A novel double anchored steel fiber for shotcrete

N. Banthia and H. Armelin

Abstract: Given the high deformability requirements of shotcrete in repair, rehabilitation, slope stabilization, ground support, and other applications, the use of fibers in shotcrete is growing. Growing also are challenges surrounding the use of fibers in shotcrete not the least of which are a high fiber rebound in the dry process, lack of standardized test techniques, and a poor understanding of reinforcement mechanisms. In the context of rebound, unfortunately, the requirements for a low rebound often clash with the requirements for a high material toughness. This paper describes a new fiber developed at The University of British Columbia where a rational balance was sought between the conflicting requirements of rebound reduction and a high material toughness. The new fiber is based on a double anchoring principle and is optimized for both reduced rebound and a high toughness in hardened shotcrete.

Key words: shotcrete, fiber reinforcement, steel fiber, toughness, rebound.

Résumé : Étant donné les exigences de haute déformabilité auxquelles le béton projeté est soumis pour des travaux de réparation, de réhabilitation, de stabilisation de pente, de consolidation de terrain et d'autres applications, le recours aux fibres dans le béton projeté est grandissant. Grandissants, également, sont les défis qui tournent autour de l'utilisation de fibres dans béton projeté, parmi lesquels, et non les moindres, sont : un important rebond de fibre en voie sèche, le manque de techniques d'essai standardisées et une compréhension insuffisante des mécanismes de renfort. Dans le contexte du rebond, malheureusement, les exigences en faible rebond sont souvent incompatibles avec les exigences en haute dureté du matériau. Cet article décrit une nouvelle fibre développée à l'Université de Colombie Britannique où un équilibre rationnel a été cherché entre les exigences conflictuelles de réduction du rebond et de haute dureté du matériau. La nouvelle fibre est basée sur un principe de double ancrage et est optimisée pour un rebond réduit et une haute dureté du béton projeté durci.

Mots clés : béton projeté, renforcement par fibre, fibre d'acier, dureté, rebond.

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Introduction

Shotcrete, when used as ground covering or support, is subjected to both quasi-static ground movements and dynamic ground deformations often of large magnitudes. Not surprisingly, the requirements of material deformability, toughness, and energy absorption are often greater in fiber-reinforced shotcrete than in conventional fiber reinforced concrete.

One primary concern with the dry-process shotcrete is the high rebound; nearly 20–40% of material and up to 75% of fiber may be lost through rebound (Armelin et al. 1997; Wolsiefer and Morgan 1993; Warner 1995). During rebound, high proportions of the fibers fail to become embedded in the resultant concrete and thus are wasted. A loss of fiber through rebound translates into a major loss of fracture toughness, deformability, and the post-crack load-carrying capacity in shotcrete.

While the issue of high rebound in dry-process shotcrete is well recognized, our understanding of the factors related to mix design (cement and silica fume contents, aggregate/cement ratio, etc.) and (or) placement variables (air pressure and volume, type of nozzle, distance and orientation of nozzle, etc.) that control rebound is far from adequate. Attempts have been made in the past to understand the kinematics of fast moving aggregate particles using high-speed photography and to model the process of rebound (Armelin et al. 1999; Armelin and Banthia 1998*a*). In the case of fibers, although fiber rebound has always been suspected to be related closely to fiber geometry, the exact influence of fiber geometry on fiber rebound is not well understood. In a previous study (Banthia et al. 1992), fiber rebound was shown to be proportional to its specific projected area defined as the fiber projected area for a unit mass. In a later, more comprehensive study (Armelin and Banthia 1998*b*), a specific fiber parameter called the modified aspect ratio ($l/\sqrt{d}$) was shown to be linearly related to fiber rebound. The results of this latter study (Armelin and Banthia 1998*c*) became the basis for designing the novel fiber described here.

On the toughness side, pullout of fibers across a matrix crack is recognized as the main mechanism that allows steel fiber reinforced shotcrete (SFRS) to be more ductile than unreinforced shotcrete. Thus, all commercial reinforcing fi-

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N. Banthia[1] and H. Armelin.[2] Department of Civil Engineering, The University of British Columbia, 2324 Main Mall, Vancouver, BC V6T 1Z4, Canada.

