Theoretical and Applied Fracture Mechanics 80 (2015) 2–13

Contents lists available at ScienceDirect

Theoretical and Applied Fracture Mechanics

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

Influence of crack propagation on electrical resistivity and ultrasonic characteristics of normal concrete assessed by sequential TPB fracture test

Václav Veselý [b,a,*], Petr Konečný [a,1], Petr Lehner [a,1]

[a] VŠB-Technical University of Ostrava, Faculty of Civil Engineering, Department of Structural Mechanics, L. Podéště 1875/17, 708 33 Ostrava-Poruba, Czech Republic
[b] Brno University of Technology, Faculty of Civil Engineering, Institute of Structural Mechanics, Veveří 331/95, 602 00 Brno, Czech Republic

A R T I C L E I N F O

Article history:
Available online 22 October 2015

Keywords:
Normal concrete
Three-point bending test
Sequential loading
Effective crack length
Electrical resistivity
Ultrasound pulse passing time

A B S T R A C T

The paper is focused on the investigation of the effect of tensile failure propagation on the change in values of electrical resistivity and ultrasound pulse passing time within the central section of beam bend specimens made of normal concrete. These two physical characteristics may be employed as a quality indicator of the concrete cover within the procedures of the assessment of the structural durability. The three-point bending test configuration was utilised to drive the crack propagation process through several loading–unloading cycles, between which, the electrical resistivity and ultrasonic measurements over the fractured region were performed. Equivalent elastic crack model was used for estimation of the fracture progression (described via the effective crack length increment) at those loading stages. The relationships between changes of the non-destructively determined parameters, the effective crack length and the distance from crack tip are discussed with respect to two variants of treatment of the test specimens' surface: the pre-dried surface and the wet surface. A difference between the ultrasonic and electrical resistivity measurements ability with respect to crack width is found in the case of wet samples.

1. Introduction

Durability of reinforced and pre-stressed concrete civil engineering and transportation structures is becoming a substantial issue currently. Maintenance and repairs of these structures during their service life and demolition afterwards are being evaluated from many perspectives [33,15,12]; the economical and ecological viewpoints are mostly accented.

General deterioration of such structures is closely connected with the level of their mechanical damage caused by the initiation and propagation of cracks [26,31,36]. Cracks in the concrete cover of the reinforced and pre-stressed structures significantly facilitate the ingress of deleterious species of chemical and biological nature, thus causing a decrease in durability of these structures [21,10].

Tensile failure of the concrete part of these most common composite structures in civil engineering is nonlinear and typically referred to as quasi-brittle [17,32,5]. The reason for the nonlinear response is in the existence of a large nonlinear zone around the propagating crack tip, where the material is being damaged via numerous failure mechanisms, such as growth, coalescence, bending and branching of micro-cracks, which results in an increase of the porosity of the material in that zone. Aggressive agents (e.g., ice-melting salts, sea water, carbon dioxide, etc.) can more easily penetrate to the level of steel reinforcement through the damaged concrete cover via preferential pathways consisting of cracks.

Approaches to simulations of these complex phenomena taking into account the effect of concrete cracking on the aggressive agents' penetration is a subject of increasing interest in recent years, both from the numerical (e.g., [18,22,14,6]) and analytical (e.g., [7,37]) standpoints. The majority of these models are based on rather significant simplifications concerning description of the physics behind these complex phenomena. Thus, exploring the effects of cracking on the ingress of aggressive agents in more detail is a very reasonable research issue.

Typical well-known procedures for the estimation of the concrete ability to resist aggressive agents, expressed via diffusion coefficient, are based on the rapid chloride penetration method (RCPT) [4,2,3] or evaluation of the electrical resistivity of concrete [24,1,13]. Estimation of these physical characteristics is typically

* Corresponding author at: Brno University of Technology, Faculty of Civil Engineering, Institute of Structural Mechanics, Veveří 331/95, 602 00 Brno, Czech Republic. Tel.: +420 597 321 384, +420 541 147 362; fax: +420 597 321 304, +420 541 240 994.

E-mail addresses: vesely.v1@fce.vutbr.cz (V. Veselý), petr.konecny@vsb.cz (P. Konečný), petrlehner@gmail.com (P. Lehner).

[1] Tel.: +420 597 321 384; fax: +420 597 321 304.

