NISS

Permeability of Cracked Steel Fiber-Reinforced Concrete

Julie Rapoport, Corina-Maria Aldea,
Surendra P. Shah, Bruce Ankenman,
and Alan F. Karr

Technical Report Number 115
January, 2001

National Institute of Statistical Sciences
19 T. W. Alexander Drive
PO Box 14006
Research Triangle Park, NC 27709-4006
www.niss.org

Permeability of Cracked Steel Fiber–Reinforced Concrete

Julie Rapoport,[1] Corina–Maria Aldea,[2] Surendra P. Shah,[1] Bruce Ankenman,[3]
and Alan F. Karr[4]

Abstract

This research explores the relationship between permeability and crack width in cracked, steel fiber–reinforced concrete. In addition, it inspects the influence of steel fiber reinforcement on concrete permeability. The feedback–controlled splitting tension test (also known as the Brazilian test) is used to induce cracks of up to 500 microns (0.02in) in concrete specimens without reinforcement, and with steel fiber reinforcement volumes of both 0.5% and 1%. The cracks relax after induced cracking. The steel fibers decrease permeability of specimens with relaxed cracks larger than 100 microns.

Keywords: permeability, fiber-reinforced concrete, steel fibers

---

[1] NSF Center for Advanced Cement–Based Materials, Northwestern University, 2145 Sheridan Rd., Evanston, IL, 60208–4400, USA

[2] Saint Gobain Technical Fabrics, P. Box 728, St. Catharines, Ontario, L2R -6Y3, Canada

[3] Department of Industrial Engineering and Management Science, Northwestern University, 2145 Sheridan Rd, Evanston, IL, 60208–4400, USA

[4] National Institute of Statistical Sciences, PO Box 14006, Research Triangle Park, NC, 27709–4006, USA

1 Introduction

Fiber–reinforced concrete is becoming an increasingly popular construction material due to its improved mechanical properties over unreinforced concrete and its ability to enhance the mechanical performance of conventionally reinforced concrete. Though much research has been performed to identify, investigate, and understand the mechanical traits of fiber–reinforced concrete, relatively little research has concentrated on the transport properties of this material.

Material transport properties, especially permeability, affect the durability and integrity of a structure. High permeability, due to porosity or cracking, provides an ingress for water, chlorides, and other corrosive agents. If such agents reach reinforcing bars within the structure, the bars corrode, thus compromising the ability of the structure to withstand loads, which eventually leads to structural failure.

Building codes require that cracks exposed to weathering be no larger than specified widths in order to assure mechanical structural integrity. However, if cracks of this size significantly increase permeability and allow corrosive agents to reach steel reinforcement, the cracks are clearly too large and the codes should be revised. Knowledge pertaining to permeability can help determine the maximum allowable size of exposed cracks in structures.

In addition, if concrete casings are uses as shielding containers for pollutants and toxic wastes, permeability is of utmost importance in order to assure that no potentially harmful leakage occurs.

Because of the important role played by permeability in structural safety, and the increasing use of fiber–reinforced concrete, this paper examines the effects of different fiber volumes (0%, 0.5%, and 1%) of steel fibers in fiber–reinforced cracked specimens. Specimens were cracked to six different levels—0, 100, 200, 300, 400, and 500 microns—using the feedback–controlled splitting tension test, also known as the Brazilian test. The specimens were then tested for low pressure water permeability.

It was thought that increasing the volume of steel fibers would decrease the permeability of the cracked specimens due to crack stitching by the steel fibers. In addition, previous work performed by Aldea *et al.* showed that a permeability threshold exists for crack width: cracks under 100 microns in cement paste, mortar, normal strength, and high strength concrete had little effect on permeability [Aldea, 1999]. Cracks over 100 microns affected permeability significantly. It was expected that this threshold would still exist for the fiber–reinforced concrete because the steel fibers do not change material porosity.

