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PRC-544.10-21
TechNote

# Fiber Effect on Reducing the Permeability of Cracked Concrete Structures—TechNote

**Keywords: crack width; durability; fiber; fiber-reinforced concrete; permeability; stress.**

## Question

Concrete structures are susceptible to cracking during their service life. These cracks become the main route through which liquids and aggressive agents penetrate into and through concrete mass. Does the use of fibers in concrete result in a reduction of crack widths compared to concrete without fibers? Does crack width reduction correlate with maintaining a lower permeability, thus improving the long-term durability of a structure?

## Answer

A properly designed concrete with a fiber-reinforcement system has a reduced crack width under service loads. The fibers can cause changes in crack morphology (higher roughness and tortuosity) and increase the likelihood of multiple crack development, crack deflection, and branching. Consequently, ingress of liquid and other aggressive agents is decreased significantly and results in a delay of permeability-related deterioration mechanisms. Therefore, all evidence points to fibers extending the service life of concrete structures.

## Introduction

Reinforced concrete structures are designed to withstand stresses caused by external loads (static, cyclic, or dynamic loads), stresses caused by internal and restrained deformations (shrinkage, thermal, and hydraulic gradients), as well as resist chemical and physical degradation mechanisms. Direct observations and testing have clearly revealed that ingress of liquid and aggressive agents into cracked concrete is much larger than in sound concrete. Cracking may allow deep penetration of air, liquid, and aggressive ions, depending on crack size and environmental conditions. These result in issues related to water tightness and reduced corrosion resistance for embedded reinforcing steel. Subsequently, widespread deterioration mechanisms through carbonation, alkali-aggregate reaction (AAR), or chemical attack in aggressive environments may be exacerbated by the presence of cracks (ACI 544.5R).

## Discussion

*Allowable crack widths*—North American (ACI 224R; ACI 224.1R; ACI 224.2R; ACI 318; AASHTO LFRD Bridge Design Specifications; CSA A23.1-2) and European (*fib* Model Code [MC2010]; BS EN 1992-1-1:2004) building codes require that cracks in concrete exposed to weathering be no larger than specified widths to ensure structural and mechanical integrity and durability (Aldea and Shah 2011). Maximum allowable crack widths ranging between 0.006 and 0.015 in. (0.15 and 0.38 mm) are specified in various design codes for most reinforced concrete structures and bridge applications exposed to aggressive environments. ACI 224R, 224.1R, and 224.2R provide information about the cracking mechanisms in concrete. Design recommendations as presented in Table 1 provide allowable crack widths versus exposure conditions in fiber-reinforced concrete, and the use of fibers as a means to control cracking in overlays. More research is needed on concrete permeability to evaluate current limits and determine the maximum allowable width of exposed cracks in structures.

**Table 1—Maximum allowable crack width $w_k$, in mm (in.), for fiber-reinforced concrete exposed to chlorides and carbonation (taken from Marcos-Meson et al. [2018])**

