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Study of Cracking in Concrete by Neutron Radiography

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The digital neutron radiography (NR) technique was employed to visualize cracks in concrete. The radiographs were obtained by the direct method with a gadolinium converter screen and the facility is installed at the radial beam tube 08 of the IEA-R1 Nuclear Research Reactor, which provides a neutron flux of around 3×10^6n s^{-1} cm^{-2} at the sample irradiation position. The samples were 5 mm thick polished slices sawn from two cylindrical concrete specimens, one of them submitted to a compressive strength test. In order to enhance crack visualization, these samples were impregnated with a high neutron absorbing substance (contrast agent). The digital radiographs presented, in terms of crack visualization, better results when compared with the digital X-ray radiographs and with the analog ones obtained by the NR technique of the same samples.

Introduction

Concrete is a construction material composed of portland cement and water which combined with some aggregates, such as sand and crushed stone which hardens due to chemical reaction, transforming it into a strong stone-like mass, after drying (Bogue, 1947; Taylor, 1992).

Cracks are small discontinuities which, under mechanical strength, may propagate into concrete giving rise to macroscopic failures in structures.

Specialized literature reports several techniques which have been employed to study cracks in concrete (Shah, 1983; Slate, 1984). Najjar, Aderhold and co-workers (Najjar *et al.*, 1986; Aderhold *et al.*, 1986) have demonstrated the effectiveness of the neutron radiography (NR) technique for this purpose, using conventional emulsion films. In this technique the sample is irradiated in a uniform neutron beam and a screen converts the transmitted neutron to ionizing radiations which are imaged on a film (Berger, 1965; Bryant and McEntire, 1985).

Ordinary concrete is composed of several chemical elements forming a material with a low neutron attenuation coefficient 'μ(n)'. The impregnation of the cracks with a high neutron absorbing substance will result in a sharp contrast between the cracks and the surrounding non-impregnated material, allowing better visualization of cracks. A chemical solution with gadolinium is commonly used as contrast agent. Its neutron absorption microscopic cross-section is at least 1000 times greater than any element of the concrete composition (Hughes and Harvey, 1955), allowing a significative improving of the technique sensitivity.

The digital image processing technique has been commonly employed to improve the visualization of analog images (Gonzalez and Woods, 1993). In the present work the NR technique, along with a system for digital image processing, was used to visualize cracks in concrete.

Experimental

Two types of cylindrical concrete specimens, with the characteristics shown in Table 1, were prepared.

Several 5 mm thick samples were sawn perpendicularly to the longitudinal axis of the specimens. The equipment employed was a circular diamond saw which provides polishing at the cut surface. During this process (~3 h) the samples were lubricated by a gently flowing water stream. Since water has a high neutron scattering microscopic cross-section (σ~200 barn for the present spectrum) it was necessary to dry the samples before irradiation because its presence would reduce the contrast and resolution of the radiographic image. The drying process was carried out heating the samples for 3 days at a temperature of 60°C.

Table 1. Main characteristics of the concrete specimens

Type	Diameter/height (cm)	Water/cement (ratio)	Cement/aggregate (ratio)
1	5/10	0.45	1/3.5
2	10/20	0.65	1/6.5

Drying process for the specimens: room temperature for 28 days

Table 2. Characteristics of the neutron beam at the irradiation position

Neutron beam diameter = 20 cm
Au–Cd ratio ~150
n/γ ratio ~5.10^5 n cm^{-2} mRem^{-1}
Collimation ratio $L/D = 60$ (L = length; D = inlet aperture diameter)
Neutron flux at the irradiation position = 3.10^6 n s^{-1} cm^{-2}
Neutron spectra mean energy = 2 meV

Before slicing and in order to induce cracks, the specimen type-2 was submitted to a compressive strength test (11 MPa) along its longitudinal axis (Aderhold *et al.*, 1986). This pressure is about 90% of the one necessary for its rupture.

