Construction and Building Materials 110 (2016) 98–105

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

# Using neutron radiography to assess water absorption in air entrained mortar

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## HIGHLIGHTS

- The effect of air content on the degree of saturation in mortar is investigated.
- The effect of initial moisture content on degree of saturation is discussed.
- Neutron radiography is used to visualize moisture ingress.
- Insight to water sorption is provided by relating it to pore size distribution.

## ARTICLE INFO

*Article history:*
Received 2 December 2015
Received in revised form 31 January 2016
Accepted 1 February 2016
Available online 11 February 2016

*Keywords:*
Concrete air content
Degree of saturation
Deicing salt
Neutron imaging
Neutron radiography
Pavement joint
Saw-cut
Unsaturated moisture ingress
Water absorption

## ABSTRACT

Concrete highway and airport pavements are designed to be long lasting; however, some concrete pavements have shown premature deterioration at the cracks and joints. It has been hypothesized that one cause of this deterioration is associated with fluid ingress, especially in cases where those fluids contain deicing salts. This paper examines fluid ingress in mortar using a cross-sectional geometry that is similar to a typical concrete pavement joint. Time-dependent and spatial aspects of fluid ingress are examined using neutron radiography (NR), which was performed using the thermal neutron radiography station at the neutron spallation source at the Paul Scherrer Institut (PSI). Specifically, this paper examines the role of the initial relative humidity (or degree of saturation) and air content on the fluid ingress. The work indicates that the initial fluid ingress reaches a specific degree of saturation relatively rapidly, where the large capillary and gel pores appear to be filled in (commonly referred to as the nick point in sorption tests) and the entrapped and entrained air pores fill in more slowly over time.

## 1. Introduction

Concrete highway and airport pavements are typically designed to last from 30 to 50 years. While a large number of pavements provide the anticipated level of performance, some concrete pavements have shown premature deterioration at cracks and joints [1]. This damage jeopardizes the life of pavements that are otherwise performing well and can result in costly repairs and substantial disruption to the travelling public. While the exact cause of this deterioration is not known, a possible cause is associated with fluids ingress, especially in cases where those fluids contain deicing salts (NaCl, $MgCl_2$ and $CaCl_2$) [2–11]. This fluid ingress can potentially lead to freeze–thaw damage due to hydraulic pressure caused by increased saturation [3–5], salt precipitation and crystallization [6], or damaging phase changes and chemical reactions [7–9]. It has been shown [3,10,11] that the degree of saturation can be related to freeze–thaw damage and that when the degree of saturation exceeds a certain value (e.g., 80–91% degree of saturation [3,10,11]) damage is inevitable. This paper examines fluid ingress around a saw-cut using neutron

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http://dx.doi.org/10.1016/j.conbuildmat.2016.02.001

radiography (NR) for the purpose of understanding how water ingress is related to the local degree of saturation during the initial hours after water absorption at the joints.

Neutron radiography NR has been used by several researchers as a powerful technique to study fluid ingress. This is possible due to the high interaction probability, mainly due to scattering, of neutron beam with hydrogen [12,13]. Rijonen and Pihlajavaara [14] performed early studies of carbonation in concrete using NR. Najjar et al. [15] used NR to examine cracking in concrete after penetrating the concrete with gadolinium, a material with a high neutron attenuation capacity. Other researchers have relied on water (or other penetrating fluids) to attenuate the neutrons. For example, Hanžič and Ilić [16] compared the capillary absorption rates of water and fuel oil into concrete. Zhang et al. [17] visualized water absorption and related the change in neutron signal to moisture content, illustrating that higher water to cement ratio materials absorb more water than lower water to cement ratio materials. Zhang et al. [18] and Kanematsu et al. [19] evaluated water penetration in cracked concrete observing that water entered cracks nearly instantly. Snoeck et al. [20] used NR to examine the use of superabsorbent polymers (SAP) to seal cracks while Trtik et al. [21] examined water transport from SAP and from lightweight aggregates [22] in hardening cement pastes using neutron tomography. Hallaji et al. [23] used NR to corroborate electrical resistance tomography reconstructions of moisture flow in cement paste. Water loss from cement mortars due to drying at early age has been studied with neutron tomography by Wyrzykowski et al. [24]. Previous work shows great potential to use NR or neutron tomography to provide the user with information on water ingress with a high level of spatial and temporal resolution.

## 2. Research objectives

The objectives of this study were twofold. First, the research sought to better understand the influence of the initial sample conditioning (i.e., the initial degree of saturation or the initial relative humidity, RH) on the water absorption. Second, the research attempted to better understand how the entrained air content influences the degree of saturation. While preliminary, this research can aid in determining the degree of saturation that may be expected after a short period of wetting at the surface of a crack, saw-cut, or joint in a concrete pavement.

