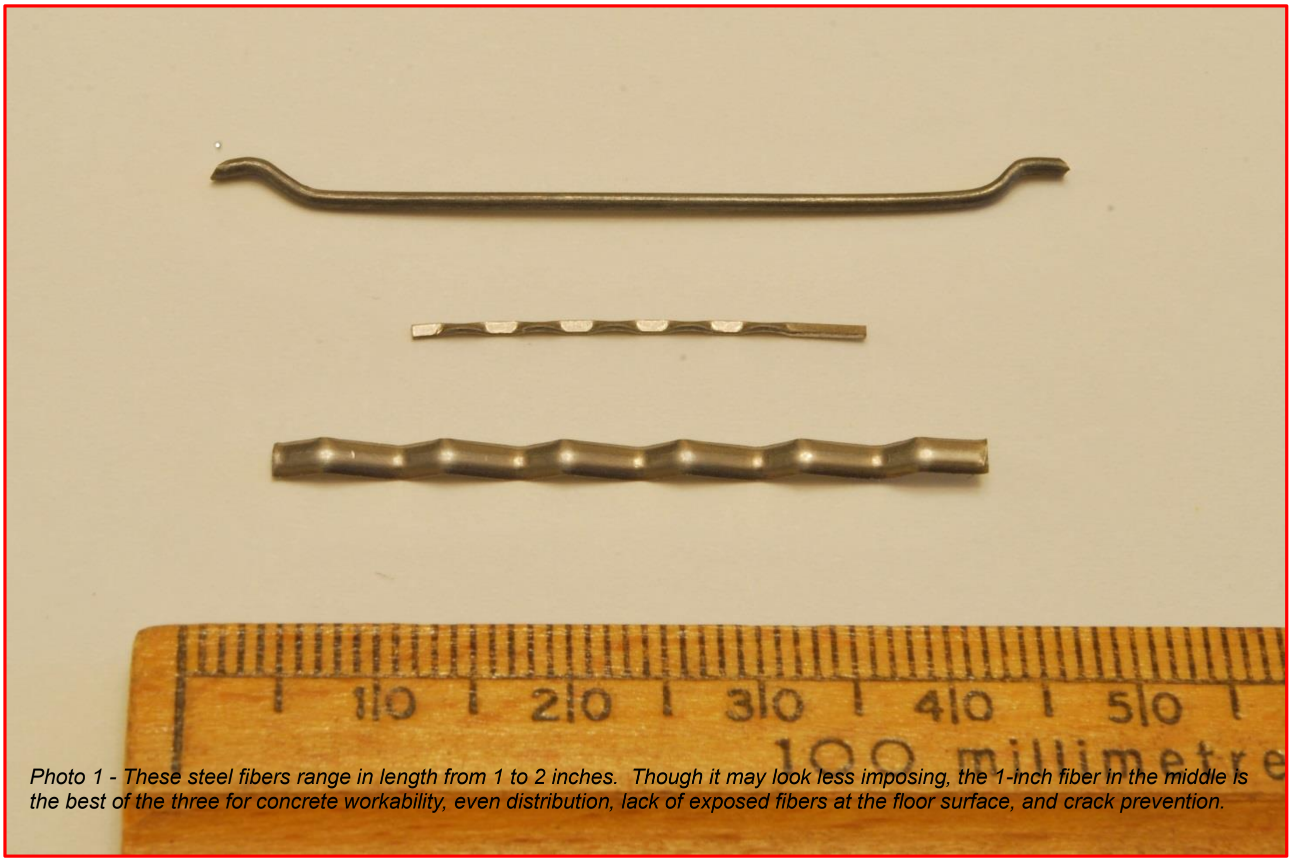

Photo 1 - These steel fibers range in length from 1 to 2 inches. Though it may look less imposing, the 1-inch fiber in the middle is the best of the three for concrete workability, even distribution, lack of exposed fibers at the floor surface, and crack prevention.

