Advances in Engineering Software 62–63 (2013) 61–71

Contents lists available at SciVerse ScienceDirect

Advances in Engineering Software

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

Fracture properties of cement and alkali activated fly ash based concrete with application to segmental tunnel lining

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ARTICLE INFO

Article history:
Available online 16 May 2013

Keywords:
Fly ash
Fiber reinforced concrete
Fracture energy
Finite element simulation
Artificial neural network
Inverse analysis

ABSTRACT

Several cement and alkali activated fly ash based concrete samples are examined in this paper with emphasis on their fracture properties. These are first obtained from an extensive experimental program. The measured loading curves are then compared with those derived numerically in the framework of an inverse approach. Here, the artificial neural network and the ATENA finite element code are combined to constitute the optimization driver that allows for a reliable determination of the modulus of elasticity, fracture energy, and tensile strength of individual concretes. A brief introduction to the numerical analysis of fiber reinforced specimens again in conjunction with inverse analysis is also provided.

1. Introduction

Substituting an ordinary Portland cement by aluminosilicate materials such as fly ash in the production of concrete has been at the forefront of engineering interest for several decades [1,2]. A recent overview of potential applications is available in [3,4]. A considerable attention in particular has been devoted to the level of paste, see e.g. [5–7, to cite a few], to acquire a fundamental understanding about the evolution of individual material phases during the alkali-activation process. Therein, various micromechanical models combined with nanoindentation measurements were used to address this subject. On the contrary, large scale macroscopic laboratory tests are typically performed when studying the level of concrete [8,9]. This approach is adopted also in this study and extended by introducing a simulation phase to derive not directly measurable mechanical parameters such as the tensile strength [10].

Since the proposed mixtures are expected to appear in the production of the segments of lining often used in hostile environment, we open the experimental part of this study by reporting in Section 3.1 on the current state of measurements of material degradation due to the activity of acid solutions. Section 3.2 then continues with mechanical testing under static conditions and concentrates on fracture properties of the proposed mixtures. Henceforth, to distinguish individual samples the word "mixture" is assumed in a broader sense as a reference to an associated concrete. While fracture properties play a central role in the modeling of quasi-brittle response of concrete, the judgment as to the practical applicability of a particular mixture in the tunnel design is driven by its compressive strength here required to exceed the value of class C50/60 concrete. Therefore, standard compressive tests were included in the experimental program.

As already suggested, a simple test to directly measure the tensile strength of concrete to be used in numerical simulations is not available. However, this material property can be derived from an inverse approach by matching the laboratory measurements and the results found by reproducing the same test numerically. This approach has been used in the past to calibrate quite complex materials including composites [11] or constitutive models such as the modified cam-clay model used in geotechnical engineering [12] or microplane model for concrete [13]. Here, we proceed in the footsteps of Lehký et al. [14,10] and use the artificial neural network (ANN) as a tool to drive the associated optimization problem. Conveniently, the ATENA finite element program [15] is exploited to simulate the fracture test numerically. Details are provided in Section 4.

Apart from proving sufficient durability the mixtures used for a tunnel lining should possess good fire resistance properties particularly with regard to spalling. It has been demonstrated that this unpleasant feature can be successfully treated by adding a relatively small volume fraction of short fibers into original mixtures [16,17]. Thus examining the influence of fiber reinforcement also on the mechanical behavior of fiber reinforced concrete seems reasonable. Though this is an ongoing research topic, some preliminary results related to numerical simulations and material

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http://dx.doi.org/10.1016/j.advengsoft.2013.04.009

parameters identification again with the help of ANN and ATENA code are discussed in Section 5.

A concise summary of the presented work is finally given in Section 6.

2. Sample mixtures

To introduce the subject we first present the list of all examined mixtures. For the sake of completeness, those already mentioned in our preliminary work [8,9] are also provided. As a reference mixture, in terms of the grading curve, see Table 1, and bonding components, we considered a standard cement based concrete (C) in the first column of Table 2, which by far exceeds the required compressive strength of 60 MPa [8,9]. The remaining mixtures assumed either partial or total replacement of cement by fly ash.

In particular, low-calcium fly ash coming from the Mělník (FAM) and Opatovice (FAO) thermal electric power plants was used. Several groups of specimens with partial replacement of cement by fly ash were considered and denoted as FAC-30-M, FAC-70-M, FAC-30-O, FAC-70-O and FAC-80-O, where numbers represent the percentage of fly ash with respect to cement, M stands for the Mělník and O for the Opatovice power plant, respectively. Specific compositions are listed in Table 2. As it is seen, no activation components were used for these mixtures. On the contrary, the last group denoted as FA-100-O assumed a total replacement of concrete by fly ash activated by strong alkaline liquids such as a mixture of NaOH pellets dissolved in tap water and sodium silicate in the form of water glass, see the last column in Table 2.

