective solutions with materials having an increasingly reduced environmental footprint

Challenges of new blended cements

For new structures that will be built in industrialized and emerging countries to expand the civil engineering infrastructure, the challenge is to achieve long service life, practical, cost-effective solutions with materials having an increasingly reduced environmental footprint [5]. To achieve this, cement industry made great efforts in substituting clinker (responsible for great part of the CO2 emissions) with supplementary cementitious materials (SCM). These modern binder systems containing limestone, fly-ash, burnt oil shale etc. in a complex blend (see e.g. European Cement Standards EN 197-1) are increasingly used worldwide. The long-term durability of reinforced concrete made with SCM is however far less established then that of Ordinary Portland Cement concrete.

This ongoing substitution is reflected in the decreasing amount of Portland cement (CEM I) and the increase of blended cements (CEM II, CEM III etc., Fig. 5). Whereas these new blends are suitable for achieving strength similar to Portland cement, thus can be used to build concrete structures, their long-term durability when used to make the final product concrete is far less established. The key durability challenge

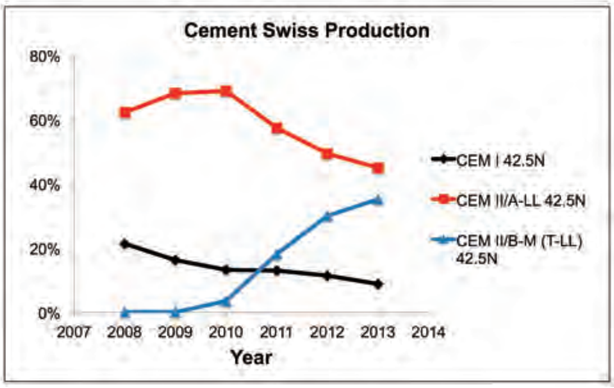

figure 5. Cement consumption showing the continuous decrease of Portland cement (CEM I)

for engineers in the design process of new concrete structures lies in predicting long-term performance of these new materials with an ever-increasing diversity of cement blends.

To address durability of reinforced concrete structures, the European concrete standard EN 206-1 defines exposure classes (a kind of standardized environmental conditions) and the (national) requirements for concrete such as water/cement ratio, minimum cover depth and minimum cement content. Concrete for a bridge in the Swiss mountains exposed to a severe climate and de-icing salts (exposure condition XD3) must be of much higher quality (lower w/c ratio, higher cover depth) compared to concrete inside a building (XC1). This prescriptive approach is based on long-term experience of the past.

Long experience with concrete structures made with Portland cement (CEM I) has shown that carbonation, thus the reaction of CO2 from the environment with the alkaline components of concrete leading to loss of the corrosion protection of the reinforcing steel, was not a problem for durability. Concrete cover, water / cement ratio and cement content according to the prescriptions for the exposure condition and good

execution were sufficient to avoid corrosion due to carbonation. For the new blended cements with SCM – despite they are increasingly used – this is questioned. Due to the reduced clinker content, the pH of the concrete pore solution is lower, the alkali reserve is strongly reduced and questions arise regarding the long-term corrosion protection of the steel [1]. Thus the traditional prescriptive approach with exposure classes and deemed-to-satisfy rules might no more be sufficient in this new situation.
The carbonation of concrete made of new, blended cements is now increasingly studied. It is quite established that the well-known laws that describe the propagation of the carbonation front into OPC concrete can be applied for new blended cements, too. However the rate of carbonation process, expressed with the carbonation coefficient K, seems to be much faster at least for some of the modern binders [6]. Thus the carbonation front reaches the reinforcing steel much earlier and the steel becomes depassivated (Fig. 6). In presence of oxygen and humidity corrosion can start [1].

