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Local detailed inspection methods to determine concrete properties on structures

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During assessment of reinforced concrete structures, information about concrete properties can give a clearer insight into the prevailing reasons for premature degradation of structures. In this paper an overview is given of methods for local detailed inspection of concrete properties in corroding reinforced concrete structures. Recommended non-destructive, semi-destructive and destructive testing methods for determining mechanical and durability properties of concrete are given, together with some practical information about performing the method and analysing obtained results. Recommended criteria for evaluating concrete quality and potential risk of corrosion due to poor concrete performance are also given.

1 Introduction

During corrosion of reinforcing steel both reinforcement and concrete get significantly degraded and the level of this degradation for both materials has to be evaluated. The main consequences of reinforcement corrosion are reduction of reinforcement cross section and mechanical properties, reduction of bond strength between concrete and reinforcement, cracking, delamination and spalling of concrete cover and change of concrete properties due to the existence of corrosion products at the concrete/reinforcement interface, as shown in Fig. 1. By performing local detailed inspection of concrete it is possible to evaluate the extent of the effect of corrosion on concrete properties, but also to get a clearer image of possible reasons for premature corrosion initiation and propagation [1, 2]. In a recent RILEM Workshop on "Present and future durability challenges for RC structures" a number of publications dealt with durability properties and control and diagnosis of concrete [3–6]. Information about concrete properties, obtained by local detailed inspection, becomes crucial during the repair of corroded reinforced concrete structure. Furthermore, concrete properties can be used as input parameters in models predicting remaining service life of corroding reinforced concrete structures.

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Recommended additional testing methods to be performed in order to determine the level of degradation of concrete caused by reinforcement corrosion are listed in Table 1.

2 Determination of mechanical properties

Compressive strength of concrete is one of the most important properties, not only because the main role of the structural material is to bear load, but also because this property is directly and indirectly related to many other concrete properties. It is also one of the first and most basic properties of structural concrete evaluated during the assessment and diagnosis of corroded reinforced concrete structures. Compressive strength measurements are usually good indicators to evaluate the degree of deterioration and can give valuable information during the assessment procedure. Knowing the compressive strength is also essential before planning any serious repair strategy.

Assessment of in situ compressive strength in structures can be performed by direct destructive methods on drilled cores, by indirect non-destructive methods such as rebound hammer and ultrasound method or by a combination of non-destructive and destructive methods.

2.1 Rebound test method

One of the most widespread methods in local detailed inspection of concrete properties is the rebound test method, commonly known as the Schmidt hammer test, which is used for inexpensive, simple, quick and non-destructive evaluation of concrete strength. This method is good for covering larger structure areas and distinguishing different groups depending on the severity of degradation. However, this method gives less accurate results and measured values should be taken on a qualitative basis rather than on a quantitative level. Before performing a rebound test it is necessary to clean the surface and make it as smooth as possible,

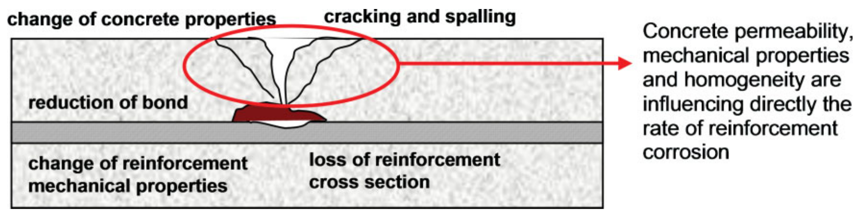

Figure 1. Effect of corrosion on reinforcement and concrete

because the roughness of the surface affects the results of the test. The results of a rebound testing are also affected by aggregate type, concrete moisture content, temperature and carbonation. In older concrete carbonation can be several millimetres deep and, in extreme cases, up to 20 mm. In such cases the rebound numbers can be up to 50% higher than those obtained on a non-carbonated concrete surface [7]. It is recommended to perform 12 readings over an area of 150 mm diameter, with no two readings being taken within 25 mm of each other. Areas exhibiting honeycombing, scaling, rough texture or high porosity must be avoided. It is recommended to perform the testing in a grid pattern, with a spacing of 20–50 mm within an area not larger than $300 \times 300\,mm^2$, as shown in Fig. 2.