http://dx.doi.org/10.1016/j.tafmec.2015.09.005
0167-8442/

performed on intact specimens without loading. However, the effect of the cracking is significant with respect to ingress of the aggressive agents. The influence of cracking on the ability of chlorides to penetrate has been studied with respect to the RCPT test and induced cracks in Djerbi et al. [11] and Marsavina et al. [22]. Djerbi et al. [11] confirmed that the size of the crack is related to the ability of chlorides to penetrate through the crack. The electric charge was applied parallel to the crack. They found that the computed diffusion coefficient in the crack of the specimen started to deviate from the value corresponding to the original intact concrete when the crack was wider than 30 μm. The diffusion coefficient in crack gradually increased until the crack width reached 250 μm. For thicker cracks, the diffusion coefficient in crack gained the value of porous media. In summary, thin cracks did not affect the flow of electric charge, whereas thick cracks increased the electric charge passed through them. Evaluation of the effect of progressing crack during the wedge splitting test, with the help of electrical resistivity, complementary crack opening displacement (*COD*) measurements and image analysis of the crack, was conducted by Pacheco et al. [27]. The electrical measurement was conducted in the transverse direction to the crack propagation (i.e., in the direction of crack opening). The relationship between the *COD* and relative resistance was found. The air-filled crack opening represented barrier for the flow of the electric current. The size of induced *COD* was in the range of 200–700 μm, which is greater than the limiting 250 μm, for *COD* sizes greater than 250 μm, the crack was fully opened in study by Djerbi et al. [11]. The test of electrical conductance transverse to the crack with its filling with water was conducted by Boulay et al. [9]. The crack provided the path way for ionic movement. The increase of electrical conductance (inverse value to resistance) was proportional to the *COD*. The studied crack widths were up to 100 μm. The change in conductivity that reflects the movement of aggressive species in the crack changed, even if the crack width was smaller than 30 μm. The tests of Boulay et al. [9] and Djerbi et al. [11] on a medium filled with cracks and voids were in accordance with the above results. Wider cracks promote the motion of ionic species through damaged area. However, all of the three above-mentioned resistivity tests of cracked concrete were conducted using special laboratory equipment and well-manufactured instrumentation.

An open question is how the measured electrical resistivity parameter is relevant, if the resistivity tests were conducted on specimens that have undergone damage to a certain extent and the measurement is performed using a typical field applicable Wenner probe based resistivity instrument. The resistivity reading via the in-situ available instrument would simulate field application to assess the quality of concrete structures with respect to cracking. Therefore, the limits of this approach are studied in the present paper, with a hypothesis that the correlation between the level of concrete cracking and the (change in) electrical resistivity is a qualitative indicator of the material's ability to resist the penetration of aggressive agents through it and is utilised for assessment of structural durability.

Note that other methods are also commonly utilised in this field, see, e.g., Bjegović et al. [8].

In the experiments conducted by the authors, selected results of which are presented in this paper, phenomena related to the introduced problem are investigated. Sequential three-point bending tests of single edge notched beams (SEN-TPB) were performed and observed on both the uncracked and cracked specimen regions. In particular, it was investigated how the aggressive agent ingress can be related to the level of tensile damage of concrete (i.e., the covering material for reinforcement bars). Changes in the electrical resistivity in the central section (in comparison to its value in the intact parts of specimen/structure) can reveal a relationship between the coefficient of diffusion of an aggressive agent (chloride) ions and the extent of the concrete fracture. In other words, an issue relevant for practical interest is estimation of the increase of aggressive agent ingress due to cracking (for example, on the surfaces of the structural parts under tensile stresses), even if the damage is not visible by naked eye.

In addition to the above-mentioned measurements of the resistivity parameter, the fracture experiments were also accompanied with ultrasound measurements in the central area of the beams. The degree of decrease of the material structure's integrity in the cracked part of test specimens was evaluated via the decrease of velocity of the ultrasound pulse propagation with the progress of tensile damage (which has been applied to various materials, e.g., concrete and marble by Prassianakis and Prassianakis [28]).

Both these non-destructive methods are used here with the ambition to employ them for rapid assessment of the quality of concrete in the tensioned regions of real structures within their quality inspection. This issue can be viewed as very important regarding the ability to ascertain/eliminate a premature degradation of reinforced and pre-stressed concrete civil engineering structures.

The paper follows and extends upon previous studies devoted to both the electrical resistivity or ultrasonic measurements already published by the authors in Veselý et al. [34] and Konečný et al. [19]; new results originating from supplementary tests conducted under different moisture conditions [35] are added here, and the entire experimental campaign is summarised in Konečný et al. [20].

2. Experiments

2.1. Tested material and specimens

Test specimens were made from a common concrete mix provided by a local commercial concrete mixing plant. The designed strength class of this used normal concrete was C30/37 XF4. Specimens were casted into steel moulds from one batch of fresh concrete and properly vibrated for 30–60 s. In addition to the standard specimens for bending tests, beams of dimensions of 100 × 100 × 400 mm, cubes of edge length 150 mm and cylinders of diameter 150 mm and length 300 mm for standard tests of the compressive strength, the splitting tensile strength and the modulus of elasticity (both static and dynamic), respectively, were produced as well. All specimens were submerged in a tank filled with water at laboratory temperature. The results from the bending tests on notched beams (see Fig. 1) are reported in this paper.

Before the fracture test, using a diamond blade saw, test beams were cut into three slices along the longitudinal axis of the beam, in planes perpendicular to the casting direction. The two surface layers created on the specimens by the bottom of the mould and the upper open surface were cut off as well (in a layer of several millimetres) to diminish the surface effect due to the aggregate

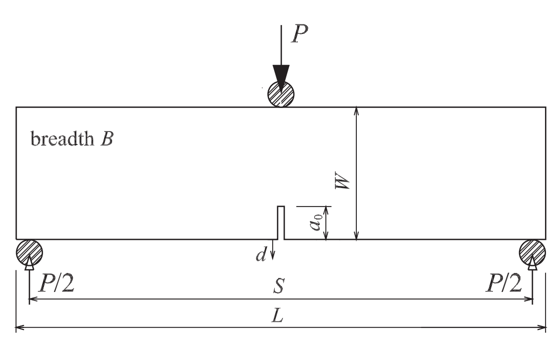

Fig. 1. Indication of specimen dimensions and measured quantities.