| | Exposure Class per BS EN 206-1:2013 and BS EN 1992-1-1:2004 | Carbonation | | | Chlorides | | | |
|---|---|---|---|---|---|---|---|---|
| | | XC2 | XC3 | XC4 | XS2 | XS3 | XD2 | XD3 |
| References | ACI 544.1R | *wk* < 0.30 (0.012) | *wk* < 0.30 (0.012) | *wk* < 0.10 (0.004) | $w_k < 0.10$ (0.004) | $w_k < 0.10$ (0.004) | $w_k < 0.10$ (0.004) | $w_k < 0.10$ (0.004) |
| | RILEM TC 162-TDF | *wk* < 0.30 (0.012) | *wk* < 0.30 (0.012) | *wk* < 0.30 (0.012) | Special* | Special* | Special* | Special* |
| | DBV:2001 | $w_k < 0.30$ (0.012) $\Delta_h$† > 20 (0.8) | $w_k < 0.20$ (0.012) $\Delta_h$† > 20 (0.8) | $w_k < 0.20$ (0.008) $\Delta_h$† > 25 (1.0) | $w_k < 0.20$ (0.008) $\Delta_h$† > 40 (1.6) | $w_k < 0.20$ (0.008) $\Delta_h$† > 40 (1.6) | $w_k < 0.20$ (0.008) $\Delta_h$† > 40 (1.6) | $w_k < 0.20$ (0.008) $\Delta_h$† > 40 (1.6) |
| | UNI/CIS/SC4 -SFRC No. 29 | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) Coated‡ | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) Coated |
| | CNR-DT 204/2006 | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) Coated‡ | $w_k < 0.30$ (0.012) Stainless§ | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) Coated‡ |
| | NZS 3101:Part 2:2006 | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) | $w_k < 0.20$ (0.008) | $w_k < 0.20$ (0.008) | $w_k < 0.20$ (0.008) | $w_k < 0.20$ (0.008) |
| | CS TR63 | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) |
| | EHE-08 | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) | Test¦¦ | Test¦¦ | Test¦¦ | Test¦¦ |
| | DAfStb Stahlfaserbeton:2012-11 | $w_k < 0.30$ (0.012) | $w_k < 0.30$ (0.012) | $w_k < 0.20$ (0.008) | NA | NA | NA | NA |
| | AFTES 2013 | $w_k < 0.20$ (0.008) | $w_k < 0.20$ (0.008) | $w_k < 0.20$ (0.008) | $w_k < 0.15$ (0.006) | $w_k = 0$ | $w_k < 0.15$ (0.006) | $w_k = 0$ |
| | SS 812310:2014 | $w_k < 0.40$ (0.015) | $w_k < 0.40$ (0.015) | $w_k < 0.30$ (0.012) | $w_k < 0.20$ (0.008) | $w_k < 0.10$ (0.004) | $w_k < 0.20$ (0.008) | $w_k < 0.10$ (0.004) |

*Special: Special provisions required.
†$\Delta_h$ is minimum sacrificial layer on exposed surfaces, in mm (in.).
‡Coated: Coated carbon-steel or stainless-steel fibers required.
§Stainless: Stainless-steel fibers required.
¦¦Test: Experimental verification required.
NA: Not applicable.

*Fiber contribution*—Microfibers are fibers with an equivalent diameter less than 0.3 mm and macrofibers are fibers with an equivalent diameter larger than 0.3 mm. Depending on their dimensions, microfibers can be up to three orders of magnitude more numerous than macrofibers in concrete at an equivalent fiber dosage. Microfibers are devoted to control microcracks (1 to 100 microns) occurring prior the tensile peak strength of concrete. As they are very numerous, they can bridge most microcracks. Macrofibers, due to their size and limited number, mainly resist opening of macrocracks (100 microns to few mm) occurring after the tensile peak strength (Rossi 1998). Additional information about the effect of fibers on cracking can be found in ACI 544.4R and ACI 544.5R.

Fiber reinforcement may not affect the formation of cracks; however, it certainly influences the way newly formed cracks grow and open. Fibers, therefore, improve crack growth resistance, increase surface roughness of individual cracks, and create a greater likelihood for crack branching (a crack separating into multiple finer cracks) and multiple crack development (numerous finer cracks on a surface instead of one large crack). According to Poiseuille's law, there is a cubic relationship between permeability rate and an idealized single-valued opening between two smooth parallel walls (Tsukamoto and Wörner 1991). Thus, modifying crack morphology in concrete (opening, roughness, and tortuosity) should have a major impact on water penetration. Indeed, crack openings are reduced by 2, 29, and 80 percent with increasing steel fiber dosage from 0 to 0.75, 1.5, and 2 percent in concrete (Hubert et al. 2015). Moreover, crack surface roughness increases from one to three orders of magnitude in synthetic and steel fiber-reinforced concrete (SFRC) depending on the fiber type and dosage (Tsukamoto and Wörner 1991; Charron et al. 2008). Therefore, finer cracks with roughened surface that result from crack branching in fiber-reinforced concrete (FRC) reduce water, ionic, and gas penetration