Cement and Concrete Research 94 (2017) 59–70

Contents lists available at ScienceDirect

Cement and Concrete Research

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

Influence of fiber type and fiber orientation on cracking and permeability of reinforced concrete under tensile loading

T. Plagué, C. Desmettre, J.-P. Charron *

Department of Civil, Geological and Mining Engineering, Polytechnique Montréal, P.O. Box 6079, Station Centre-Ville, Montreal, QC H3C 3A7, Canada

ARTICLE INFO

Article history:
Received 20 July 2016
Received in revised form 18 November 2016
Accepted 10 January 2017
Available online 31 January 2017

Keywords:
Durability
Permeability
Concrete
Fiber reinforcement
Tensile properties

ABSTRACT

During the service life of structure, cracks developed due to various internal or external stresses. These cracks offer a preferential path for the ingress of water, gas and aggressive ions through the concrete. This increase of concrete's permeability promotes the structure deterioration. A good understanding of structure permeability is thus required to design durable structures. An innovative permeability device was used to measure the impact of fiber orientation and fiber type on the water permeability of high performance fiber reinforced concrete (HPFRC) tie-specimens submitted simultaneously to a uniaxial tensile loading. Specific casting techniques provided tie-specimens with three fiber orientations (favorable, average and unfavorable) that can be found in fiber reinforced concrete (FRC) structural elements. Experimental results showed average fibers angles relative to the loading direction of tie-specimens of about 39°, 42° and 54° respectively for the favorable, average and unfavorable orientations. As fiber orientation become less favorable (from 39° to 54°), the tensile strength (f_t) of characterization specimens reduced up to 33%, while the increase in permeability (K_w) tie-specimens achieved 1990% at fixed load and 600% at fixed stress in the rebar. For HPFRC casted with the same procedure, synthetic fibers provided a lower efficiency to control cracking at material and structural scales, and to limit water permeability in comparison to steel fibers. The impact of fiber orientation is clearly more significant on water permeability of HPFRC than on their mechanical behavior. These results provides insights of the impact of fiber orientation on durability of reinforced FRC structures.

1. Introduction

Durability of reinforced concrete structures relies on the transport of water and aggressive agents through concrete by several mechanisms as permeability, diffusion, capillary absorption, etc. Among these mechanisms, permeability, defined as the movement of a fluid through a porous saturated medium under a pressure gradient, can be used as a durability index especially when the concrete is cracked. The increase of permeability favors the ingress of water, gas and aggressive ions into the concrete, which promotes its deterioration by freeze-thaw, sulfate attack, alkali-aggregate reaction or reinforcement corrosion [1–3]. These deteriorations limit the lifetime of concrete structures and raise their direct costs combining construction and rehabilitation works, and indirect costs related to socioeconomic and environmental impacts resulting from these rehabilitations. In this context, durability is now more than ever an important concern for infrastructures owners and stakeholders.

During their lifetime, structures developed cracks due to various internal stresses (shrinkage, creep) and external stresses (mechanical and environmental loads). Cracks offer an easy path for aggressive agents to penetrate into concrete by permeability. Thus, to design durable structure, it is necessary to identify and evaluate parameters influencing the permeability of cracked concrete. Studies performed on unloaded concrete specimens with one single crack showed that the water permeability of cracked concrete is mainly controlled by the crack widths [4–8]. To be more representative of the reality of the structures, which are continually loaded and randomly cracked, some researchers studied the permeability of longer concrete specimens under tensile loads [9]. Permeability was also measured recently on reinforced concrete tie-specimens submitted to tensile loads to reproduce more efficiently the global behavior of tensile zones found in reinforced concrete structures [10,11].

Research works on loaded concrete clearly showed that fiber reinforced concretes (FRC) have a reduced water permeability in comparison to ordinary concrete. The addition of fibers provides a lower porosity and a higher tortuosity to the concrete matrix, thus reducing permeability at uncracked state [12]. Moreover, fiber's ability to bridge cracks results in thinner cracks and thus provide a lower permeability at cracked state [10].

* Corresponding author.
E-mail addresses: thibaut.plague@polymtl.ca (T. Plagué), clelia.desmettre@polymtl.ca (C. Desmettre), jean-philippe.charron@polymtl.ca (J.-P. Charron).

http://dx.doi.org/10.1016/j.cemconres.2017.01.004

Table 1
Compositions of concretes (0.75 % vol. of fibers).

Material	HPFRC-ST	HPFRC-SY
Cement (kg/m^3)	500	500
Silica fume (kg/m^3)	50	50
Water (kg/m^3)	237	237
Superplasticizer (l/m^3)	11.3	14.1
Viscosity agent (l/m^3)	0.9	0.9
Sand (kg/m^3)	814	812
Coarse aggregate (kg/m^3)	678	657
Steel fiber dosage (kg/m^3)	58.5	–
Synthetic fiber dosage (kg/m^3)	–	6.83
Water/Binder ratio (−)	0.43	0.43

Table 3
Spreads and mechanical properties of concretes.

