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Digital laminography assessment of the damage in concrete exposed to freezing temperatures

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ABSTRACT

The research explores the possibility of using digital laminography as a non-destructive inspection X-ray method to image the damage existing in concrete exposed to low temperatures. Freezing–thawing and scaling tests were performed and digital laminography was used to determine the degree of damage existing inside the concrete samples. First, digital laminography was performed on the concrete sample and then a visual inspection was done by slicing the sample after it was vacuum-impregnated with epoxy in order to compare the differences in crack width.

1. Introduction

The successful evaluation of the extent and severity of cracks caused by frost action is important for determining the life cycle of concrete structures. Visual inspection of concrete surfaces has been standard practice because it is the simplest method, and up until now it has been difficult to evaluate damage inside the concrete. Any robust evaluation of the long-term performance of a structure is difficult without knowing what is happening inside the material. Therefore, non-destructive methods to evaluate the internal damage of concrete structures have been developed to meet these needs.

Typical non-destructive inspection techniques include stress wave propagation and electrical methods [1]. While these methods can evaluate the internal damage of a concrete structure non-destructively, their spatial resolution is low, and visualization using three-dimensional reconstruction is difficult. To complement these methods, X-ray imaging, such as computed tomography and laminography, are being studied [2]. Computed tomography makes it possible to evaluate the internal three-dimensional damage in materials, but the technique has low portability making it hard to transport to the field. The complex geometry and the large dimensions existing in civil engineering structures often prevent the complete distribution of the detectors around the structure, which is required to obtain a sharp image. On the other hand, digital laminography, which is used in dentistry and for inspection of circuit boards, is an attractive methodology to inspect reinforced concrete structures.

This paper reports on the use of digital laminography as a means to determine the presence of cracks and delaminations in concrete exposed to low temperatures. Two specimen types were prepared in order to explore a range of crack types associated with freezing damage. These include internal microcracking and surface scaling [3–5]. Internal cracking from freeze–thaw cycling results in expansion, loss in mechanical properties, and eventually the destruction of concrete [3]. The leading mechanism of destruction is caused by the phase transformation of water into ice, which has a 9% volume expansion. In fully saturated pores of concrete exposed to low temperatures, as volume expansion occurs, the space gets taken up by ice and the unfrozen water is pushed away from the freezing site. The water travels through the porous cement paste until it reaches an air-filled void (escape boundary) where the water freezes avoiding the development of large stress in the matrix [3,6]. If the concrete does not have an adequate air void system, ice is formed in the matrix generating cracks.

Surface scaling, however, is characterized by the loss of small flakes of cement paste or mortar and is limited to a few millimeters near the concrete surface [3,4]. In cold climate conditions, ice forms on the surfaces of bridges and highways. Salt is placed on these surfaces to lower the freezing-point temperature which causes ice to melt, thereby increasing friction on the roadway. A recently proposed mechanism for surface scaling is the bi-material effect. The mechanism of destruction is caused by mismatch in thermal expansion of the

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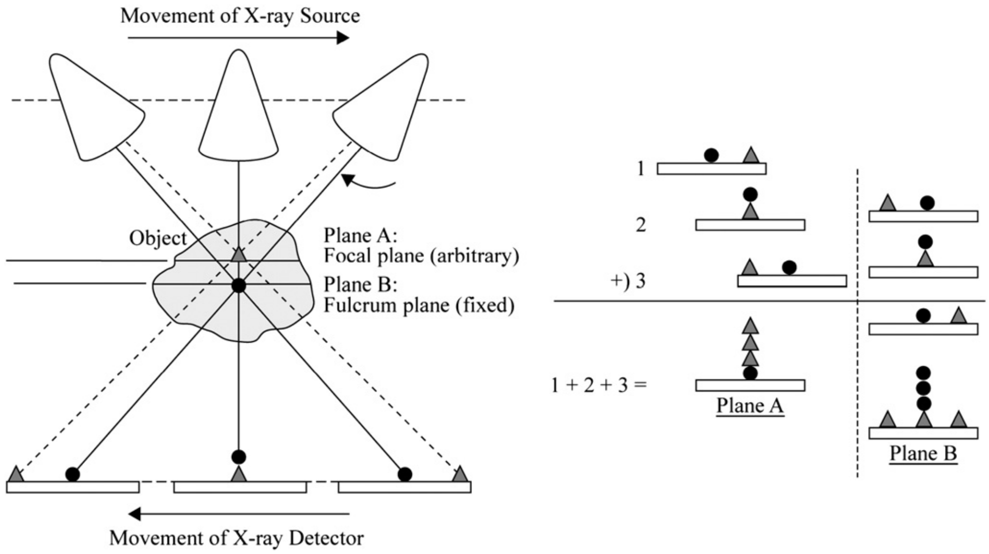