2.2 Ultrasonic method

Another widely used non-destructive method for assessing strength and homogeneity of concrete is the pulse velocity method. By measuring pulse velocity at points according to a

Figure 3. Pulse velocity measurements of the concrete

Table 1. Recommended testing for detailed analysis of concrete properties

Defects caused by reinforcement corrosion	Testing method
Changes in mechanical properties:	Non-destructive
Loss in strength	Rebound test (strength/homogeneity)
Loss of bond	Ultrasonic measurement (strength/homogeneity)
Changes in homogeneity	Semi-destructive – Pull-out-test (bond)
	Destructive – Drilling cores (strength)
Changes in concrete penetrability properties	Gas permeability
Increase of air permeability	In situ method
	On specimens
Increase of water permeability	Initial surface absorption
	Water permeability
	In situ method
	On specimens

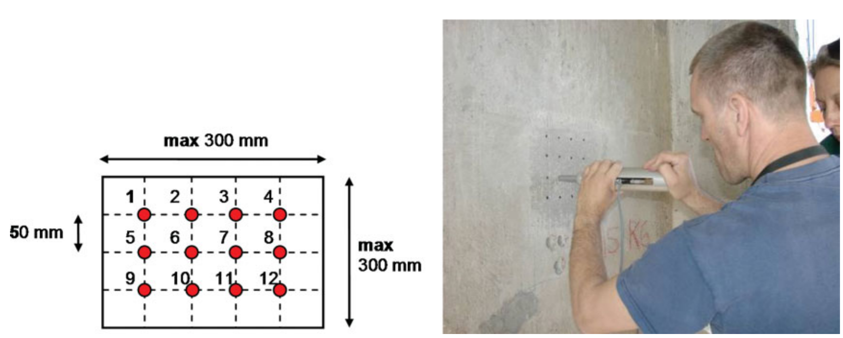

Figure 2. Recommended concrete area for rebound test

regular grid on the surface of a concrete structure an indication for the evaluation of the strength can be obtained (see Fig. 3), if the relationship between compressive strength and ultrasound pulse velocity is previously established, i.e. on the cores taken out from that specific structure. The size of the grid on the tested concrete surface will depend on the dimensions of the structure and the amount of variability encountered.

Measurement readings can be affected by temperature, moisture of concrete, presence of reinforcement and cracks. The concrete surface should be smooth and without cracks to obtain reliable readings of ultrasonic pulse velocity for sound concrete. In the case of cracked or delaminated concrete, ultrasonic pulse velocity measurements can be used to estimate the depth of the defect. For example, an estimate of the depth of the crack visible at the surface can be obtained by measuring the transit times across the crack for two different arrangements of the transducers placed on the concrete surface. Furthermore, the evaluation of the efficiency of crack repair can also be done by performing ultrasonic pulse velocity measurements before and after the repair. When performing more ultrasonic tests on different concrete elements for comparison purposes, similar circumstances should be insured; such as temperature, moisture of concrete, age, existence of reinforcement. The ultrasonic pulse is slower when passing through the concrete, comparing to the steel. In the case steel reinforcement in concrete is present, the obtained value for velocity will be higher than the real value, which can give misleading results when evaluating concrete quality. To avoid this, the location of the steel reinforcement must be defined beforehand with respect to the path of the ultrasonic pulse velocity [8] (see *Reichling* et al., this issue).

Considerable engineering judgment is needed to properly evaluate a measurement. With ultrasound pulse measurements it is possible to identify poor quality concrete which could be the cause of reinforcing bar problems.

2.3 Semi-destructive method: Penetration resistance and pull-out test

The need to estimate the strength of structural concrete without taking cores from the structure has led to the development of a range of semi-destructive test methods. One of the semi-destructive testing methods available for the determination of concrete mechanical properties is the penetration resistance and/or pull-out test. The penetration resistance test is applicable to assess the uniformity of concrete and to delineate zones of poor quality or deteriorated concrete in structures [9]. The pull-out method is used to determine the concrete strength of the cover-layer for an existing structure and gives instant compressive strength estimation for residual strength of existing structures [8].

The parameter that characterizes the values obtained by penetration resistance is called penetration index and is represented by the length of the probe that has not penetrated into the concrete. The shallower the depth of the probe penetration, the stronger is the concrete tested. The relation between strength and depth of penetration greatly depends on the hardness of the aggregate because the coarse aggregate particles become fractured in the penetration tests [9]. The surface to be tested must have a brush finish or smoother to yield accurate results. The steel probes enter the concrete at a very high energy level which can sometimes cause spalling and shattering of aggregate and parts of concrete. That is why this test should always be performed with eye and ear protection. During pull-out testing an expanded split ring is pulled out from a previously drilled hole in the concrete, during which concrete between the expanded ring and the counter pressure at the concrete surface is being compressed (see Fig. 4). The force necessary to pull the ring out from the concrete is a direct measure of the compressive strength and can be converted into concrete compressive strength by means of calibration. During both of these tests a minor damage to the structural element is created. The pull-out test can, however be non-destructive if a minimum pull-out force is applied that stops the failure but makes certain that a minimum strength has been reached.