2 Experimental Methods

Three test series were investigated for permeability: concrete with no fibers (control), concrete with a steel fiber volume of 0.5% (V_f=0.5%), and concrete with a steel fiber volume of 1% (V_f=1%). Ordinary type I Portland cement was used. Washed, graded pea gravel with a 3/8 inch (9.5mm) maximum size was used as coarse aggregates. River sand was used as fine aggregates. The steel fibers were manufactured by Bekaert and were two inches (50mm) long, 0.5mm (0.02in) wide, and had hooked ends. A small amount of superplasticizer was used. Table 1 shows the mix design for each test series. Each test series was cast into 100 $\times$ 200mm (4x8in) cylinders, which were

Figure 1: Brazilian splitting tensile test setup.

demolded after 24 hours and cured at room temperature underwater in a 100% relative humidity room until the time of sample preparation. Samples were tested eight to ten months after casting.

2.1 The Splitting Tension Test (Brazilian Test)

Specimens were cut to two inches (50mm) in thickness with a circular saw. They were then cracked to a specified crack mouth opening displacement (CMOD) of 100, 200, 300, 400, or 500 microns using the Brazilian splitting tension test. Figure 1 shows the experimental apparatus for the Brazilian test. A specimen was loaded in a 4.448MN (1000 kip) MTS compressive testing machine, with a 489kN (110 kip) load cell. A 100x25mm (4x × 1in) strip of plywood was placed between the specimen and the steel platens on both the top and bottom of the specimen to evenly distribute the load across the loading areas of the specimen. The Brazilian test compressed a circular specimen, which caused tensile stresses throughout the center region of the specimen. This induced cracking in the specimen. (See Wang *et al.*) A strain gauge extensometer, with maximum displacement of 0.5mm (0.02in), or a linear variable differential transducer (LVDT), with maximum displacement of 1mm (0.04in), was attached to each face of the specimen to measure crack width. The average displacement of the two strain gauges or LVDT's was used as a feedback signal to control the cracking. Cracks were induced at an opening rate of 0.1375μ/sec (0.00349in/sec) to the specified CMOD and the loading and cracking histories were recorded. The strain gauges were used to induce cracks up to 300 microns. The LVDT's were used to induce the 400 and 500 micron cracks. After the cracks were induced, the specimens were unloaded and the cracks relaxed somewhat. The relaxation was measured.

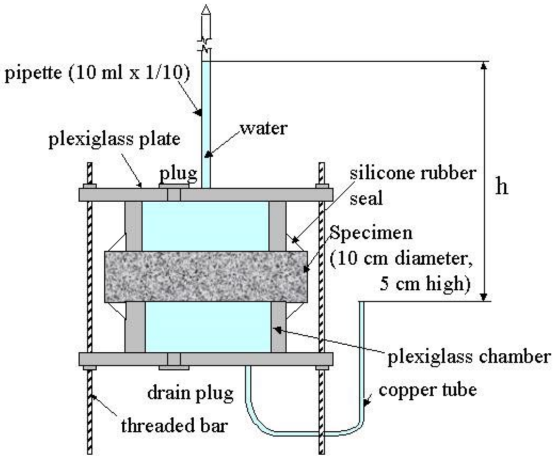

Figure 2: Water permeability test setup.

2.2 The Water Permeability Test

After the specimens were cracked, they were prepared for the water permeability test. Specimens were vacuum saturated following the procedure set forth in ASTM C 1202, the standard for the rapid chloride permeability test [Standard]. Specimens were placed in a vacuum jar and pumped down to a vacuum of about 1mm Hg for 3 hours. Deionized water was then added to the jar and the vacuum was maintained for one more hour, after which the vacuum pump was turned off and the specimens remained in the water for another 18 hours.

After saturation, each specimen was removed to a water permeability test setup shown in Figure 2, which is fully described by Wang *et al*. To test permeability, the system was filled with water. Additional water was added to the pipette. The water flowed through the concrete and out the copper tube. The change in water level in the pipette was used to calculate the water flow through the specimen, and thus, the permeability of the material. After the initial water level in the pipette dropped by a specific amount, more water was added to the pipette with a syringe.

The initial permeability of the system was much higher than the final permeability. It is possible that the specimens were not perfectly saturated when the tests began. As such, water was run through the system until the permeability leveled off to an approximately constant value. In general, water was run through each specimen for about 24 hours before data were taken. In specimens with large cracks, where the water flowed quite quickly, water had to be added to the system several times over these 24 hours. Once the permeability seemed to reach its final value, ten readings were taken and averaged to find the permeability coefficient of the material.