THE LONG AND SHORT OF IT:

How Steel-Fiber Length and Strength Affect Concrete Floors

Suppose you had to choose between two products, sight unseen. One is said to be long and strong; the other, shorter and not as strong. No further information is provided.

Given that choice, you might be tempted to pick the first product. Long and strong -- that has a certain ring to it.

But if the products in question are steel fibers, those attractive adjectives can steer you wrong. Though fiber length is a complicated subject, for most purposes shorter fibers work better than longer ones. And strength turns out not to matter at all.

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FIBER LENGTH

The steel fibers sold for use in floors range in length from 1 to 2-1/2 inches. The 2-1/2-inch dimension seems close to the practical upper limit. Beyond it, tangling becomes a big problem. In contrast, the 1-inch dimension is nowhere near the lower limit. Fibers less than 1-inch long are usable and may even offer advantages -- a subject we will get to later. But for now, the market offers steel fibers from 1 to 2-1/2 inches long.

Within that range, fiber length affects concrete floors in at least five ways:

- Concrete workability;
- Fiber distribution;
- Exposure of fibers at floor surface;
- Crack prevention;
- Residual strength or flexural toughness.

Four of those ways favor shorter fibers. Only the last, residual strength, goes the other way and supports an argument for longer fibers.

FIBER-RELATED EFFECTS THAT FAVOR SHORTER FIBERS

Short fibers outperform long ones when it comes to concrete workability, fiber distribution, exposure of fibers at the floor surface, and crack prevention.

The American Concrete Institute defines workability as "that property of freshly mixed concrete...which determines the ease and homogeneity with which it can be mixed, placed, compacted, and finished." Fibers make concrete less workable -- a statement that holds for every kind of fiber, and for every length. But the effect on workability varies hugely with fiber type, dosage, and length. Shorter fibers reduce workability less than longer fibers, and the difference can be dramatic. When you hear concrete finishers complain that steel fibers make their jobs hard, you almost always find that their bad experiences occurred with fibers at least 2 inches long.

Fibers work best when dispersed evenly throughout the concrete mix. Sometimes this ideal is not achieved, and there can be two causes for that -- both related to fiber length. This first cause goes back to workability. If a mix has low workability, fibers may not spread evenly throughout the batch. That problem is more likely with longer fibers, simply because they have a larger effect on workability. The second cause involves fiber balling. Fibers can tangle and form balls. Balling is rare with short fibers, but common with long ones. Balling is the main reason that fiber length tops out at about 2-1/2 inches. To reduce balling, some manufacturers supply their longest fibers in collated form. This means the fibers are stuck together in small groups, using a weak glue. The idea is that the glue holds the fibers together long enough to prevent tangling, and then dissolves. Collation does indeed reduce balling, but it adds cost and complexity. Shorter fibers don't need to be collated.

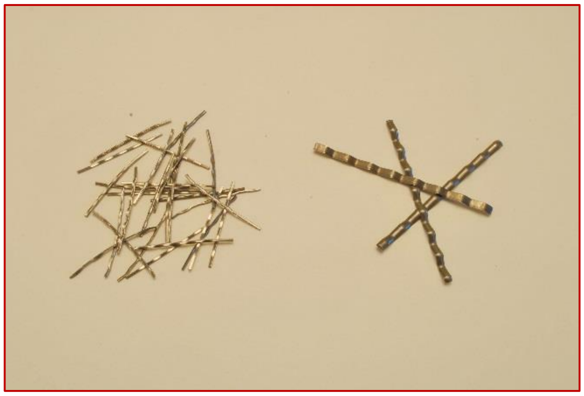


Photo 2 - Fibers on the left are 1 inch long. Those on the right are 1-1/2 inches long. Both piles weigh the same, but the shorter fibers are more numerous and, more importantly, their total length is greater, making them better at preventing cracks.