One approach to achieve the required long service life also with modern binders would be to include also part of the propagation period

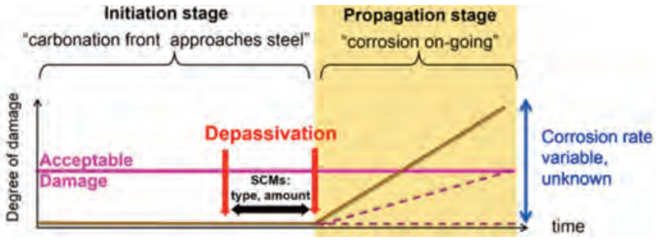

figure 6. Schematic representation of the service life of a reinforced concrete structure ("Tuutti diagram") showing the importance of the propagation-stage of corrosion in carbonated concret

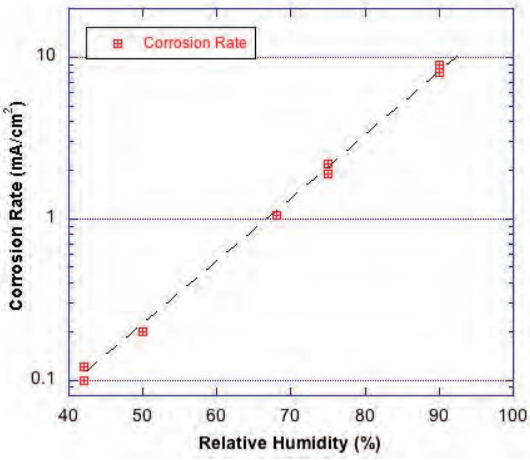

figure 7. Effect of the relative humidity of the environment on corrosion rate of steel in concrete

(Fig. 6) – thus the intensity of the corrosion rate of steel in carbonated concrete becomes of outmost importance. In principle, the corrosion rate will vary according to the exposure conditions and the concrete quality [1] and work on Portland cement concrete shows an exponential increase of corrosion rate with relative humidity (Fig. 7). Detailed and quantitative information for concrete made of modern binders is lacking. A research project at the Institute for Building Materials at ETH Zurich "Corrosion rate of steel in carbonated concrete" is addressing this open question. In order to limit the time needed for full carbonation, thin samples made of cement paste and mortar containing different modern binders are produced (Fig. 8). On these samples the corrosion rate, oxygen diffusion (Fig. 9) and resistivity can be measured as a function of composition, exposure condition (relative humidity) and time. Results of this research will allow a much stronger link between durability related performance characteristics of the new cements and the properties of concrete. In particular it will become clear under which conditions the corrosion rate in carbonated concrete made with blended cements can be considered negligible.

Publications and reports used for the citations

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[2] "Corrosion Costs and Preventive Strategies in the United States" PUBLICATION NO. FHWA-RD-01-156, US Department of Transportation, http://corrosionda.com/summary.htm

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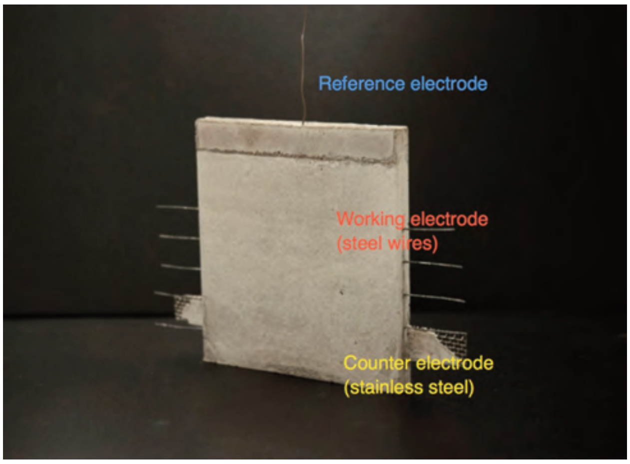


figure 8. Example of a sample to study corrosion of steel in carbonated cement paste or fine mortar