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[1]Corresponding author (e-mail: banthia@civil.ubc.ca).
[2]Present address: Target Products, 7550 Conrad Street, Burnaby, BC V5A 2H7, Canada.

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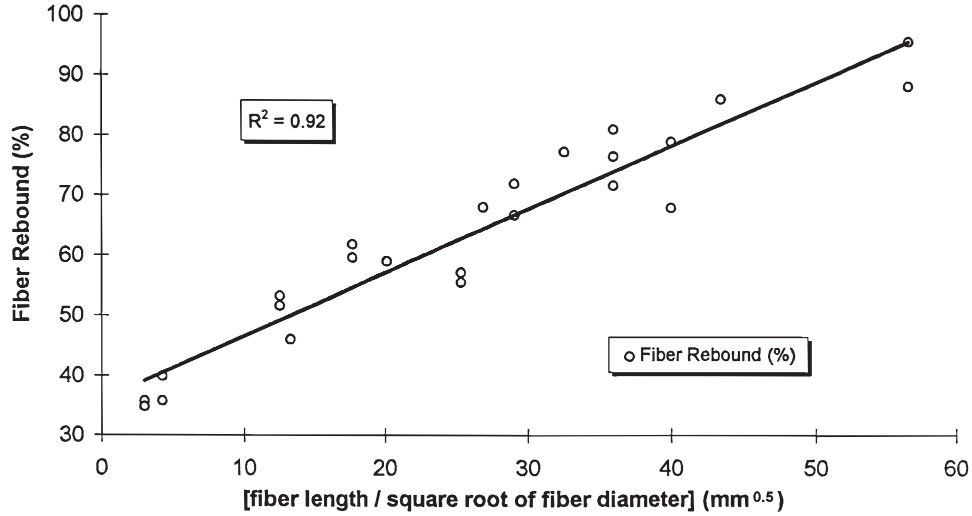
Fig. 1. Fiber rebound (percent by mass) vs. modified aspect ratio ($l_f/\phi^{1/2}$).



bers presently available in the market are deformed at the ends or along their length, to enhance the anchorage of the fiber with the cementitious matrix and generate a greater pullout resistance and energy (Naaman 1998). Unfortunately, the fiber geometrical requirements for a higher toughness (i.e., a high aspect ratio) are in direct conflict with those required for a reduced rebound (i.e., a low aspect ratio). Thus an optimized fiber geometry for cast concrete is not necessarily optimal for shotcrete.

Fiber rebound and its reduction

It is clear that the amount of fiber rebound seriously affects the toughness of the resulting in situ fiber reinforced shotcrete and rebound reduction is key to obtaining a highly toughened shotcrete. For a rational design of a shotcrete fiber from the objective of a reduced rebound, the results obtained by Armelin and Banthia (1998*c*) were considered. They conducted a series of experiments using circular cross section steel fibers having diameters of 0.5, 0.61, 0.65, 0.76, and 1 mm and lengths of 3, 12.5, 19, 24.5, and 40 mm. Fibers of each diameter were made to each length. Shotcrete was produced using the dry mix technique and the fiber rebound was evaluated for the above combinations of length and diameter. Their results are plotted in Fig. 1, where it can be seen that there is a substantially linear relationship between fiber rebound R_f and a modified aspect ratio given by fiber length divided by the square root of fiber diameter, i.e.,

$$[1] \qquad R_f = f l_f/\phi^{1/2}$$

where R_f is the fiber rebound, l_f is the fiber length, and ϕ is the fiber diameter.

It is apparent that a reduction in rebound R_f significantly increases the amount of fiber retained in the in-place shotcrete. For example, if the fiber rebound is reduced from the 75% figure that characterizes the fibers presently in the market to 50%, the in situ fiber content is doubled for the final shotcrete produced. Further, to reduce the fiber rebound to below about 70%, which is less than that of conventional fibers, the ratio of fiber length over the square root of fiber diameter ought to be below 30 $mm^{1/2}$.

