Cement and Concrete Research 108 (2018) 152–166

Contents lists available at ScienceDirect

Cement and Concrete Research

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

Application of neutron imaging to investigate fundamental aspects of durability of cement-based materials: A review

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ARTICLE INFO

Keywords:
Neutron radiography
Neutron tomography
Durability
Service life
Moisture transport
Cement-based materials

ABSTRACT

Service life and durability of reinforced concrete structures have become crucial issues in all industrialized countries because of their economic and ecological relevance. Limited durability is frequently due to deterioration of steel and cement-based materials, such as mortar and concrete, by interactions with water and aggressive aqueous solutions. Neutron imaging has proved to be a powerful non-destructive technique to study quantitatively water content and water movement in porous materials. A neutron beam is much more attenuated by hydrogen in water than by most other elements present in cement-based materials.

In this review, focus is placed on applications of both two-dimensional neutron radiography and three-dimensional neutron tomography to investigate specific aspects of durability and deterioration of cement-based materials. Examples of results obtained by qualitative and quantitative investigations of moisture movement in cracked and uncracked cement-based materials are presented. Self-healing, efficiency of water repellent treatment, internal curing, frost damage, fire spalling, ettringite formation and observations of various reinforced concrete components are addressed. The results obtained by neutron imaging provide a solid basis for better understanding of deterioration mechanisms of cement-based materials. Recent improvements of neutron imaging facilities have allowed unexpected possibilities to study complex processes in cement-based materials. The potential for further research based on this promising technology is outlined and discussed.

1. Introduction

Hydraulic cements and concrete were first developed and widely used approximately 2000 years ago during the Roman Empire, from which time several impressive monuments, aqueducts and bridges have survived until today. With the fall of the Roman Empire, the knowledge and technology related to the production of hydraulic cement got lost. The production of modern Portland cement is usually linked with a patent obtained in 1824 by Joseph Aspdin, who used the name Portland cement because of its appearance, which was similar to the expensive natural stone called Portland stone. The prototype of modern cement, however, was first produced by Isaac Johnson in 1845, by clinkering a mixture of clay and chalk at sufficiently high temperature. Today concrete is the single most frequently applied construction material worldwide.

The service life of modern reinforced concrete structures, however, is not sufficient in many cases. The cost of repair and replacement of existing reinforced concrete structures has become in many countries so important that motorways cannot be used as planned. It is estimated that approximately 20% of the existing bridges in the US are classified as structurally deficient or functionally obsolete. A similar situation exists in many other countries. The repair cost of bridges and infrastructure is so enormous that not all necessary repair measures can be carried out in time; it has become necessary to establish ten-year financial plans in many countries. This aggravating situation requires quick and long-lasting solutions. The main reasons for the limited service life of reinforced concrete structures must be understood to improve the repair methods and durability of reinforced concrete (RC)

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https://doi.org/10.1016/j.cemconres.2018.03.003
Received 16 July 2017; Received in revised form 22 January 2018; Accepted 12 March 2018
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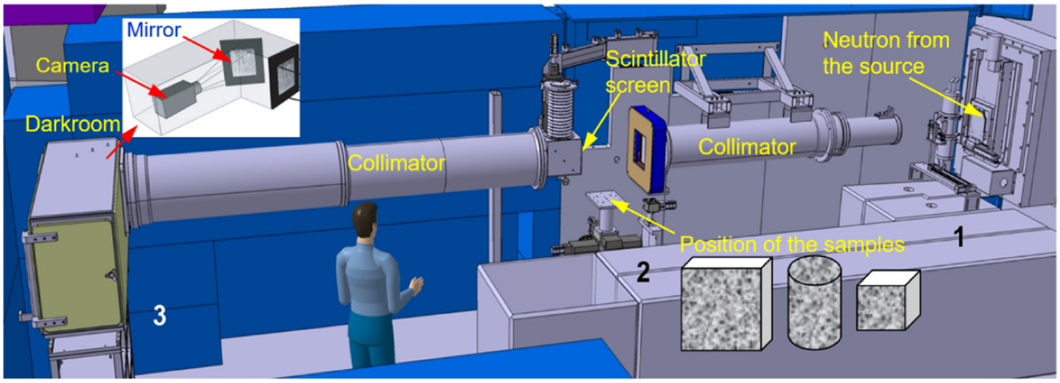

Fig. 1. A simplified layout of a neutron imaging system.
Adapted from an image from Paul Scherrer Institute [24].

structures [1,2].

