IN-SITU TESTING OF THE PERMEABILITY OF CONCRETE

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Abstract
Reinforced concrete is one of the most widely used structural materials, because it offers good durability properties, a range of engineering solutions and a variety of aesthetic opportunities. To obtain required properties of concrete as a structural material in the laboratory and on site is not the same. Real properties of material which is placed and cured on site in different environmental conditions stay unknown. Therefore it is obvious that there is a strong need for the application of the non-destructive methods in testing of concrete structures on site.

When using NDT methods the main goal is to obtain reliable results but for a method to be “good” also some other requirements should be satisfied, i.e. method must be simple and truly non-destructive. In this paper two non-destructive methods for measuring permeability properties of in-situ concrete are presented. Methods include measuring of initial surface absorption and air permeability. Testing was performed with the two instruments developed at the Faculty of Civil Engineering in Zagreb, Croatia. Results from NDT methods measurements are analyzed and discussed in order to evaluate the measurement techniques and the quality of the concrete.

Keywords
Permeability of concrete, in-situ permeability, concrete transport mechanisms.

1. INTRODUCTION
Reinforced concrete structures come into contact with different climatic conditions, different aggressive mediums and are exposed to mechanical damage. In order to fulfil durability requirements concrete must have adequate resistance to different actions.
Durability of reinforced concrete is primarily influenced with the ability of aggressive substances to penetrate into the concrete. In order to predict durability of concrete it is necessary to know properties of concrete and ways in which aggressive substances penetrate into concrete, i.e. transport mechanisms in concrete [1].

Processes of transport in concrete take place through porous structure of cement paste and cracks by one of three mechanisms: diffusion, absorption and flow under pressure. Diffusion is the process by which a liquid, gas, or ion can pass through the concrete under the action of a concentration gradient. Absorption is the process by which concrete takes in a fluid due to capillary suction. Flow under pressure is the process caused by pressure differential and concrete property which characterizes resistance to flow is termed permeability. In practice the term permeability is also used for transport caused by other transport mechanisms (absorption and diffusion) [2,3]. It can be concluded that when the transport mechanisms in concrete are discussed, actually it is discussed about the analysis of the concrete permeability.

In this paper two methods for measuring in-situ concrete permeation properties are presented. Measurement instruments are constructed at the Department of Materials at the Faculty of Civil Engineering in Zagreb (FCE). Methods are intended for testing initial surface absorption and air permeability. Tests of permeability properties included in-situ methods and laboratory methods and the correlations of results between methods which measure permeability caused by the same transport mechanism are presented in this paper.

2. DESCRIPTION OF TESTING METHODS

Concrete permeability testing is performed by different methods which are grouped according to the transport mechanism which gives methods for measuring diffusion, absorption and permeability. [3] Depending on different parameters, such as transport mechanism, amount of transported substance, depth of penetration, property of concrete known as permeability can be evaluated. On the basis of measured permeability properties life span of the concrete or concrete structure can be evaluated. [4]

2.1 Absorption measurement

The penetration of liquids in concrete as a result of capillary forces is called absorption. Under perfect conditions the magnitude of capillary rise follows a linear relationship with the square root of time elapsed and the constant of proportionality is called the sorptivity [3]. In realistic situation, during the testing of concrete in-situ, achieving the unidirectional penetration of water is a problem. Because of that the absorption characteristics of concrete are usually measured indirectly [5]. In this chapter two methods for testing absorption of concrete are presented. First method presented is a standard laboratory method defined by the Croatian standard HRN U.M8.300, and the second method is for in-situ concrete testing according to the procedure developed at the FCE in Zagreb at the Department of Materials.