Fiber anchorage mechanisms

The state-of-the-art in fiber design may be divided into two large groups with respect to their anchorage mechanisms, namely fibers that rely on a “dead anchor” and those that rely on a “drag anchor”. Dead anchors generally are produced by deforming the fiber with a hook or cone adjacent to each of its ends. Under stress, in an aligned fiber (i.e., under axial tension) the anchor is generally designed to fail (e.g., pullout) at a maximum resistance below the strength of the steel. However, these dead anchors, after failure, have a significantly reduced capacity to resist pullout displacement.

Drag anchors, on the other hand, generally are formed by enlarging the fiber adjacent to its end in such a way that during pullout, the enlargement generates friction with the matrix as the fiber is dragged out of the concrete. This type of fiber generally develops a lower maximum pullout resistance as compared to the dead anchor, but its effect tends to last for a greater pullout displacement and therefore greater pullout energy is consumed by the end of the pullout process.

The double anchorage fiber

In the new fiber developed at The University of British Columbia, the requirements for a lower rebound as discussed above were combined with the requirement for an optimal anchorage. The novel fiber, called the double anchorage fiber (or DD fiber — the two Ds representing a “drag” anchor and a “dead” anchor), is different from the other commercial fibers in that a low $l_f/\phi^{1/2}$ ratio is maintained and the two anchoring mechanisms (dead and drag) are rationally combined in the same fiber. For a reduced rebound, the ratio of fiber length to the square root of fiber diameter is kept less than 30 $mm^{1/2}$ (Fig. 1). The fiber thus may possess a length between 20 and 35 mm and a diameter of between 0.6 and 1 mm.

Fig. 2. A side view of the DD fiber.

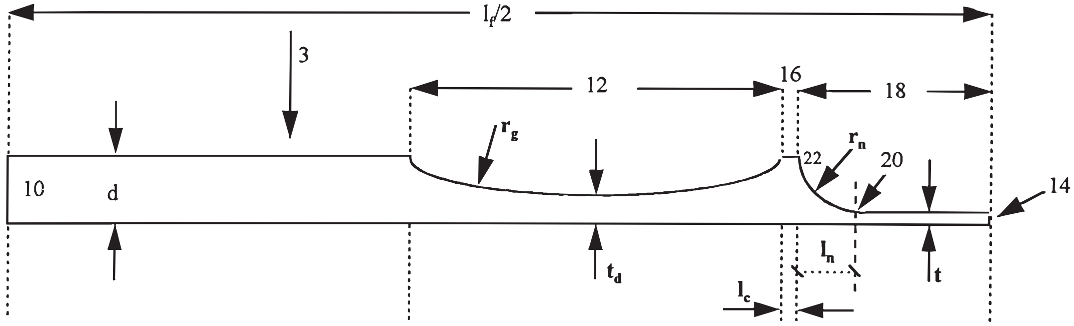
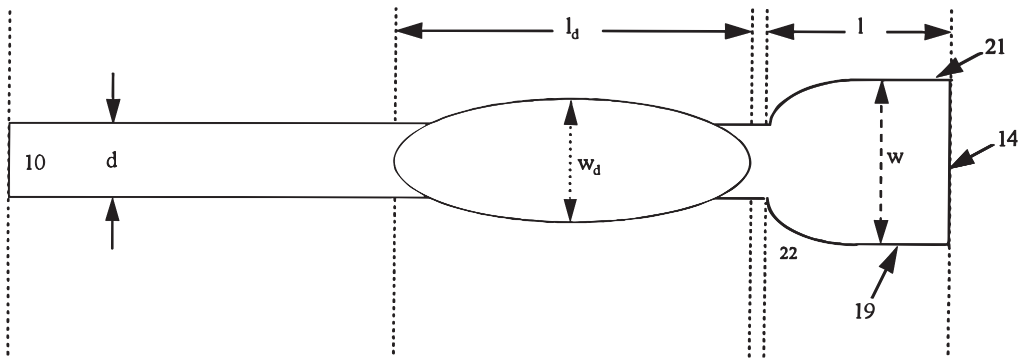


Fig. 3. Plan view looking at the direction of the arrow 3 in Fig. 2.