As previously cited, crack visualization is strongly enhanced by the presence of a contrast agent into the cracks. An aqueous solution of gadolinium nitrate used for this purpose has been dropped on the

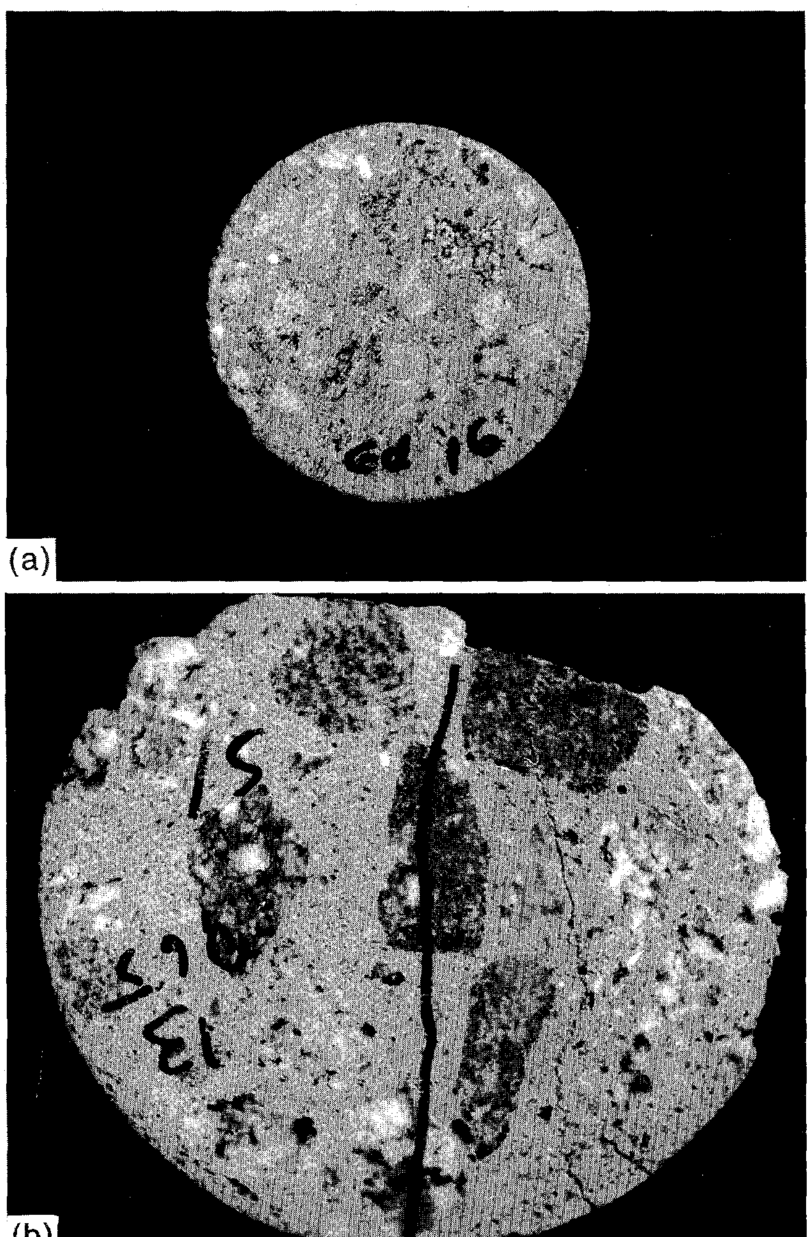

Fig. 1. (a) Conventional photograph of the S1 sample (5 cm dia) sawn from specimen type-1. (b) Conventional photograph of the S2 sample (10 cm dia) sawn from specimen type-2 submitted to compressive strength (11 MPa). Right of the divisory line with contrast agent; left without.

previously heated (50°C) and polished surface of the samples. The solution spread on the surface and penetrated into the cracks. The excess water evaporated leaving deposited the gadolinium nitrate crystals. In order to remove crystals from the surface, the samples were cleaned by rubber scrubbing.

The neutron beam passing through the sample is strongly absorbed by the gadolinium crystals resulting in a significant difference between the neutron intensities after passing the impregnated and the non-impregnated regions.