While concrete finishers worry about workability and fiber distribution, building owners fear exposed fibers. You hear stories of floors with fibers sticking up all over, and nobody wants that. More often than not, such stories turn out to be about fibers made of plastic, not steel. But steel fibers can also show at the floor surface in numbers that people find objectionable, and that happens more often when the fibers are long. Some builders who prefer long fibers routinely apply dry shakes to their floors, just to cover up the fibers. That practice is so common in parts of Europe that many people there think a dry shake -- despite all its costs and risks -- is an essential part of a steel-fiber-reinforced floor. But you don't need a dry shake with shorter fibers.

Photo 3 - Exposed steel fibers, 2 inches long. Clearly more went wrong here than fiber length, but length was a contributing factor. Nothing as bad as this has ever been reported where 1-inch fibers were used.

So far we have looked only at what we might call the negative benefits of shorter fibers. Reduced workability, non-uniform fiber distribution, and exposure of fibers at the floor surface are all unwanted effects, and in each case the value of shorter fibers is that they make the unwanted effect less likely or less severe. That's good as far as it goes, but now we get to a positive benefit that lies at the heart of what steel fibers are meant for: crack prevention.

Steel fibers prevent cracks by stopping microcracks from growing into cracks you can see. Shorter fibers do this job better than longer ones, but the reason for that is not obvious and takes some explaining.

The key to preventing cracks is to make sure there are fibers near every microcrack. It's easy to stop microcrack growth if you nip it in the bud, and the way to do that is to have fibers all over. This leads some people to conclude that fiber count -- the number of fibers in a given volume of concrete -- is what matters most for crack prevention. And making fibers shorter, if everything else stays the same, will always increase fiber count.

So is fiber count the reason short fibers are better at preventing cracks? No, that's not the whole story, as a quick thought experiment will reveal. Count out 100 steel fibers, 2 inches long. Now get out your snips and cut each fiber in half. At a stroke, you halved the fiber length and doubled the fiber count. But did you double the ability of those fibers to prevent cracks? No, because the total fiber length available to intercept microcracks did not change. It was 200 inches (100 pieces each 2 inches long), and it's still 200 inches (200 pieces 1 inch long). The shorter fibers might perform slightly better because they are more evenly distributed, but they would not be twice as effective.

What matters most for crack prevention is not the length of each fiber, but the total fiber length, which depends on fiber thickness. Thinner fibers result in more total length, as the graph shows. This effect is mathematically independent of individual fiber length.

Does that mean, then, that individual fiber length is largely irrelevant to crack prevention? The answer would be yes, if fiber length and diameter were independent variables -- but they aren't. In real life, when you make fibers longer you have to make them thicker, too. If you don't, the long thin fibers will tangle. The difference can be dramatic. A CFS 100-2 fiber, which is 1 inch long, has an equivalent diameter of 0.023 inch. Another widely used fiber, which is 2 inches long, has an equivalent diameter of 0.045 inch. A pound of CFS 100-2 fibers, laid end to end, would measure 692 feet. A pound of the longer fibers, also laid end to end, would measure just 181 feet. Pound for pound, the shorter fibers provide almost four times as much total length. That makes them better at preventing cracks.

Ironically, short fibers are better at crack prevention because they are really long -- long in the way that counts the most.

We have, then, four good reasons to prefer short fibers over long ones. If that were the whole story, arguments over fiber length would vanish. Everyone would use short fibers. But there is one more length-related effect to consider.

THE EXCEPTION -- RESIDUAL STRENGTH

Some floor designers rely on a property called residual strength or flexural toughness. This is the ability of fiber-reinforced concrete to resist bending after it has cracked. If you bend unreinforced concrete till it cracks, its resistance to further bending drops to zero, and so we say that unreinforced concrete has zero residual strength. But if you bend fiber-reinforced concrete till it cracks, fibers bridge the crack and provide some resistance to further bending. That resistance is called residual strength, and you can measure it.

Longer fibers improve residual strength in standard tests. That is the main reason -- practically the only reason -- to use long fibers.