Moisture transport in cement-based materials is an important physical process with direct influence on both service life and durability. If the surface of concrete is in direct contact with water, hydration products may be washed out by leaching. Thus, near-surface zones are weakened and become more sensitive to frost action. In the case of contact with wastewater, deterioration of the concrete surface can occur and it can be accelerated due to the acid attack caused by nitrifying biofilms [3]. If water gets in contact with a pre-dried surface of concrete, it will be quickly absorbed and transported deep into the pore space by capillary suction. Because of capillary absorption, aggressive compounds dissolved in water can be transported quickly deep into the pore space of concrete. This process is much faster than diffusion of ions in saturated concrete. Drying of concrete always results in shrinkage of the outer dry zones, and this process leads to a moisture gradient and formation of cracks due to a combination of self-restraint and external restraint. Cracks induced by drying will in turn further facilitate the ingress of water and aggressive ions.

For determination of moisture content in cement-based materials, many destructive and non-destructive methods exist, such as the gravimetric method, electrical conductivity, nuclear magnetic resonance spectroscopy, humidity sensors and radiation attenuation techniques [4–10]. Among these methods, neutron imaging was identified as a suitable and unique technique to study moisture transport and water-related durability issues of cement-based materials, because neutrons are strongly attenuated by the hydrogen in water and are comparatively insensitive to the dominant other components (such as Si, Ca, Al, Fe, S, O, Na and K) in the solid skeleton of cement-based materials.

Several neutron imaging reviews have been presented with respect to applications in earth science, materials science and nuclear science [11–16]. Perfect et al. [12] presented a literature review on neutron imaging of static and dynamic experiments involving hydrogen-rich fluids in geo-materials and other engineering porous media. Kardjilov et al. [13] presented an overview of the most important recent advances using neutron imaging in materials science, including fuel cells, crystalline phases and magnetic materials. In the field of nuclear materials, de Beer [14] presented an overview of the advantages of neutron radiography/tomography. Winkler [15] reviewed aspects relevant to the applications of neutron radiography/tomography in earth sciences, especially for rocks and fossils. Recently, Kaestner et al. [16] summarized the developments and applications of 3D neutron tomography for studying water dynamics in soils. However, none of these reviews focused specifically on the applications of neutron imaging for studying durability aspects of cement-based materials. These applications, however, are rapidly emerging and possess a number of promising specific aspects.

In the present contribution, the potential of neutron imaging to investigate durability issues of cement-based materials is outlined. First, the principle of neutron imaging and the specific advantages of neutron imaging compared to other methods are briefly outlined. Then, specific applications oriented toward durability, are briefly described. Characteristic results of applications of this advanced method to observe moisture content and moisture transport in uncracked and cracked cement-based materials, to follow self-healing procedures, and to visualize the effect of water repellent treatments on moisture movement will be presented. In addition, it will be shown that it is also possible to assess quantitatively the processes of internal curing, mechanisms of frost damage and spalling due to thermal gradients, and delayed formation of ettringite. Finally, the potential for further promising applications of neutron imaging is discussed. This review is meant to be helpful for colleagues who are working with cement-based materials to become more familiar with the techniques and the potential of neutron imaging and the different fields of its application.

2. Neutron imaging

2.1. Neutron imaging facilities

Neutron imaging is based on measuring the transmitted intensity of neutron beams through an object, either in two dimensions (radiography) or three dimensions (tomography). Currently, > 80 research facilities perform neutron imaging in over 41 countries. The main facilities are listed in the literature [12,17,18]. In addition, several new facilities, for example, CARR and CSNS in China [19,20], LAHN in Argentina [21], DINGO at ANSTO in Australia [22] and ODIN at ESS in Sweden [23], are under development.

The basic experimental set-up of a neutron imaging facility consists of a neutron source, a collimator functioning as a beam formatting assembly, a detector and the investigated object, which is placed between the exit of the collimator and the detector, as shown in Fig. 1. A perfect imaging result is possible only when these individual components are optimized.

2.2. Principle of neutron radiography

Neutron radiography is the projection of the object in two dimensions. The information is averaged over the thickness of the object along the beam projection path. According to the Beer-Lambert law, the intensity of the transmitted beam, I (n/cm^2 s), can be described as follows:

$$I = I_0 \cdot e^{-\Sigma \cdot \tau} \tag{1}$$

where, I_0 (n/cm^{2}s) is the intensity of the neutron beam leaving the

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