2.4 Destructive method: Drilling cores

In practice, a minimum of three cylinders diameter 100 mm is necessary for getting an overview of compressive strength for elements of the same group of degradation or for one type of concrete, but with no significant confidence. In order to evaluate compressive strength with acceptable confidence level, according to European standards, a larger number of cores need to be taken out and tested. When cores are drilled in a structure severely degraded by corrosion, special attention and supervision of engineering specialists should be organized, in order to avoid further degradation and potential loss of structural stability. Drilling cores, regardless of the fact that it gives the most reliable and accurate results of compressive strength, is usually

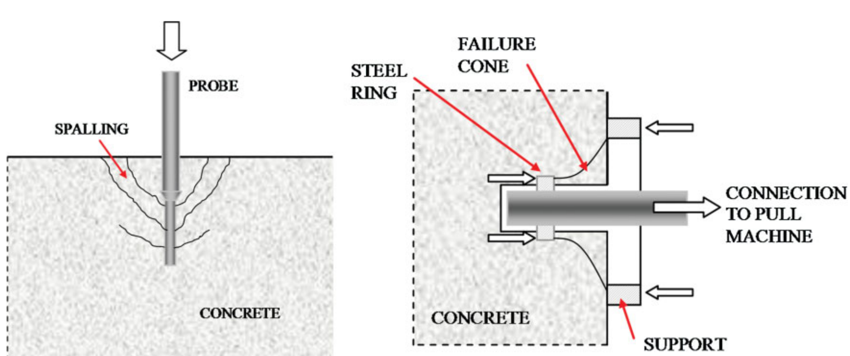

Figure 4. Schematic drawing of the penetration resistance and pull-out test

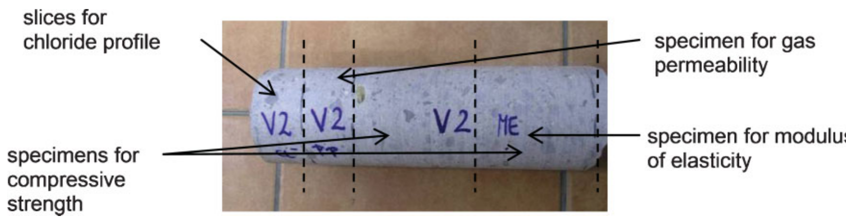

Figure 5. Example of the optimum use of drilled core [10]

economically or due to stability issues unjustified. That is why sometimes a very small number of coring is allowed. Specimens drilled from a structure should be maximally exploited to gather as much as possible information. Generally, it is recommended to drill longer cores between reinforcing bars, which gives the possibility of preparing several specimens and performing several tests on the same drilled core, such as determination of the modulus of elasticity, compressive strength, permeability testing or cutting slices for chloride profile (see Fig. 5).

2.5 Recommended criteria for mechanical properties evaluation of concrete

Compressive strength can be estimated from results obtained by the rebound test, ultrasonic pulse velocity or pull-out testing only if there is a calibration curve demonstrating the relationship between non-destructive or semi-destructive testing and compressive strength on drilled cores for that specific concrete. However, results of non-destructive and semi-destructive testing are very good indicators of concrete quality or changes in concrete quality due to the corrosion propagation. Criteria for the evaluation of concrete quality depending on rebound number and ultrasonic pulse velocity are given in Table 2.

Table 2. Criteria for concrete quality based on ultrasonic measurement [8]

Ultrasonic pulse velocity (km/s)	Rebound number	Concrete quality
3.5–4.5	>40	Good to excellent
3.0–3.5	30–40	Doubtful
2.0–3.0	20–30	Poor
<2.0	<20	Extremely poor/surface cracks

3 Determination of concrete penetrability properties

The transport of substances within concrete directly depends on the prevailing cause of transport that can take place due to a hydraulic gradient, concentration gradient, moisture and/or temperature. Processes of flow under pressure, absorption and diffusion of substances through the concrete depend on the pore system and the quantity of water contained in the pores. Therefore, material properties determine the safety, service life and behaviour of a structure, and material degradation mechanisms determine the behaviour of a structure as a whole [11, 12].