One half of the double anchorage (DD) fiber is shown in Figs. 2 and 3. The other half is essentially the same, as each fiber is symmetrical on opposite sides of its mid length. The fiber comprises both a dead anchor, 18, and a drag anchor, 12, placed at the end of the fiber and separated by a zone of stress concentration weak link, 16 (Fig. 2). The weak link, 16, is expected to fail under load. Failure of the weak link releases the dead anchor and activates the drag anchor. By properly proportioning the fiber, the weak link is constructed to fail at a load lower than the maximum load-carrying capability of the fiber.

The drag anchor is formed by a pair of laterally projecting side flanges in the same plane but on opposite sides of the longitudinal axis of the fiber. The laterally extending side flanges are formed by reducing the fiber thickness from d to t_d without producing areas of significant stress concentrations that would otherwise reduce the axial tensile strength of the fiber. The dead anchor is formed by a second pair of laterally projecting side flanges produced once again by reducing the thickness from d to t such that $t < t_d$ and the dead anchor is wider than the drag anchor, i.e., $w > w_d$.

The drag anchor functions in essentially the same way as a conventional drag anchor in conventional reinforcing fibers. However, the maximum drag force or axial force applied to the fiber in order to permit the drag anchor to be dragged through the concrete is less than the maximum force necessary to break the dead anchor. The incremental added forces that are carried by the dead anchor under peak conditions cause the stress in the weak link to exceed the allowable such that either the weak link breaks off or the dead anchor gets deformed or folded resulting in its release. Thus the dead anchor functions to reinforce the concrete until its failure occurs either by breakage at the weak link or by its own folding or deformation. In either case, as will be seen later, the energy that can be absorbed by the fiber is substantially greater than can be absorbed by conventional anchor structures. The combined anchor system permits the application of a higher total pullout load without the risk of fiber breakage as the dead anchor releases before the stress in the remainder of the fiber including the drag anchor exceeds its capacity. The drag anchor is designed to carry at least 80% of the peak load and preferably 90% or higher, so that the incremental load carried by the dead anchor is small and the load-carrying capacity of the fiber is not reduced dramatically when the dead anchor is released.

Figure 4 shows the pullout test data and demonstrates the effectiveness of combining the two anchors as done in the DD fiber in terms of an improved energy absorption capacity. The commercial fiber having only a drag anchor (curve 1 in Fig. 4 for the "flattened-end" (FE) fiber) provides a relatively gradual increase in stress as the displacement (pullout) is increased to about 1.5 mm. On the other hand, for a fiber with a dead anchor (curve 2 in Fig. 4 for the "hooked-end" fiber), the peak or maximum stress that can be applied is significantly higher, approximately 900 MPa (tensile strength of the steel used in all cases is 1100 MPa), but the displacement that can be tolerated is less than approximately 0.5 mm. In both cases, the nominal fiber stress quickly diminishes (more so for the dead anchor than the drag anchor) as displacement is increased beyond the point of peak stress. For the fiber having a combination of the dead and drag anchors (curve 3, Fig. 4), a very significant increase in stress that can be tolerated is noticed, i.e., the nominal stress for the fiber reaches above 1000 MPa while accommodating a

Fig. 4. Pullout displacement vs. nominal stress plots when only the “drag” anchor is present (curve 1), when only the “dead” anchor is present (curve 2), and when both anchors are combined as in a DD fiber (curve 3) (f_c' = 40 MPa).