The experimental facility used in this work is installed at the beam hole 08 of the 2 MW pool type IEA-R1 nuclear research reactor where the thermal neutron flux is $\sim 10^{13}$ n s^{-1} cm^{-2} near the reactor core (Assunção *et al.*, 1994). Its main characteristics are listed in Table 2.

The neutron radiographs were obtained by the direct method with a metallic gadolinium converter screen (100 μm thick), positioning the polished surface of the samples very close to the face of an aluminium cassette containing the film and the converter screen in a tight contact. In this way the distance crack-converter screen ranged from 1 to 6 mm and for this geometry the maximal image

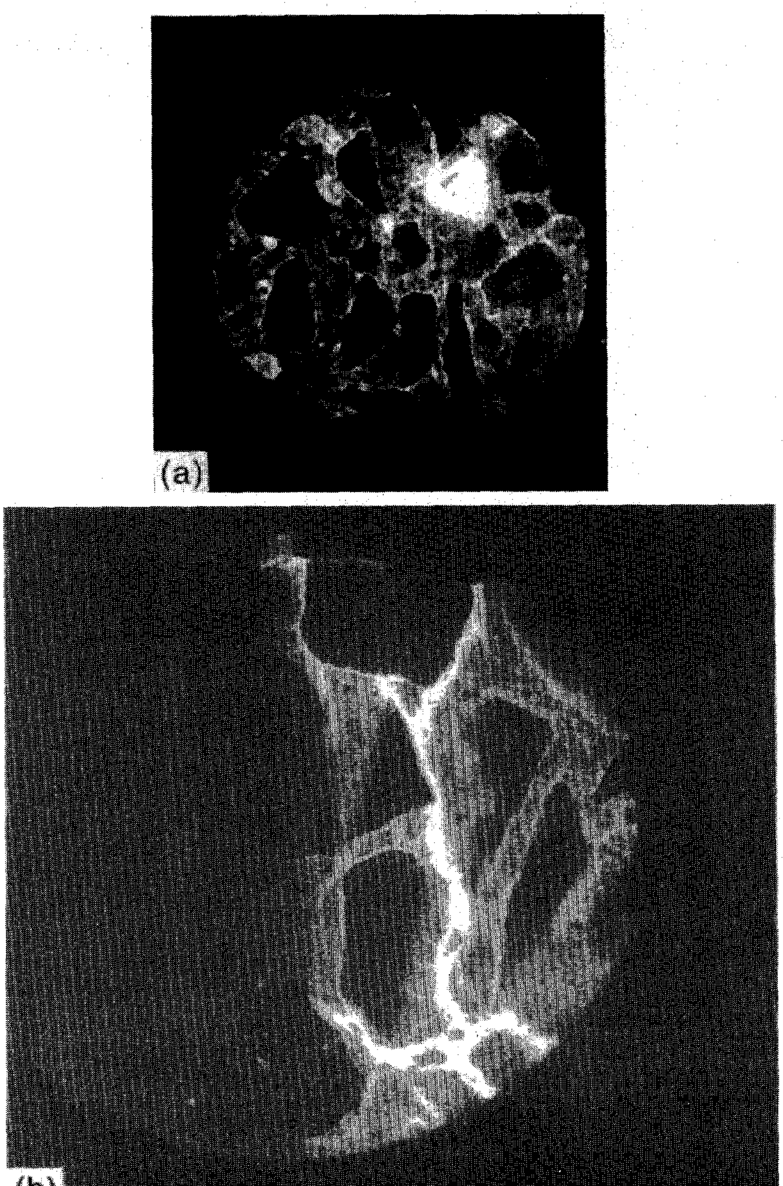

Fig. 2. (a) Digital neutron radiography of the S1 sample; and (b) digital neutron radiography of the S2 sample.