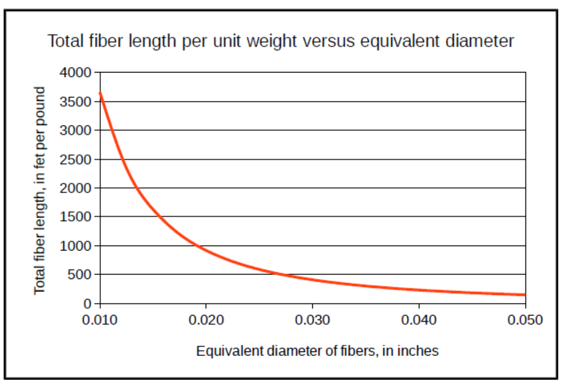
But is it a good reason? That depends on whether you believe in residual strength.

OK, maybe "believe in" is too strong a phrase. Nobody denies that residual strength exists. But plenty of people question its effect on floor performance, the accuracy of the methods used to measure it, and its usefulness in floor design. At CFS, we doubt the value of residual strength and think it can lead to underdesigned floors. We recommend designing fiber-reinforced floors the same as unreinforced floors. Make the slab thick enough so that the bending stress does not exceed the concrete's modulus of rupture, with a reasonable safety factor. If you do that, residual strength becomes irrelevant and longer fibers confer no benefit.

GO SHORT

For every purpose but one, shorter fibers are the better choice. To get workable concrete, go short. To avoid balling and get an even distribution of fibers throughout the concrete mix, go short. To see the fewest exposed fibers on the floor surface and avoid the complications of a dry shake, go short. And -- last but definitely not least -- if you want to prevent cracks, go short.

Should you ever go long? Maybe -- if you find the arguments for residual strength persuasive, and if your floor design relies on high test results for that property, and if you are willing to put up with all the drawbacks. Even then the case is hardly overwhelming, though, because short fibers also provide residual strength and can match the results obtained with long fibers, though a higher dose may be needed.



This graph shows how the total length of fibers available to intercept cracks goes up as fibers get thinner. To make fibers thin without raising the risk of tangles, you have to make them short. To move left on the graph, you need shorter fibers.

HOW SHORT?

If 1-inch fibers work better than longer ones, why stop there? The graph above shows that if we could get equivalent diameters below 0.020 inch, we could see dramatic increases in total fiber length. That would only be possible with fiber lengths well under 1 inch. Such fibers can be made, so why not use them?

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It's a good question, but more research is needed to answer it. Experiments with extremely short fibers suggest they can greatly improve concrete strength, but no one has tried them on a full-size floor slab. Presumably there is some minimum length below which fibers become less effective, but we don't yet know what it is.

What we do know is that 1-inch fibers work well and have been used successfully on millions of square feet. For now, 1 inch is the length to use. But stay tuned, because that could change.

STRENGTH

Compared to fiber length, fiber strength is simple. It just doesn't matter.

The steel fibers now on the market range in tensile strength from 90 to 300 ksi. That's quite a spread, but it's less significant than it looks because strength has almost no effect on real-world performance. Steel fibers almost never fail from being too weak. They fail from being pulled loose. The limiting factor is not the strength of the steel, but the anchorage.

Undoubtedly there is some critical strength below which fibers would break before the anchorage failed. But all available steel fibers exceed that critical strength, so there is no reason to choose between them based on strength.

ASTM A820, "Standard Specification for Steel Fibers for Fiber-Reinforced Concrete", confirms this view. The ASTM standard requires the same minimum strength for all steel fibers, regardless of type or size. The average tensile strength needs to be at least 50 ksi, and no test result should fall below 45 ksi. That's it. ASTM A820 doesn't rank fibers by strength, or imply that stronger fibers are better or different in any meaningful way. It doesn't even list strength as a property that buyers might wish to specify.

When choosing steel fibers, don't be misled by words that make good advertising copy. Pay attention to the properties that really affect performance. For most purposes, short fibers beat long ones, and strength doesn't matter.