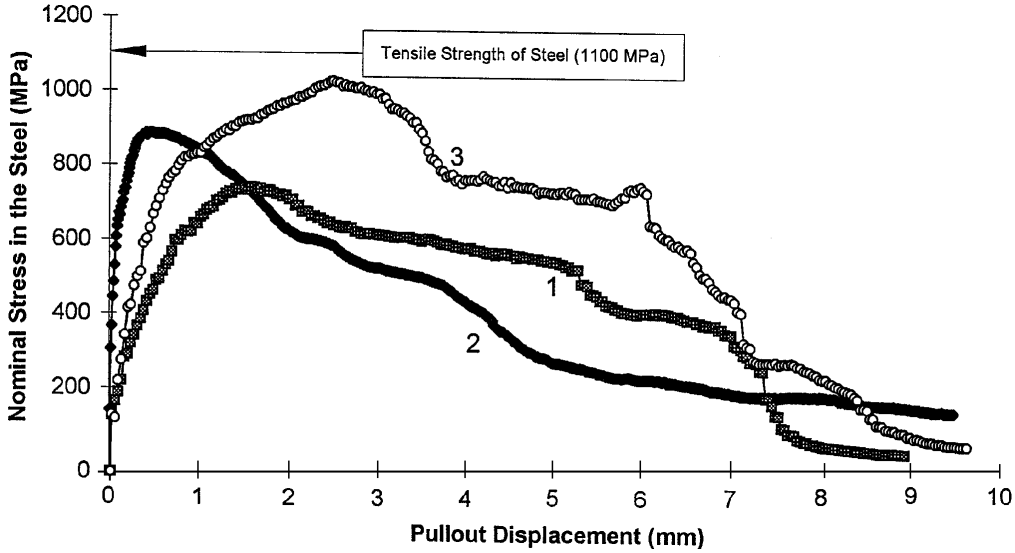
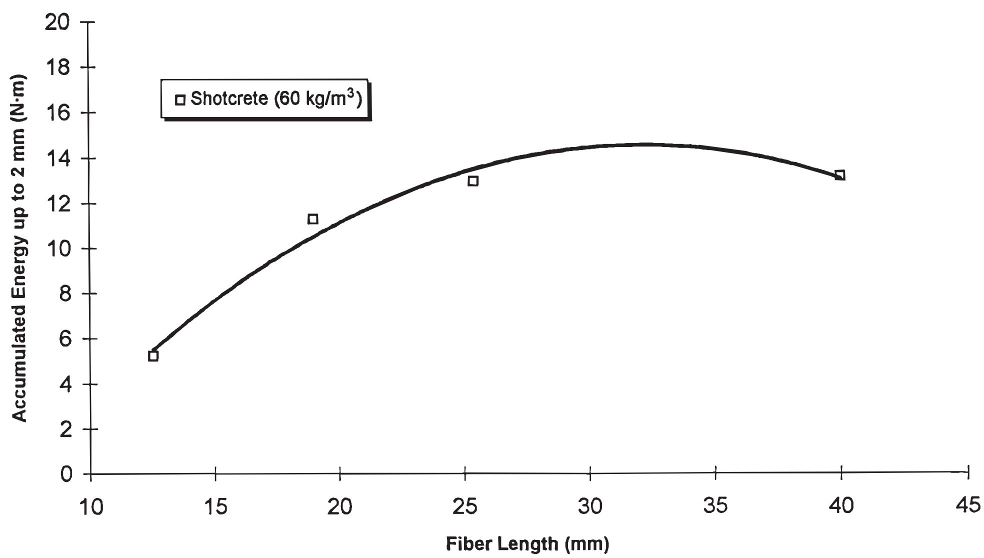


Fig. 5. Fiber length vs. shotcrete fracture energy for four different lengths of the DD fiber.



displacement of about 2½ mm. After this, the fiber stress drops off but does not reduce to that of the commercial drag anchor per se until a very substantial amount of pullout has taken place, i.e., of the order of about 7 mm. At the peak values of applied load, either the weak link fractures or the dead anchor is deformed and released, and this is expected to occur prior to the fiber reaching its tensile capacity or a general failure. It is apparent that significant improvements in the amount of pullout energy that can be absorbed is obtainable using the combination anchors as done in the DD fiber.

