Materials Letters 195 (2017) 1–4

Contents lists available at ScienceDirect

Materials Letters

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

Visualization of rapid penetration of water into cracked cement mortar using neutron radiography

Peng Zhang [a,c,*], Zhaolin Liu [a], Songbai Han [b], Linfeng He [b], Harald S. Müller [c], Tiejun Zhao [a], Yu Wang [b]

[a] Centre for Durability & Sustainability Studies, Qingdao University of Technology, Qingdao 266033, PR China
[b] Neutron Scattering Laboratory, China Institute of Atomic Energy, Beijing 102413, PR China
[c] Institute of Concrete Structures and Building Materials, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

ARTICLE INFO

Article history:
Received 16 October 2016
Received in revised form 13 January 2017
Accepted 18 February 2017
Available online 22 February 2017

Keywords:
Neutron radiography
Crack
Porous materials
Cement mortar
Water penetration
Visualization

ABSTRACT

The penetration of water and other aqueous solutions into cracked cementitious materials is important in a variety of engineering contexts. The quick process of water penetration into cracked cement mortar during the first few seconds has been visualized for the first time with high temporal resolution of 10 fps by neutron radiography (NR). The results indicate that cracks are filled with water instantaneously by capillary action whenever they come in contact with water. The water front travelled more than 20 mm during the first second. Time-dependent moisture distributions in the cracked cement mortar during water penetration testing have also been quantitatively analysed.

1. Introduction

As cementitious materials are brittle, cracks can form under different conventional conditions. Cracks are preferential paths for the ingress of water or other aqueous solutions containing aggressive ions into the materials, which often leads to severe deterioration [1]. Since cracks are in many cases inevitable and design codes allow crack formation up to a critical crack width, the influence of cracks on water transfer merits investigation.

Neutron radiography is an excellent method for determining water penetration in cementitious materials since water attenuates thermal neutrons more strongly than the other material components [2–6]. Some researchers have applied this method to detect water penetration into cracks of cementitious materials at early times. The earliest neutron image was obtained at 24 s or more after water imbibition [4–6]. However, in previous studies, due to camera limitations and the thickness of the specimens, a relatively long exposure time has been needed. The rapid penetration of water into cracked cementitious materials in the first few seconds has never been observed and quantified before.

In this study, neutron radiography with a sCMOS (scientific Complementary Metal Oxide Semiconductor) sensor system has been applied to visualize the fast process of water penetration into cracked cement mortar. This rapid process has been followed for the first time with high temporal resolution imaging in the first few seconds. The time-dependent moisture distributions have also been analysed quantitatively.

2. Materials and methods

2.1. Materials and preparation of test specimens

Materials used to produce the mortar included 500 kg/m^3 ordinary Portland cement, type 42.5; 1650 kg/m^3 river sand with a maximum grain size of 2.5 mm; and 300 kg/m^3 water. A small beam with a cross section of 25 mm × 100 mm and a length of 300 mm was prepared. The specimen was reinforced with two steel bars with diameter of 8 mm, as shown in Fig. 1. After two months curing at 20 ± 2 °C and ≥95%RH, the sample was loaded by three-point bending under well-controlled conditions to induce one crack in the middle. The crack width created in this case was 0.2 mm. From the centre part of the cracked beam, a slice with a 100 mm width was cut. Finally, the slice, with dimensions of

* Corresponding author at: Centre for Durability & Sustainability Studies, Qingdao University of Technology, Qingdao 266033, PR China.
E-mail address: zhp0221@163.com (P. Zhang).

http://dx.doi.org/10.1016/j.matlet.2017.02.077
0167-577X/

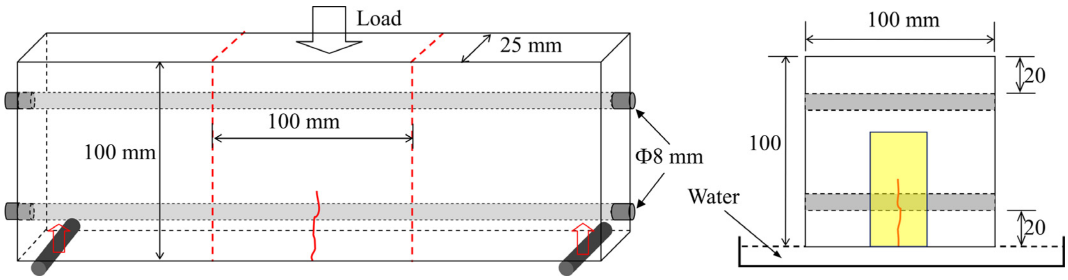

Fig. 1. Formation of a centre crack under three-point bending (left) and the detached centre part for the observation of water penetration (right).