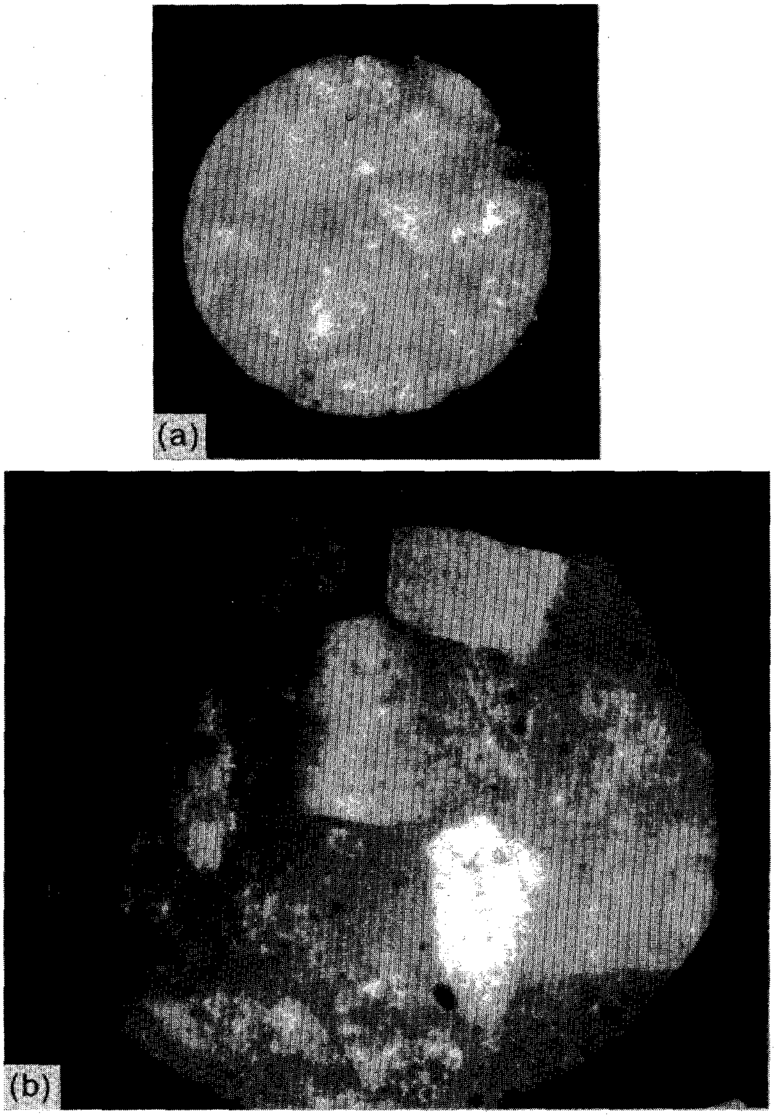

Fig. 3. (a) Digital X-ray radiography of the S1 sample; (b) digital X-ray radiography of the S2 sample.

resolution was approx. 100 μm. The irradiation time employed was 5 min and the maximal total dose rate measured at the sample surface was only 0.05 mRem h^{-1}. The film used was the Kodak-AA (conventional for X-ray radiography) which presented an optical density around $D = 3.0$ [$D = \log(I_0/I)$ where I_0 and I are the incident and transmitted light intensities] when irradiated in the direct neutron beam.

The digitized images were obtained by fixing the processed films on an optical negatoscope (1000 W) and scanning the analog images by means of a manual scanner which converts the transmitted light intensities in a 256 gray levels scale, with a resolution of 200 dpi. These images were stored in a 486-PC computer and processed for contrast and edge enhancement, by using a commercially available software.

Results and Discussion

Figure 1(a) and (b) shows conventional photographs of two selected samples, S1 and S2, which were sawn from specimens 1 and 2, respectively. Some surface voids and a large crack crossing S2 samples are visible. The contrast agent was applied on all polished surface of S1 sample and only on the right side of the divisory line of the S2 sample [see Fig. 1(b)].

The samples were initially inspected using an optical microscope (40 ×) and only a few cracks in S2 sample could be observed. Furthermore, the gadolinium nitrate crystal deposits were not visible in both samples.