Further optimization

As noted before, the requirements for a reduced rebound conflict with those for a high toughness. To find the optimal balance, an experimental route was taken. Fibers were made from a fixed diameter wire with a 0.89 mm diameter formed with lengths of 12.5, 19, 25.4, and 40 mm, and all were tested at the rate of 60 kg/m^3 in dry-process shotcrete to determine their accumulated fracture energy under flexural loading of a standard ASTM C1018 test on 100 × 100 × 350 mm beam specimens (area under the flexural load versus displacement curve to a displacement of 2 mm). The results obtained are plotted in Fig. 5 where it is apparent that a fiber length of somewhere between 20 and 40 mm, preferably about 25 mm, was found to be optimum. Next, after selecting an optimum length of 25.4 mm, fibers of diameters of 0.61, 0.76, and 0.89 mm were tested. The results of these tests are shown in Fig. 6, where it is clearly indicated that a fiber diameter of about 0.75 mm (0.74 to 0.8 mm) was optimum. Based on these results, a length l_f = 25.4 mm and a diameter d = 0.76 mm were adopted, and the other fiber dimensions shown in Figs. 2 and 3 were calculated. In this arrangement, the diameter r_g of the indentation forming the

Fig. 6. Fiber diameter vs. shotcrete fracture energy for three different diameter DD fibers.

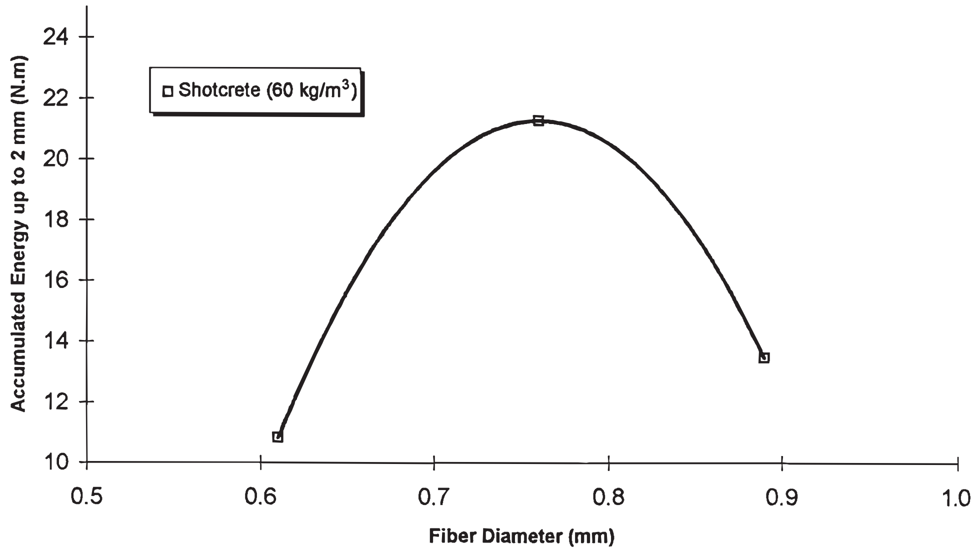


Fig. 7. Comparing DD fiber with other commercial fibers in flexural toughness testing using ASTM C1018 (average rebound values for hooked-end and pinched-end (flattened-end) fibers between 50% and 60%; for DD fiber, 40–50%).

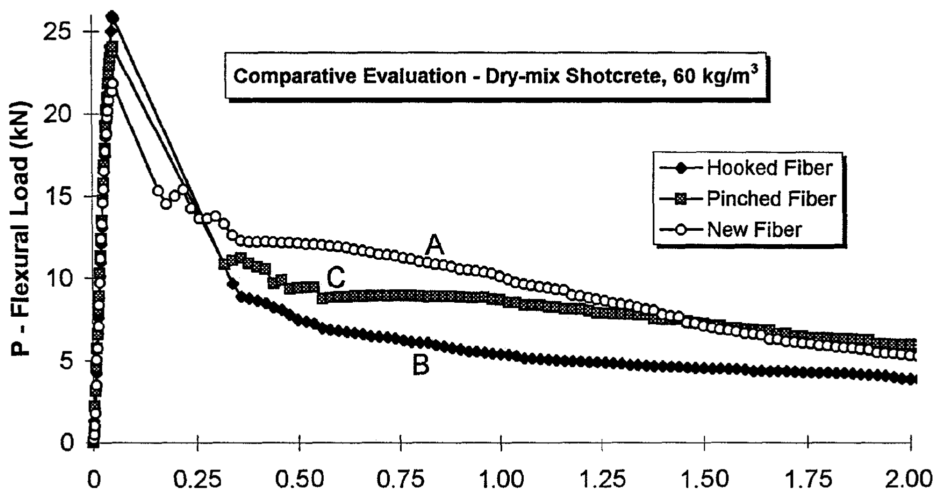


Table 1. DD fiber in dry-process shotcrete.