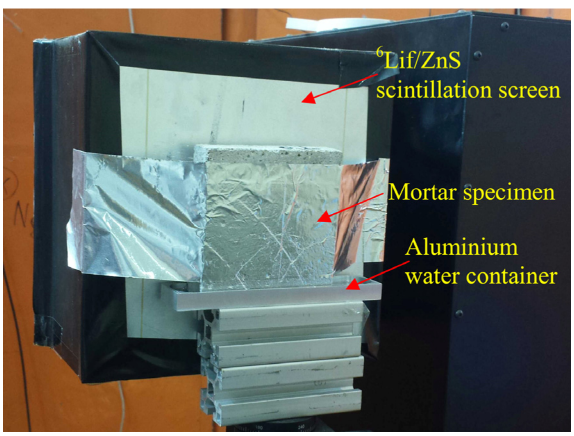

Fig. 2. Photo of the test setup for water penetration testing with neutron radiography.

100 × 100 × 25 mm, was ready for the water penetration test in the neutron beam.

2.2. Neutron radiography test

The test was performed at CARR (China Advanced Research Reactor), China Institute of Atomic Energy. More details about the facility can be found in [7,8]. A neutron flux of 1.2×10^8 (n/cm^2·s) was used. The spatial resolution was 67.8 µm per pixel. A 0.1 mm thick neutron sensitive ^{6}Lif/ZnS scintillation screen was used. To obtain a quick readout speed, a new generation scientific CMOS sensor was installed. To have a compromise between the frame rate and the quality of the neutron images, the selected frame rate was 10 fps.

Before the test, the sample was dried in an oven at 50 °C until a constant weight was achieved. The square surfaces and two opposite small surfaces were then covered with aluminium foil. The specimen was fixed with the scintillation screen and positioned in front of the neutron beam, as shown in Fig. 2. An aluminium container filled with water was put beneath the sample without contacting each other. After the first image had been taken in the dry state, the water container was lifted up gradually until the bottom surface of the sample contacted the water. The process of water penetration into the cracked mortar was then followed by neutron radiography. More details about the technique and data processing can be found in [6,9]. Finally, the differential images from any time related to the initial time were obtained. The wetting images were normalized with respect to the initial image in the dry state so that only the inflowing water was resolved.

3. Results and discussion

Water penetration into the cracked mortar was extremely rapid. Fig. 3 depicts the time sequence of neutron images showing water moving into the crack in the first few seconds. Ten neutron images were taken in the first second. The position of the lower steel reinforcements is indicated by grey stripe in both the initial dry image at 0 s, as well as on the image at 1.0 s. Neutrons are preferentially absorbed by hydrogen. Therefore, a local increase of water content in mortar can be visualized by darkening in the image. The results indicate that water penetrated into the crack instantaneously by capillary suction whenever the surface of the mortar was put in contact with water. Within the first second, water had already travelled 20 mm and arrived at the steel reinforcement. This rapid process has for the first time been clearly observed by neutron radiography.

The spatial moisture distributions in the reinforced mortar have been analysed quantitatively during the rapid process of water penetration. Results at 0.1, 0.5, 1.0 and 2.0 s are selected and shown in Fig. 4. The corresponding water content along the horizontal axis in the rectangular area ① marked in the sample, which is close to the sample surface, was analysed and shown in the right of Fig. 4. Water moves into the crack immediately after contact with the sample. The position of the crack can be easily recognized from the areas that contain the highest moisture content in the sample. Then, water gradually penetrated into the porous mortar matrix horizontally adjacent to the crack. The moisture distributions remain more or less symmetrical with respect to the crack.

4. Conclusion

Neutron radiography is a powerful technique to capture the early time dynamics of the rapid penetration of water into cracked cement-based material. The work developed here visualized for the first time this quick process during the first few seconds with high temporal resolution. Cracks are instantaneously filled with water by capillary action whenever they come in contact with the water. Within the first second, the wetting front already travelled more than 20 mm. Water then penetrated further into the adjacent regions from the water-filled crack. The time-dependent spatial moisture distributions in the cracked cement mortar have also been quantified. These results will help to better understand deterioration processes in cracked reinforced concrete.

Acknowledgements

Financial supports from 973 Program (2015CB655100), National Natural Science Foundation of China (51420105015, 51278260) and 111 Program are gratefully acknowledged. The Alexander von Humboldt Foundation and China Scholarship Council are also acknowledged.