Figure 2(a) and (b) shows the digital neutron radiographs of the same samples. Cracks in the S1 sample (from the non-compressed specimen) were visible only in the cement–stone interfaces. It is possible that these cracks had been induced in the sawing process. The cracks of the S2 sample (from the compressed specimen), located in the cement–stone interfaces, however, are brighter and sharper than those from S1. The compressive strength enhanced the existing cracks (Najjar *et al.*, 1986; Aderhold *et al.*, 1986) making the crystal impregnation and thus the neutron absorption easier. Furthermore several cracks were also visible in the cement paste of the S2 sample. These were certainly induced by the compressive strength, since they did not appear in the S1 sample.

In terms of crack visualization the digital neutron radiographs presented better results when compared with the obtained by the same NR technique, using emulsion films.

The technique sensitivity was estimated in terms of the minimal discernible thickness of the crystal deposits, observed by the unaided eye directly to the films. Neglecting the scattered neutron contribution, it was calculated by (Rumyantsev, s.d):

$$d(\min) \cong 0.02/(\mu_{\text{crystal}} - \mu_{\text{concrete}})$$

where μ_{crystal} and μ_{concrete} are the linear attenuation coefficient values for nitrate gadolinium crystals and for concrete, respectively. The former was theoretically calculated (Menezes, 1994), and the latter was experimentally determined. The obtained values were $\mu_{\text{crystal}}(n){\sim}310\ \text{cm}^{-1}$ and $\mu_{\text{concrete}}(n){\sim}0.1\ \text{cm}^{-1}$ and hence the sensitivity was approx. $d(\min){\sim}0.6\ \mu\text{m}$. Since the crack images in the films are bright lines, it is possible to attribute to the crystal deposits into the cracks, thicknesses greater than 0.6 μm. For the non-impregnated concrete the sensitivity was $d(\min){\sim}2$ mm, making impossible crack visualization.

The optical density readings of the films corresponding to the impregnated stones of the S2 sample were about 10% smaller than those for the non-impregnated ones while for the cement paste this value was about 20%. This means that the cleaning process employed to remove the crystals of the sample surface has been more effective in the stones.

The image of cracks in S2 sample exhibit, as already reported by Najjar (Najjar *et al.*, 1986), a width which is apparently enhanced when compared with those visible in microscope. This can be explained by considering that in the first case the images are two-dimensional projections of cracks which are non-perpendicular to the surface plane of the sample.

These same samples were also inspected by means of the X-ray radiography technique using the same film employed in the neutron radiographs. In this experiment a conventional X-ray equipment (125 kV, 8 mA) was used with an exposure time of 30 s. The digital radiographs obtained are shown in Fig. 3(a) and (b). As can be seen [Fig. 3(a)], cracks were not visible in S1 sample, while in the S2 sample [Fig. 3(b)] only a few cracks were observed, with lower contrast and lower sharpness than those obtained by neutron radiography. For the present X-ray beam the linear attenuation coefficient values are $\mu_{\text{crystal}}(X){\sim}13\ \text{cm}^{-1}$ and $\mu_{\text{concrete}}(X){\sim}0.4\ \text{cm}^{-1}$. The former was theoretically calculated and the latter is reported in the literature (Rumyantsev, s.d). The minimal discernible thickness for the crystal deposits has been determined, as previously for the NR case, and the sensitivity obtained was $d(\min){\sim}16\ \mu\text{m}$. This value is about 25 times greater than that obtained by the NR technique.

Several dark spots in the X-ray radiography of the S2 sample [Fig. 3(b)] have been observed. By visual inspection of the sample itself, the spots were identified as surface and included voids with thicknesses greater than 0.5 mm, which is the minimal discernible thickness for the non-impregnated concrete. Some of the surface voids are visible in Fig. 1.

Conclusions

The main conclusions which can be drawn from the results obtained in the present work are:

- NR technique using conventional emulsion films, as already reported in the literature, has a high sensitivity for crack identification;
- digital processing improves the crack visualization when compared with the results obtained directly in the films;
- the minimal discernible thickness of the gadolinium nitrate crystal deposits into the cracks, by the NR technique, is about 0.6 μm. This value is approx. 25 times smaller than the one evaluated for the conventional X-ray radiography.

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