The calculations to determine permeability coefficient are detailed by Aldea *et al.* (Aldea, 1999). The water flow through the system is assumed to be continuous and laminar; therefore, Darcy's law can be applied. Because the flow is continuous, the amount of water flowing out of the pipette is shown to be:

$$dV = A'\left(\frac{dh}{dt}\right), \tag{1}$$

where V is the total volume of water that travels through the sample, A' is the cross-sectional area of the pipette, h is the head of water formed by the height of the chamber and water in the pipette, and t is the time required for a certain amount of water to travel through the system.

Darcy's law states:

$$Q = kA\frac{h}{l}, \tag{2}$$

where Q is the flow rate through the specimen (dV/dt), k is the permeability coefficient and the parameter under study, l is the thickness of the specimen, and A is the cross-sectional area of the concrete.

By combining and integrating these equations, the permeability coefficient is found to be:

$$k = \left(\frac{A'l}{At}\right)\ln\left(\frac{h_0}{h_i}\right), \tag{3}$$

where h_0 and h_i are the heads of water at the beginning and end of the test, respectively.

In addition, the theoretical flow rate of a liquid through a cracked material is found to be proportional to the cube of the crack width, which indicates that the permeability of a specimen with a larger crack will have a much greater permeability than a specimen with a smaller crack (Aldea, 2000).

3 Results and Discussion

Cracks were induced to a specified CMOD. The cracks then relaxed somewhat once they were unloaded. Figure 3 shows CMOD vs unloaded crack width for all three test series. The unreinforced concrete (no steel fibers) shows the most crack relaxation where the cracks relax by about 62% on average. The cracks in the concrete with steel fibers seem to relax less, with an average relaxation of about 55%. This indicates that the fiber-reinforced concrete undergoes more inelastic (unrecoverable) deformation than the unreinforced concrete. The data shown in the following graphs are of permeability versus *relaxed* crack width.

Two specimens in each test series were cracked to each specified CMOD. The cracks relaxed and the samples were tested. (The final CMOD after relaxation for each crack level was quite close for each treatment. The difference in CMOD of relaxed cracks was generally no more than 5 microns for the 100 micron cracks, and 20 microns for the cracks larger than 100 microns.) The data for each test series are shown in Figure 4. Two features are of interest. The first is that, at higher levels of cracking, steel reinforcing fibers clearly reduce permeability. Further, the 1% steel fiber test series reduces permeability more than the 0.5% test series. More steel reduces permeability. This is most likely due to the stitching and multiple cracking effect that the steel