Results of penetrability properties testing can give a quantifiable overview of the level of degradation of concrete due to corrosion of reinforcement and the resulting change in concrete pore structure. These results are especially useful when information exists on concrete penetrability properties from the "birth" of the structure, performed during quality control testing at the construction stage. Furthermore, an overview of concrete penetrability properties can clarify and certify the reasons for premature propagation of corrosion.

3.1 Air permeability testing

Gas permeability of concrete is defined as a property which characterizes the ease with which gas passes through the concrete. Gas permeability can be correlated to carbonation of concrete and is a good indicator of concrete durability properties.

a) b) c)

Figure 6. Different instruments for testing air permeability on site

Table 3. Criteria for concrete quality based on penetrability testing [14–16]

Chloride migration coefficient (m^2/s)	Absorption after 1 hour ($mL/m^2/s$)	Water permeability (m^2)	Air permeability (m^2)	Concrete quality	Risk of corrosion due to concrete penetrability
$2–8 \times 10^{-12}$	0.10	$<10^{-12}$	$<10^{-18}$	Good	Low
$8–16 \times 10^{-12}$	0.10–0.20	$10^{-12}–10^{-10}$	$10^{-18}–10^{-16}$	Fair	Average
$>16 \times 10^{-12}$	>0.20	$>10^{-10}$	$>10^{-16}$	Poor	High

Gas permeability tests can be performed under steady state conditions on drilled concrete specimens when a constant pressure over the specimen is maintained, and under non-steady state conditions of flow by a non-destructive air-permeability test method [13].

In situ air permeability testing (see Fig. 6) usually works with a non-steady state condition of flow, due to the fact that it is a hard task to maintain a constant gas pressure over the concrete. One of the main problems during air permeability testing on site is ensuring tightness between the air chamber and the concrete surface. This problem is solved with elastic sealants, additional fastening bolts or creation of vacuum that prevents detachment of the chamber from the concrete surface. If there is no sufficient tightness between chamber and concrete, this area will be permeable and test results will not be reliable. To ensure that the test is working properly and that results indicate concrete permeability it is recommended to repeat the test at the same location after some time, i.e. after more than 30 min to let the concrete surface refill with air. It is also recommendable to restrain the testing area and avoid dissipation of air through the surrounding concrete. To do so it is recommendable to seal the surface around the testing area with impermeable coating a few minutes before performing the air permeability test.

3.2 Capillary absorption

The penetration of liquids in concrete as a result of capillary forces is called absorption. With this method the open porosity of concrete can be evaluated. Since this porosity is responsible for transport of fluids through concrete, the capillary absorption measurement method can be used to obtain a quick estimation of concrete protective abilities when it comes to chloride-induced corrosion. It is recommended to perform absorption measurements after air permeability measurements and before water permeability measurements, when for instance the instrument shown in Fig. 6c is used. In the air permeability test no water is used, so the tested area will be dry and in a water permeability test higher pressure is used and water will go deeper in concrete pores than it would with capillary forces. The surrounding test area should be covered with impermeable coating to avoid a dissipation of water. To ensure that the test is working properly and that the results indicate concrete sorptivity it is recommended to repeat the test at the same location, after the tested concrete has dried. In order to achieve a linear relationship between absorption and time it is recommended to test the concrete for 20 min, to obtain enough information. It is also recommended to neglect the first few minutes, since there is a higher suction of water at the beginning of the test which leads to having a zero intercept on absorption vs. time curve.

3.3 Recommended criteria for penetrability properties evaluation of concrete

Currently for most of the penetrability properties there are no uniform evaluation criteria given in European standards, but there are numerous initiatives to prepare them in order to facilitate a performance-based design, quality control and assessment of concrete structures. Commercially available instruments usually have their own set of criteria that can be used to evaluate concrete quality. Criteria for all aforesaid penetrability properties, that can in general be used as a guidance when determining the quality of concrete and its possible effect on corrosion development, are given in Table 3.

4 Conclusions

During full and detailed surveys of corroded reinforced concrete structures, it is recommended to take into account the properties of both reinforcement and concrete. Information about concrete properties, especially if compared to concrete properties tested during construction or ‘‘birth’’ of the structure, can give important insight into the propagation of corrosion in time and the extent of damage caused by corrosion. Nowadays, numerous methods for testing concrete properties are available, both in practice and in literature. The main principles and scope of most widely used and optimal, with the respect to cost/benefit ratio, testing methods are presented in this paper. These methods, together with the recommended criteria for analysis of results, can be used during surveys as a guidance for the estimation of concrete quality and its possible effect on the corrosion process.

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