To study the effect of fiber reinforcement, we limited our attention to standard concrete (C) samples only. These were modified by adding 0.5% of volume of synthetic fibers Forta-Ferro. This amounted to 4.5 kg of fibers per 1 m^3 of the mixture. As demonstrated in Section 5, the numerical simulations of such composites can reproduce the laboratory tests rather well. These results are quite encouraging promoting further research towards FAC fiber reinforced systems in the future.

3. Experimental program

This section summarizes the derivation of basic mechanical properties from laboratory measurements. The amount of material degradation at various stages of exposure to acid solution is linked here to the evolution of the dynamic modulus of elasticity. The three-point bending tests discussed next were performed to provide the standard fracture properties including the fracture energy and fracture toughness. These tests also allowed for back calculation of the modulus of elasticity and then independently for the compressive strength measured on cubic samples cut from the fractured specimens.

Table 1
Fraction of grains.

Fraction	Amount per 1 m^3 of mixture in (kg)
0/4	705
3/8	130
8/16	865

Table 2
Selected mixtures.

Material	Amount per 1 m^3 of mixture in (kg)				
Mixture →	C	FAC-30	FAC-70	FAC-80	FA-100
CEM I 52,5 R	460	322	138	92	–
Limestone powder	40	40	40	40	–
Water	150	150	150	150	51
Fly ash (M/O)	–	138	322	368 (FAO)	400 (FAO)
NaOH	–	–	–	–	29.4
Water glass 34%	–	–	–	–	127.5
Slaked lime	–	–	–	–	12
Glenium ACE	4.2	4.2	4.2	4.2	12

3.1. Corrosive environment

This particular experiment serves to address a potential influence of a long term action of aggressive groundwater on mechanical properties of examined mixtures. Following the discussion with experts in tunnel construction we chose a sulfate solution as the decisive element in evaluating the resistivity of tunnel lining. A dynamic modulus of elasticity is adopted here to verify the potential material degradation. The measurements were carried out with the help of a non-destructive ultrasound method on cubic $150 \times 150 \times 150$ mm specimens. The MATEST Ultrasonic tester (palmer "High Technology" with microprocessor for combined ultrasonic and rebound hammer data acquisition and processing C372N) was employed to determine the time of wave propagation. The dynamic modulus of elasticity E_{DYN} then follows from

$$E_{DYN} = \rho \frac{\frac{L}{T}^2}{k^2}, \tag{1}$$

where ρ is the bulk weight of the material, L and T represent the length of a measuring base and an average time of wave propagation, respectively, and k is the dimensionless coefficient depending on the relation of L and T attaining the value of either 1 or 1.0541.

Since this is an ongoing experiment, we report only the results collected in a relatively short period of 17 months for concrete specimens and 13 months for alkali activated fly ash based mixtures. Table 3 lists the actual values of dynamic moduli for a particular period of time. Note that the initial value corresponds to dry conditions. This value typically increases upon soaking the specimen into a liquid solution, which explains the initial increase of this value measured after 4 and 7 months, respectively. An onset of degradation process, although at a very slow rate, can be observed when comparing the initial values with those corresponding to time period of 17 (C, FAC-30-M specimens) and 13 (FA-100-O specimens) months. Taking the change of E_{DYN} in water as a reference value equal to zero, we may evaluate the influence of aggressive solution upon plotting the change of E_{DYN} for a given solution with respect to this reference value. The results appear in Fig. 1.

Table 3
Dynamic modulus of elasticity E_{DYN}.

Mixture	Solution	Initial value	4 months	11 months (7 months)	17 months (13 months)
C	H_2O	53.7	58.9	57.7	57.7
C	Na_2SO_4	55.4	61.7	58.9	56.9
C	Mg_2SO_4	54.0	61.0	60.8	57.6
FAC-30-M	H_2O	52.2	61.1	55.6	52.9
FAC-30-M	Na_2SO_4	52.0	57.5	57.1	54.8
FAC-30-M	Mg_2SO_4	52.2	59.6	59.5	57.1
FA-100-O	H_2O	28.7	–	(35.9)	(33.4)
FA-100-O	Na_2SO_4	28.3	–	(33.5)	(32.5)
FA-100-O	Mg_2SO_4	30.1	–	(36.5)	(33.8)