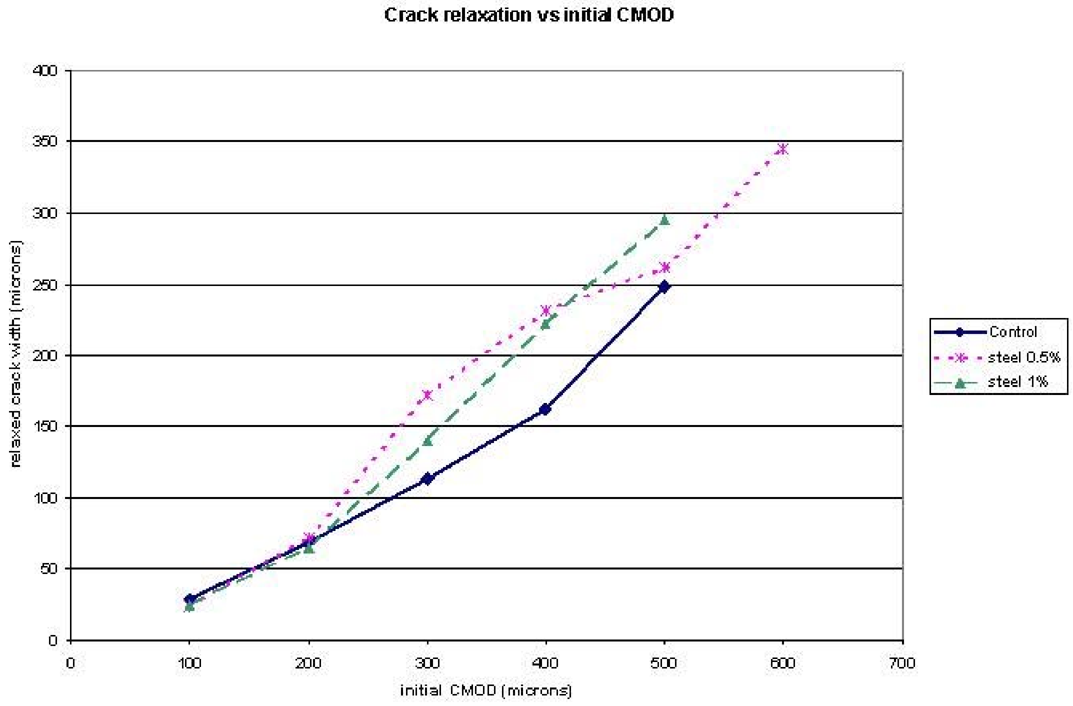

Figure 3: Initial CMOD vs. crack relaxation.

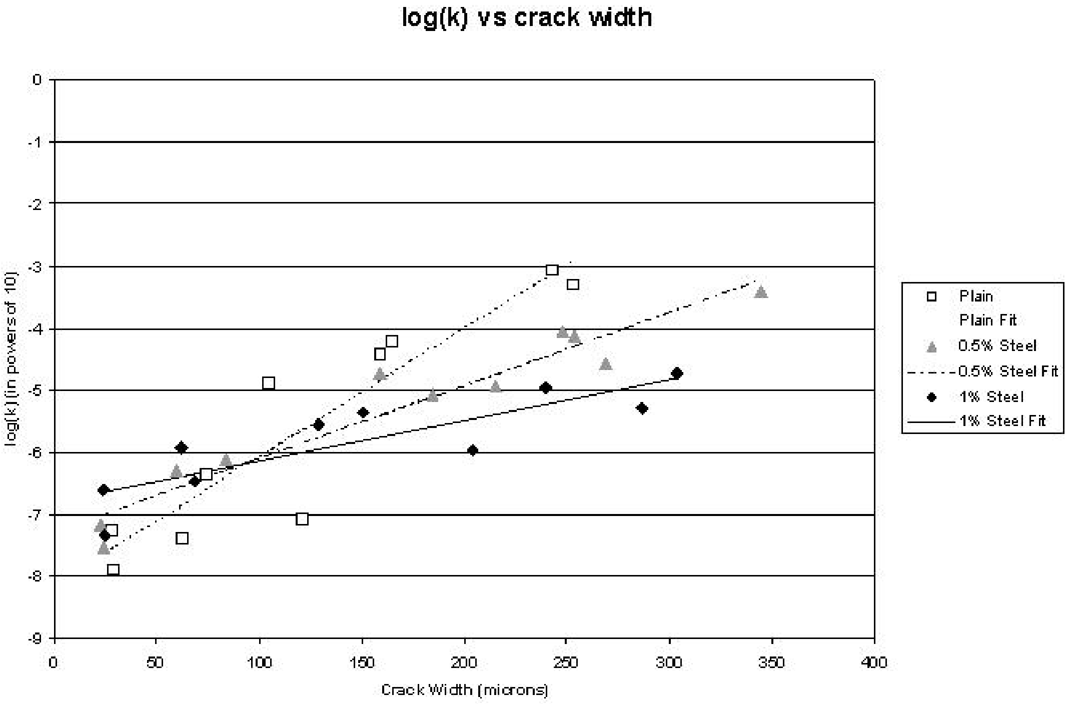

Figure 4: Permeability vs. crack width.