Fig. 1. Illustration of digital laminography (modified from [11,12]).

ice/brine layer and a thin layer at the surface of concrete [7]. Cracking begins in the ice/brine layer and propagates into the concrete surface. Damage is most detrimental at approximately 3% salt concentration and decreases as the concentration increases [5]. At higher salt concentrations, more brine forms and weakens the ice layer, which prevents it from exerting high enough stresses to crack the concrete surface [8].

The following section provides a general overview of digital laminography. Following this, images produced from application of the technique to samples cracked by freeze–thaw and salt scaling are provided. The study concludes with a discussion of the benefits and limitations of the proposed methodology within the scope of the proposed application.

2. Overview of digital laminography

Conventional projection radiography has been widely used since Wilhelm Röntgen invented X-rays in 1895. Although a major breakthrough in clinical diagnostics, it had the inherent limitation of compressing a three-dimensional object into a two-dimensional image. In 1916, the French dermatologist André Bocage proposed using laminography, which could make a specific radiological cross section of the object at a given depth. Together with Massiot, he also developed a laminography device [9,10]. The origin of the word “laminography” is from the “lamino” meaning “thin plate” (laminar) and the Greek word “graphe” meaning “drawing”. Laminography is also called geometrical tomography, motion tomography, and conventional tomography.

Since its development, laminography has played an important role in X-ray inspection activity as a new method to replace conventional projection radiography. Once computed tomography was developed for practical use, however, the interest in laminography decreased [11]. Given the limitations in using computer tomography to evaluate large concrete structures, there has been a renewed interest in applying laminography to such structures [2].

Laminography generates a specific radiological cross section by enhancing the contrast of an X-ray image and eliminating structures outside of it by using various projections. These projections are generated by a synchronized motion between an X-ray source and a detector. The acquisition techniques of the projections can be broadly classified into the three types of the synchronized motion between the X-ray source and the detector parallel motion, complete isocentric, and partial isocentric motion. This geometric focusing technique is why laminography is often referred to as geometrical tomography [11,12].

Table 1
Concrete mix proportions for freeze–thaw (FT) and salt scaling (SS) specimens

Material	Weight (kg/m^3)	
	FT	SS
Portland cement	377	400
Water	216	228
Coarse aggregate	812	705
Fine aggregate	901	931

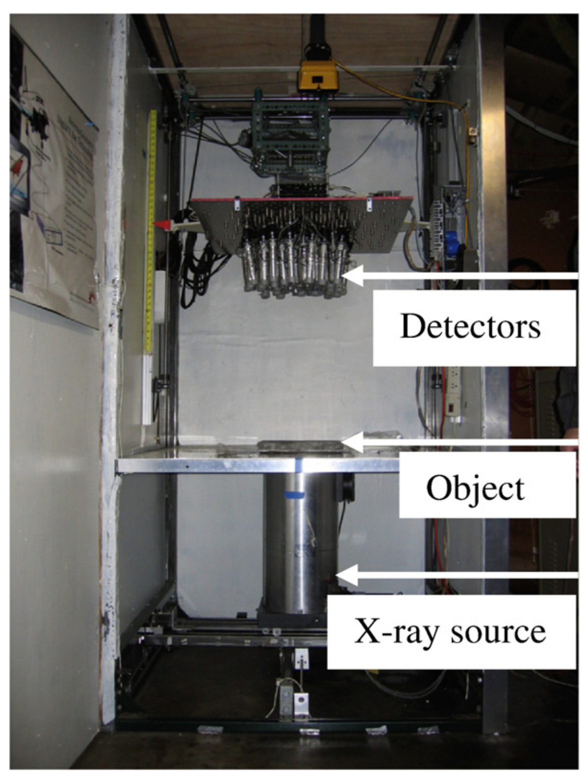

Fig. 2. Motionless Laminography X-ray (MLX®).