2.1.1 Laboratory capillary absorption test

In the sorptivity test (according to Croatian standard HRN U.M8.300) the rate of the inflow of water is measured when water is allowed to be absorbed unidirectionally by a dry concrete under negligible pressure. Test specimens are coated with an epoxy resin on their sides to prevent any water movement through the sides during the test. The test specimen of uniform cross section is placed with one surface just in contact with water. The water level should not be more then 5 mm above the base of the specimen. The mass of water absorbed by capillary
rise is measured at time intervals of 1, 5, 15, 30, 60 minutes and so on until 25 or more hours. A graph is then plotted between the mass of water per unit area of inflow surface and square root of time, as shown in Figure 1. The slope of this plot is called the capillary absorption coefficient (in the literature often called the sorptivity) of concrete in units (kg/m$^2$ h$^{0.5}$).

![Figure 1: Typical graphs of capillary absorption test](image)

2.1.2 Modified initial surface absorption test

Initial surface absorption is defined as the rate of flow of water into concrete per unit area after a stated time interval from the start of the test and at a constant applied head and temperature [3]. Measurement principle described here is very similar to one described by the BS 1881: Part 5:1970. Modification is made in the way of recording the flow of water into concrete and is described here. A circular cap with a surface area of 5000 mm$^2$ is clamped watertight onto the concrete surface and filled with water from the reservoir. No air should be trapped in the cap so cap is made of transparent material to allow the detection of air bubbles. All air bubbles are released through the air vent placed on the top of the cap (see Figure 2). The water reservoir is placed in a way that a level of water in the reservoir is 200±5 mm above the concrete surface. Outflow from the reservoir is monitored and recorded in the following way. Centre of the reservoir is hollow. Through this centre a circular tube is placed. Around this tube a buoy is placed at the top of the water surface. The vertical movement of the buoy, i.e. water level is monitored by the sensor placed at the side of the reservoir and the data is sent on the personal computer through A/D converter. Before the start of the measurement calibration is made which converts vertical movement of the water level in the reservoir to the volume of water outflow from the reservoir. Outflow from the reservoir is equal to the water inflow into the concrete. The initial surface absorption value is than calculated and expressed in units ml/(m$^2$ s).

Using this method it is possible to follow the water inflow into concrete continuously. In the case of this research the inflow of water was registered every second which resulted in no limitation of the registering the rate of the inflow at discrete time intervals, as it can be seen in Figure 3. The only limitation is that the reservoir must be connected to the power source.
2.2 Gas permeability measurement

Gas permeability of concrete is defined as property which characterizes the ease with which gas passes through the concrete [3]. Gas permeability tests can be performed under steady state conditions when a constant pressure over the specimen is maintained, and under non-steady state conditions of flow. Steady state permeability tests are performed in the laboratory while non-steady state tests are usually performed in-situ [3]. In this chapter two methods for testing gas permeability of concrete are presented. First method presented is a laboratory according to the European standard EN 993-4, and then the method for testing concrete in-situ according to procedure developed at the FCE in Zagreb at the Department of Materials.
2.2.1 Laboratory gas permeability test

In the gas permeability test a cylindrical specimen is placed in a measuring cell and sealed on its curved face. The pressure of gas is then applied at one face of the specimen and maintained constant. When a steady state flow conditions are achieved the rate of flow through the specimen is measured. From knowledge of sample geometry, gas characteristics, rate of flow and applied pressure specific coefficient of permeability is calculated according to the equation 1 [6, 7].

\[ K = \frac{2Q \eta L}{A} \frac{2p_a}{(p^2 - p_a^2)} \]  

Where:
- \( K \) – specific permeability coefficient \([m^2]\),
- \( Q \) – rate of flow \([m^3/s]\),
- \( \eta \) – dynamic viscosity of the gas \([Pa/s]\),
- \( L \) – thickness of the specimen in the direction of the flow \([m]\),
- \( A \) – cross-sectional area of the specimen \([m^2]\),
- \( p \) – absolute inlet pressure \([Pa]\),
- \( p_a \) – absolute outlet pressure \([Pa]\).

Gas used for testing of concrete in this paper was nitrogen [6]. Three tests were performed on each specimen under three different pressure levels and for each pressure level specific permeability coefficient was calculated. The result is then calculated as the mean value of the obtained coefficients.