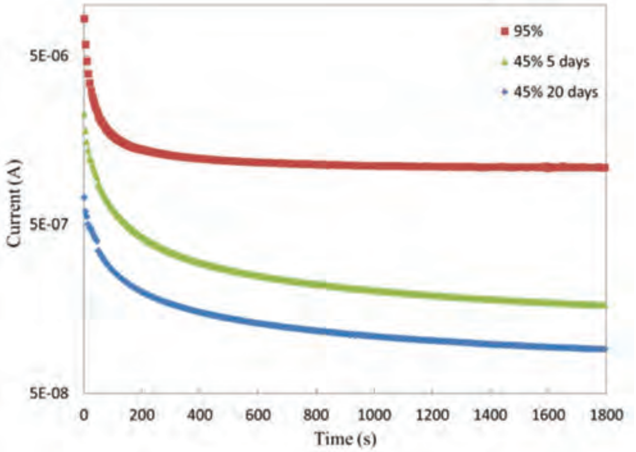
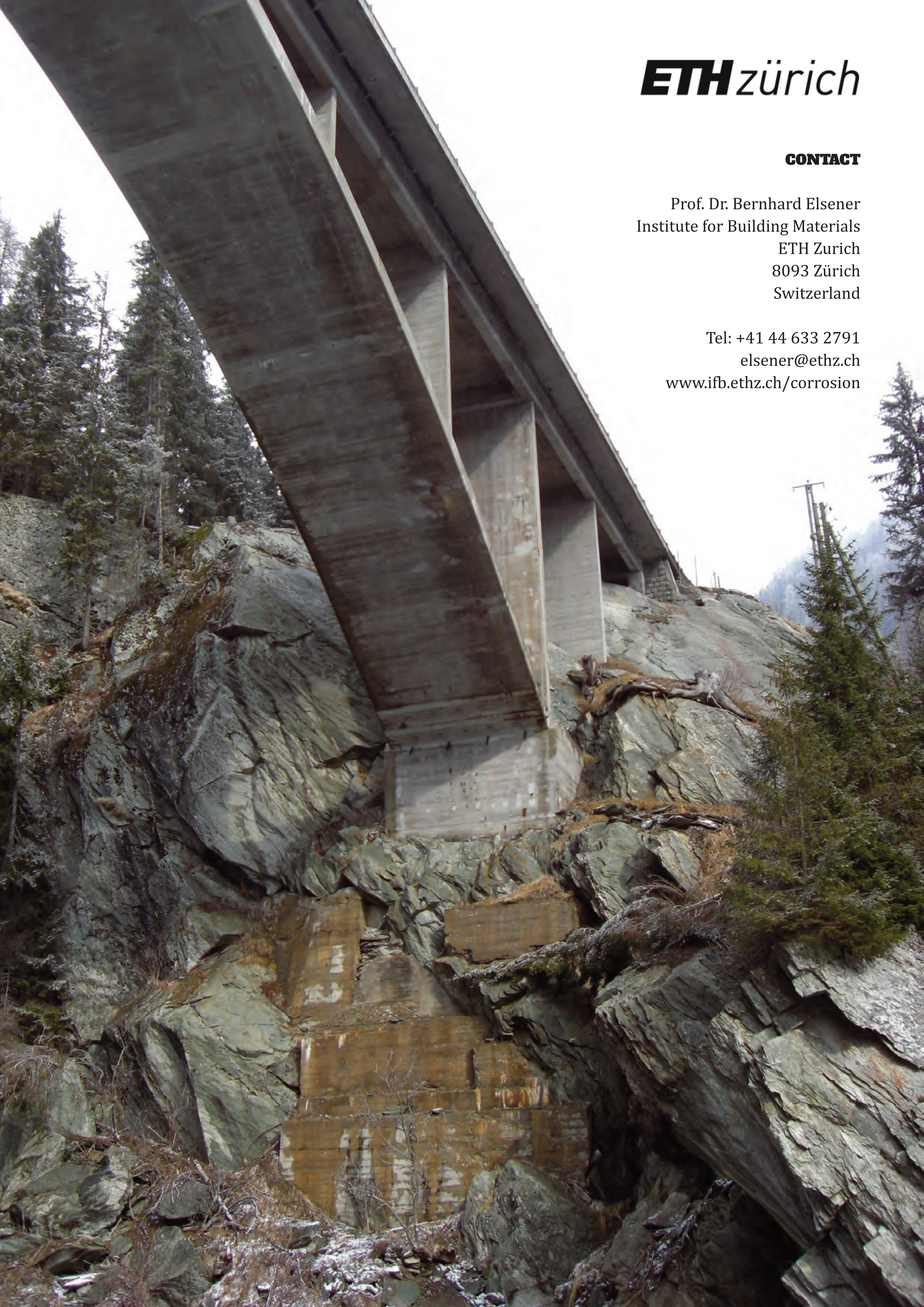


figure 9. Cathodic polarization of the steel wires to determine the oxygen content in cementitious material (sample see Fig. 8)



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