## 3. Experimental program

### 3.1. Mixture constituents and proportions

Two mortar mixtures were prepared with two different air contents, to represent a concrete that had a low volume of entrained air and a concrete that had a high volume of entrained air (13% and 31% air by volume as measured in the paste, which corresponds to 4% and 9% air by volume in concrete, a general lower bound and upper bound in industry), as shown in Table 1. It should be noted that while there may exist some difference in water absorption behavior of mortar and concrete, since cement paste is the main phase absorbing water in both mortar and concrete, similar water absorption behavior can be reasonably expected from both materials.

All the specimens were made with ordinary Portland cement (OPC, Type I) and a natural river sand with a fineness modulus 2.71, a maximum aggregate size of 5.0 mm, a specific gravity of 2.58, and an absorption capacity of 1.8%. The mortar had a water to cement ratio ($w/c$) of 0.42, which is in the typical range of concrete pavements used in the state of Indiana (and similar to those used in other slip-form paving concrete in North America). Table 1 presents the mixture design. The mortar was 55% aggregate by volume and the remaining materials (water, cement and air) were assumed to comprise the paste phase. Mixing was performed in accordance with ASTM C192-06 [25]. All the specimens in this work we kept sealed at 23 ± 1 °C for the first 24 h. The samples were then demolded at 24 h and were then cut to appropriate geometries using a wet saw.

### 3.2. Specimens geometry

Two specimen geometries were used in this study: cylinders (25 mm height by 100 mm diameter) and a saw-cut geometry (12.5 mm thick × 100 mm × 100 mm square section with a 35 mm wide × 20 mm tall reservoir and a 5 mm wide by 25 mm deep saw-cut (see Fig. 5 below). Cylindrical specimens were used for testing unidirectional water absorption according to ASTM C1585-04 [26]. Saw-cut specimens were used to study water penetration around the vicinity of a saw-cut geometry using NR. All specimens were cut from larger specimens as described below.

### 3.3. Sample preparation procedures

The cylinders were cut from larger cylinders (100 mm diameter × 200 mm length) 24 h after casting. The prismatic samples were cut from larger prisms 300 mm × 100 mm × 100 mm containing the 35 mm × 20 mm reservoir notch. This reservoir notch was used to hold fluid in this test, however in a conventional contraction joint in pavement construction this notch would be used to hold the joint backer rod and joint sealant [27]. In practice when the joint sealants fail this reservoir and saw cut is where the salt water solution accumulate and damage occurs. The saw cut was made in the prism at the age of 24 h and the prism was then cut into thin (12.5 mm) square samples (100 mm width by 100 mm height). It should be noted that the cutting specimens at an early age may result in some damage at the cutting plane. However, since the saw-cuts are generally made at early ages, to better simulate the field conditions in this work, the samples were cut at the age of 24 h. After cutting, specimens were demolded then stored at 23 ± 1 °C for 27 days sealed with two layers of plastic bags. At an age of 28 days, the specimens were removed from the plastic bags and placed in either 50 ± 1 or 80 ± 1% RH and 23 ± 1 °C environments where they were kept for more than a year. Table 2 lists the air content and conditioning relative humidity of each specimen. Multiple samples were prepared with a minimum of two samples being tested for each condition.

The method for specimen conditioning prior to water absorption testing can substantially influence the results of the test [28–30]. If the specimen is not properly conditioned, it can lead to a misinterpretation of the actual fluid absorption behavior [3–5]. Due to the significance of conditioning and necessity for the specimens to reach equilibrium, the standard curing procedure specified in ASTM was not used [28–30]. The procedure that was used in this study allowed the specimens to equilibrate for over a year to enable them to reach equilibrium. The results of

**Table 2**
Naming convention, air content and conditioning relative humidity for the specimens used in the present study.

| Specimen name[a] | Air content of the paste (%) | Relative humidity (%) |
|---|---|---|
| AC-50% RH-13% air | 13 | 50 |
| AC-80% RH-13% air | 13 | 80 |
| AH-50% RH-31% air | 31 | 50 |
| AH-80% RH-31% air | 31 | 80 |

[a] The first number shows the initial humidity of the specimen (e.g., 50–13 is 50% RH); the second number shows the air content of the specimen (e.g., 50–13 is 13% air by volume of paste). AC and AH only indicate sample groups based on air content.

**Table 1**
Mixture proportions and constituent materials.

| Air content of paste by volume (by volume of mortar[a]/concrete[b]) (%) | Cement (Type I) (kg/m$^3$) | Water (kg/m$^3$) | Sand (kg/m$^3$) |
|---|---|---|---|
| 13 (6/4) | 573.3 | 240.8 | 1333.3 |
| 31 (14/9) | 524.5 | 220.3 | 1219.8 |

[a] In calculating the equivalent air content in mortar, 45% paste by volume of mortar was assumed.

[b] In calculating the equivalent air content in concrete it was estimated that 30% by volume of the concrete was paste.