2.2.2 Air permeability measurement – FCE in-situ method

When performing gas permeability test in-situ it is difficult to maintain constant gas pressure over the concrete. Therefore methods of measurement which do not require constant gas pressure are developed [8, 9]. The method developed at the FCE consisting of a vacuum chamber mounted on the surface of the concrete and the change in the pressure over a period of 20 minutes is monitored. Inner diameter of the chamber, which is actually the diameter of the tested surface area, is 50 mm. In order to carry out an air permeability test the pressure inside the chamber is decreased to slightly below -700 mbar. Pressure is decreased via the syringe (Figure 4). The rise in pressure is monitored by the pressure sensor installed on the chamber which is connected to a PC through A/D converter. A plot of natural logarithm of pressure rise against time is linear. The slope of the linear regression curve between 5th and 20th minutes is then used as an air permeability index, with units \( \text{ln(bar/minute)} \), as given in Figure 5. This way of determining the air permeability is very similar to the method used by Autoclaim permeability system [10]. The main difference is that in the method described suction is used instead of an overpressure test.

Presented method is very convenient for in-situ testing because the entire system is very simple and light (about 0.5 kg without the PC) and no additional power source is needed since the power for the pressure sensor comes from the PC.

When testing air permeability in-situ one of the problems is how to ensure airtightness between the chamber and tested surface. This problem is solved using permanently elastic sealant. This sealant also serves for attaching the chamber to the surface so no additional bolts of adhesives are necessary. Another problem is how to ensure that air is drained from the concrete and not from the surroundings. This problem is solved by spraying the chamber.
surrounding surface with transparent car coating (see Figure 4) approximately 10 cm in diameter around tested surface.

![Figure 4: Schematic of the air permeability measurement](image)

**Figure 4: Schematic of the air permeability measurement**

![Figure 5: Calculation of air permeability index](image)

**Figure 5: Calculation of air permeability index**

### 3. EXPERIMENTAL PROGRAMME

Four different types of permeability testing were applied as listed in Table 1, which included determination of gas permeability and capillary suction properties by standard laboratory methods and by instruments for in-situ NDT measurements, as previously described. Testing was performed on four concrete mixtures, whose compositions are presented in Table 2. Mixtures M1, M2 and M3 are prepared with the same cement type CEM I 52,5N and with the addition of silica fume, while mixture M4 was prepared with the cement CEM II/B-S 42,5N without the addition of silica fume. Concrete was cured in the moulds for first 24 hours and then stored in the curing room with relative humidity between 95-100%.
until the age of 28 days. Age of specimens in the time of the test was between 35 and 40 days. Concrete specimens were prepared before testing all in the same way, by drying in the oven at the temperature of 105°C. Dimensions of specimens are given in Table 3.

Table 1: Permeability tests performed on concrete specimens

<table>
<thead>
<tr>
<th>Property measured</th>
<th>Test method</th>
<th>Measured quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capillary absorption</td>
<td>HRN U.M8.300:1985</td>
<td>Coefficient of capillary absorption</td>
</tr>
<tr>
<td>Initial surface absorption</td>
<td>ISAT-Modified</td>
<td>Rate of initial surface absorption</td>
</tr>
<tr>
<td>Gas permeability</td>
<td>EN 993-4:1995</td>
<td>Gas permeability coefficient</td>
</tr>
<tr>
<td>Air permeability</td>
<td>FCE in-situ method</td>
<td>Air permeability index</td>
</tr>
</tbody>
</table>