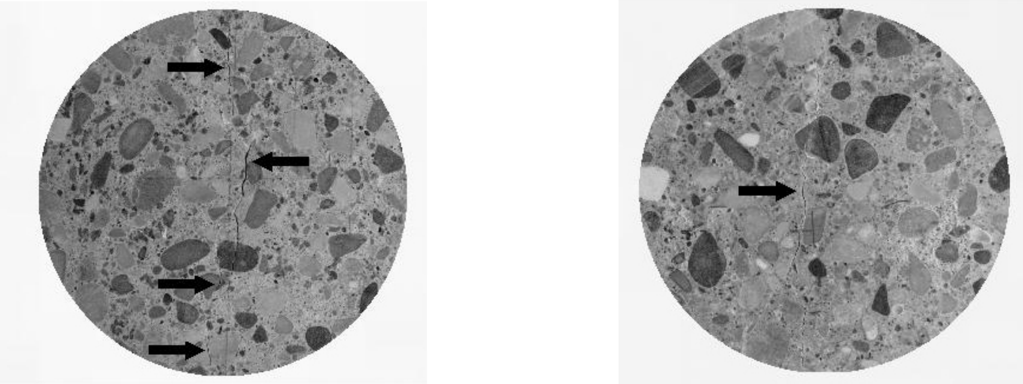

Figure 5: *Left:* (a) Multiple cracking in steel 1% specimen cracked to 500 microns. *Right:* Single crack in unreinforced specimen cracked to 500 microns

.

fibers have. The steel fibers might stitch the cracks at the ends, perhaps shortening the length of the crack, and reducing crack area for permeability.

In addition, the steel fibers induce multiple cracks in the concrete. The steel fibers distribute the stress evenly throughout the material. Instead of the stress building around the biggest flaw and causing a large crack to open there, the stress builds around several flaws and causes several smaller cracks to open. Figure 5a) shows a steel 1% specimen cracked to 500 microns exhibiting multiple cracking. The cracks have been highlighted to make them easier to see. Figure 5b) shows a control (unreinforced) specimen, also cracked to 500 microns. Only one large, central crack is visible. Because permeability is related to the cube of the crack width, several smaller cracks will be less permeable than one large crack. Therefore, it is not surprising that steel fibers should reduce the permeability of cracked concrete. It is possible that a higher fiber volume will further reduce the permeability of cracked concrete. However, at some fiber volume, an optimum might be reached, above which more fibers will increase permeability. Others have shown such optima to exist in microfiber reinforced concrete (Tsukamoto, 1990, 1991).

The other feature of interest in Figure 4 is that below a crack width of about 100 microns, steel reinforcing fibers do not seem to affect permeability much at all. Aldea *et al.* showed a similar occurrence with unreinforced concrete, mortar, and paste. This indicates that below cracks of 100 microns, reinforcing does not affect permeability (Aldea, 1999).

Statistical tests were performed on the slopes of the permeability lines shown on the semi-log scale in Figure 4. The tests found that the permeability of cracked concrete decreases with increasing fiber volumes. The tests are run at a 95% confidence level for cracks wider than 100 microns. For cracks smaller than 100 microns, the permeability difference is not statistically significant at the 95% confidence level. A thorough explanation of the statistical test is located in Appendix A.

4 Conclusions

Two major conclusions can be drawn from this research:

1. At larger crack widths, steel reinforcing macrofibers reduce the permeability of cracked concrete. The higher steel volume of 1% reduces the permeability more than the lower steel volume of 0.5%, which is still lower than the permeability of unreinforced concrete. This is probably due to the crack stitching and multiple cracking effects of steel fiber reinforcement. The permeability differences above 100 microns in all test series are statistically significant at the 95% confidence level.

2. Below cracks of about 100 microns, steel reinforcing macrofibers do not seem to affect permeability of concrete.

5 Acknowledgements

The research was performed at Northwestern University, the headquarters of the NSF–Funded Center for Advanced Cement–Based Materials. Support from the NSF through grant DMS–9313013 to the National Institute of Statistical Sciences is greatly appreciated. The authors wish to thank Steve Hall, Steve Albertson, John Chirayil, and Joclyn Oats for their great help with sample preparation and apparatus design.