	Date (days)	HPFRC-ST-F	HPFRC-ST-A	HPFRC-ST-U	HPFRC-SY-F
f_c (MPa)	28	59.8	59.9	59.5	59.9
	50	67.4	64.4	64.3	61.2
f_t (MPa)	28	–	–	–	–
	50	4.41	4.10	2.96	3.30
E_c (MPa)	28	32,400	34,000	34,300	33,300
	50	32,600	37,600	35,600	35,000
Slump flow (mm)	–	490	540	610	620

Logically, parameters influencing the action of fibers in the concrete matrix may have an impact on the permeability. They must be investigated to tailor FRC according to the durability expected for structural applications. It was demonstrated that increasing concrete matrix strength favors anchorage of fibers [13] and reduces permeability [11]. It was also shown that increasing the dosage of steel fibers [8], synthetic fibers [14], or a combination of those [15], decreases water permeability. Besides, until now no study was dedicated to the impact of fiber orientation on permeability of cracked concrete, although literature indicates that fibers orientation strongly influences the tensile and bending behaviors of FRC by modifying the fiber efficiency to bridge cracks [16–18]. Moreover, fiber orientation varies within any FRC structure due to formwork and rebar configurations and concrete flowability, and from one FRC structure to another, therefore the impact of this parameter on FRC durability must be established.

The general objective of this project is to determine the influence of the fiber orientation and fiber type on water permeability of FRC structures. A permeability device developed at Polytechnique Montreal [11, 19] was used to perform water permeability and crack openings measurements simultaneously with the application of tensile loadings on reinforced concrete tie-specimens.

2. Methodology

2.1. Experimental program

Tie-specimens were submitted to water permeability and cracks width measurements simultaneously to the application of a quasi-static uniaxial tensile loading at the age of 50 days. The tie-specimens were made of self-consolidating high-performance fiber-reinforced concretes (HPFRC) with a water to binder ratio (w/b) of 0.43 and containing 0.75% in volume of macrofibers. Two macrofiber types were tested: hooked-end steel fibers (HPFRC-ST) and synthetic fibers (polypropylene-polyethylene mix) (HPFRC-SY). The compositions of the HPFRC-ST and HPFRC-SY are presented in Table 1 and the geometrical and mechanical properties of both fibers are summarized in Table 2.

For steel fibers, three fiber orientations which can be found in fiber-reinforced concrete (FRC) structural elements were tested: favorable (HPFRC-ST-F), average (HPFRC-ST-A) and unfavorable (HPFRC-ST-U) orientations. The favorable orientation corresponds to the situation where fibers are the best aligned with the tensile load direction (longitudinal axis of the tie-specimen), on the contrary the defavorable orientation represent the situation where fibers are the worst aligned. The average orientation is the intermediate condition, some tests demonstrated that HPFRC-ST-A orientation is similar to the one obtained with a normal workability concrete after vibration. The tie-specimens with synthetic fibers were only tested with the favorable orientation (HPFRC-SY-F) since the higher flexibility of this fiber type does not allow easily fiber alignment and determination of fiber orientation by image analysis techniques.

Four tie-specimens per conditions (HPFRC-ST-F, HPFRC-ST-A, HPFRC-ST-U and HPFRC-SY-F) were submitted to permeability tests under loading. After the tests, three slices were sawn from one tie-specimen of each steel fiber orientation, perpendicularly to the tensile load and thus parallel to the cracks, to measure the fiber orientation. The slices were taken adjacent to the three main cracks.

HPFRC workability and mechanical properties were measured for each condition, results are summarized in Table 3 and Fig. 2. The spread was measured by the slump flow test according to ASTM C1611 [20]. The compressive strength (f_c) and the Young's modulus (E_c) were determined at 28 days and 50 days (age of the permeability test) in accordance with ASTM C39 [20]. The tensile strength (f_t) was determined at 50 days on notched core cylinders (Fig. 1a) in accordance with RILEM-TC-162 [21]. These cylinders were obtained from 95-mm diameter cores extracted from larger concrete blocks that were produced with the same casting techniques used for the tie-specimens production (Section 2.2.1) in order to have a similar fiber orientation. Fig. 1 show pictures of typical tensile failure plans obtained for the HPFRC-ST-F, HPFRC-ST-A and HPFRC-ST-U conditions respectively.

The tie-specimens contain one Grade 400W 10M rebar along the longitudinal axis. The rebar properties were measured in accordance with ASTM A615 [22]. They had a Young's modulus of 210 GPa and yield and ultimate strengths respectively equal to 470 MPa and 580 MPa.

2.2. Experimental procedures

2.2.1. Specimen preparation

The tie-specimens represent a rebar and the surrounding concrete found in the tensile zone of beams, thick slabs or walls subjected to bending loads. For these structural elements submitted to bending load, the stress gradient is small and the tensile stress is nearly uniform in the concrete cover. Applying a uniaxial tensile loading on the tie-specimen is thus representative of the loading stress in these structural elements. The tie-specimen has a length of 610 mm, a cross-section of 90 × 90 mm^2, and contains a 10 M (11.3 mm in diameter) centered rebar. These characteristics were chosen in a previous work [19] to obtain realistic concrete cover and cracking pattern distribution found in reinforced concrete structures.

Table 2
Fibers properties.

Fiber type	Length (l)	Diameter (d)	Aspect ratio (l/d)	Young's modulus	Tensile strength
Steel fibers (ST)	35 mm	0.55 mm	65	210 GPa	1345 MPa
Synthetic fibers (SY)	38 mm	–	55	9.5 GPa	600–650 MPa