Table 2: Concrete compositions and concrete properties

<table>
<thead>
<tr>
<th>Mix composition</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement type</td>
<td>CEM I 52,5 N</td>
<td>CEM I 52,5 N</td>
<td>CEM I 52,5 N</td>
<td>CEM II/B-S 42,5 N</td>
</tr>
<tr>
<td>Sand [kg/m³]</td>
<td>1050</td>
<td>955</td>
<td>961,5</td>
<td>860</td>
</tr>
<tr>
<td>Gravel 4/8 [kg/m³]</td>
<td>282</td>
<td>373</td>
<td>375,5</td>
<td>172</td>
</tr>
<tr>
<td>Gravel 8/16 [kg/m³]</td>
<td>470</td>
<td>466,5</td>
<td>469,5</td>
<td>688</td>
</tr>
<tr>
<td>Water [kg/m³]</td>
<td>142</td>
<td>126</td>
<td>104</td>
<td>202,5</td>
</tr>
<tr>
<td>Cement [kg/m³]</td>
<td>430</td>
<td>460</td>
<td>400</td>
<td>450</td>
</tr>
<tr>
<td>Superplastizicer [%]</td>
<td>1,1</td>
<td>1,1</td>
<td>1,2</td>
<td>0,6</td>
</tr>
<tr>
<td>Air entrainer [%]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0,06</td>
</tr>
<tr>
<td>Silica fume [kg/m³]</td>
<td>21,5</td>
<td>23</td>
<td>40</td>
<td>-</td>
</tr>
<tr>
<td>Air content [%]</td>
<td>4.2</td>
<td>5.0</td>
<td>7.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Slump [mm]</td>
<td>50</td>
<td>130</td>
<td>90</td>
<td>130</td>
</tr>
<tr>
<td>Compressive strength at 28 days [MPa]</td>
<td>70,1</td>
<td>45,7</td>
<td>55,2</td>
<td>45,0</td>
</tr>
</tbody>
</table>

Table 3: Specimens dimensions

<table>
<thead>
<tr>
<th>Test</th>
<th>Type and size of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M1</td>
</tr>
<tr>
<td>Gas permeability</td>
<td>Cylinder</td>
</tr>
<tr>
<td></td>
<td>Φ/h= 150/50 mm</td>
</tr>
<tr>
<td>Air permeability</td>
<td>Prism</td>
</tr>
<tr>
<td></td>
<td>250/250/120 mm</td>
</tr>
<tr>
<td>Capillary absorption</td>
<td>Cylinder</td>
</tr>
<tr>
<td></td>
<td>Φ=100 mm</td>
</tr>
<tr>
<td>Initial surface absorption</td>
<td>Prism</td>
</tr>
<tr>
<td>(ISAT)</td>
<td>250/250/120 mm</td>
</tr>
</tbody>
</table>

4. RESULTS OF TESTING

Results of testing are given in Figure 6 (a-d) and Figure 7 (a-b). In Figure 6 from (a) to (d) parallel are given results for all mixtures. Values given in the diagrams are the average values from 3 tested specimens for each type of testing.
Figure 6: Results of testing for concrete mixture M1, M2, M3 and M4 for (a) capillary absorption, (b) ISAT, (c) gas permeability and (d) air permeability determination

Figure 7: Results of testing (a) capillary absorption properties and (b) gas/air permeability properties

In Figure 8a and 8b are given correlations between standard laboratory measurements and in-situ NDT methods for capillary absorption and for gas/air permeability determination.
5. CONCLUSION

Concrete as a structural material is very heterogeneous material, whose properties depend very much on the composition materials, placing and curing techniques, environmental conditions etc. Therefore it is obvious that properties of the laboratory concrete and on-site concrete are not the same, and that there is a strong need for the application of non-destructive methods in order to evaluate the “real” concrete properties which is placed in the structure.

The aim of this study was to perform in parallel standard laboratory testing methods and in-situ NDT methods for a determination of concrete permeability properties. Two non-destructive methods for measuring permeability properties of concrete were applied, for measuring initial surface absorption and air permeability, with the two instruments developed at the Faculty of Civil Engineering in Zagreb. These results from NDT methods measurements were compared with the results of standard laboratory testing. Based on the performed testing and following analysis basic correlations were obtained, with the correlation coefficients between 0.80 and 0.85. These results indicated that developed NDT methods are quite reliable, but further research will be done in order to evaluate them statistically and to determine the influence of moisture and temperature during different on site conditions.

ACKNOWLEDGEMENTS

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