References

Aldea, C-M., Shah, S. P., and Karr, A. F. “Permeability of cracked concrete,” *Materials and Structures*, **32** (1999) 370–76.
Aldea, C-M., Gandehari, M., Shah, S. P., and Karr, A. F. “Estimation of water flow through cracked concrete under load,’*ACI Materials Journal*, **97(5)** (2000) 567–75.
“Standard method for electrical indication of concrete’s ability to resist chloride ion penetration,” ASTM C 1202–94, *Annual Book of ASTM Standards* (1994), 04.02, 620–625.
Tsukamoto, M. “Tightness of fibre concrete,” *Darmstadt Concrete: Annual Journal on Concrete and Concrete Structures*, **5** (1990) 215–225.
Tsukamoto, M., Wörner, J.-D. “Permeability of cracked fibre–reinforced concrete,” *Darmstadt Concrete: Annual Journal on Concrete and Concrete Structures*, **6** (1991) 123–35.
Wang, K., Jansen, D. C., and Shah, S. P. “Permeability study of cracked concrete,” *Cement and Concrete Research*, **27(27)** (1997) 381–93.

A Appendix: Statistical Significance of Permeability Differences

For each fiber content, a regression line was fit to the log (base ten) of the permeability. Each data point and the three regression lines are plotted in Figure 4. The regression provides a slope with a standard error and an intercept with a standard error for the three concrete mixes, each containing a different level of steel fiber (see Table 2).

As the amount of steel fiber increases, the slope of the regression line decreases indicating that for large cracks (greater than about 100 microns), steel fibers reduce the permeability. To determine if the slopes of the regression lines are significantly different for the different amounts of steel fiber, confidence intervals were created for the difference between the slopes of the regression lines. A 95% confidence interval for the difference between two slopes, with standard errors m_1 and m_2, respectively, is calculated as follows:

$$m_1 - m_2 \pm t_{0.25,\mathrm{df}}\sqrt{s_1^2 + s_2^2}.$$

The quantity $t_{0.25,\mathrm{df}}$ is the 0.975 quantile of the t distribution with df degrees of freedom. If the regression for m_1 has n_1 data points and the regression for m_2 has n_2 data points, then

$$\mathrm{df} = \frac{(s_1^2 + s_2^2)^2}{\left(\frac{s_1^4}{(n_1-2)} + \frac{s_2^4}{(n_2-2)}\right)}.$$

The first row of Table 3, shows the confidence intervals for the difference between the slopes for plain concrete and concrete containing 0.5% steel fiber. The second row shows the confidence interval for the difference between the slopes for concrete containing 1.0% steel fiber and 0.5% steel fiber. Neither confidence interval contains zero which confirms the conclusion that increasing the percentage of steel fiber in the concrete significantly (95% confidence) increases the slope of the lines.

The regression lines cross at about 100 microns suggesting that below 100 microns addition of steel fiber actual increases the permeability. However, when confidence intervals for the differences between the intercepts of the regression lines are calculated, we find that the differences in the intercepts are not significantly different from zero. Based on this, a reasonable conclusion is that steel fibers actually have little or no effect on permeability of concrete with cracks smaller than 100 microns.

Mix	Cement	Water	Sand	Gravel	Superplasticizer	Steel Fiber Volume
Control	1	0.45	2	2	0.006	—
Steel 0.5%	1	0.45	2	2	0.006	0.5%
Steel 1.0%	1	0.45	2	2	0.006	1.0%

Table 1: Mix proportions by weight, with steel fibers by volume

Steel Fiber Level	Intercept	Standard Error of the Intercept	Slope	Standard Error of of the Slope	Number of Data Points
Plain	-8.1322	0.4462	0.020657	0.003064	10
0.5%	-7.2691	0.2181	0.011784	0.001097	10
1.0%	-6.8022	0.2482	0.006601	0.001381	10

Table 2: Regression Results

Comparison of Slopes	Difference ($m_1 - m_2$)	Standard Error of the difference ($\sqrt{s_1^2 + s_2^2}$)	df	$t_{0.025,\text{df}}$	Confidence interval of the difference
0.5% Steel - Plain	0.0089	0.0033	10.0	2.23	(0.0016, 0.0161)
1.0% Steel - 0.5% Steel	0.0052	0.0018	15.7	2.13	(0.0014, 0.0089)

Table 3: Confidence intervals for the differences in the slopes