Criterion	Hooked-end fiber (DR30/50)	Flattened-end fiber (N0730)	DD fiber
ASTM I_{20}	3.28	4.09	8.37
ASTM I_{30}	5.43	7.28	12.83
ASTM I_{50}	9.01	13.29	20.27
JSCE, T (N·m)	9.82	14.25	18.15
JSCE, F (MPa)	1.47	2.14	2.72

drag section 12 was 10.7 mm, the thickness t_d was about 0.46 times diameter d, and the width w_d was 1.45 times the diameter d. Based on the dimensions r_g and t_d, the length l_d was derived. The length l of the dead hook section was set at 1.4 times the diameter d of the fiber, and the thickness t was 0.23 times the diameter d, which produce a width w of 2.36 times the diameter. The dimension l_c was 0.2 mm, and l_n and radius r_n for this example were equal and less than 0.5 mm, respectively. Other details of the fiber may be found elsewhere (Banthia and Armelin 1999).

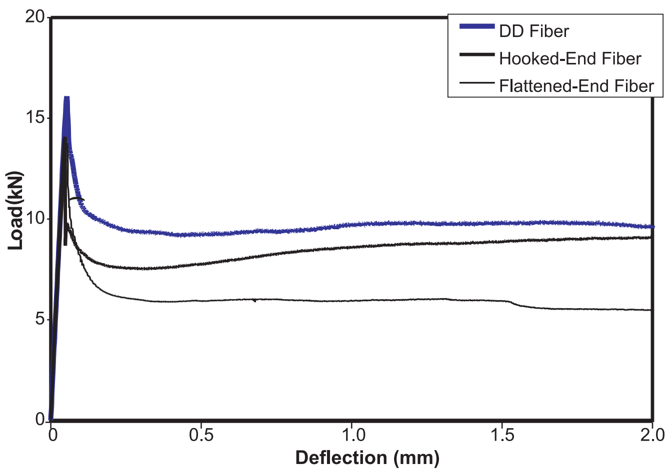
Double anchorage fiber in dry-process shotcrete

Fibers as described in the above example were produced in sufficient quantity and compared with two other commercial fibers. For comparison, the ASTM C1018 tests were performed on at least five beam specimens (100 × 100 × 350 mm) for each fiber sawed from shotcrete. The mixes contained 19% by mass of (CSA Type 10) cement, and 65% and 16%, respectively, of sand and rounded 3/8” aggregate. The mix developed a 28-day compressive strength of 51 MPa. The results of these tests (averages of four to seven replicates) are plotted in Fig. 7 wherein curve A is an average plot of the results obtained using the DD fiber, curve B is the average plot obtained using hooked-ended fibers, and curve C is the average plot using the pinched end (flattened-end or the FE) fiber. It is apparent that the DD fiber is able

Table 2. DD fiber in wet-process shotcrete.

	Fiber type at 40 kg/m^3			Improvements in DD fiber	
Criterion	DD fiber	Hooked-end fiber (DR30/50)	Flattened-end fiber (N0730)	Over hooked-end fiber (DR30/50)	Over flattened-end fiber (N0730)
JCI (MPa)	2.84	2.46	1.76	16%	61%
EFNARC (J)	932	808	745	na	25%

Fig. 8. Typical load–deflection plots for wet-mix shotcrete with DD, hooked-end, and flattened-end fibers.



to accommodate more load-carrying capacity and therefore consume more fracture energy (the area contained by the curves in Fig. 7) than either of the other two fibers. Some performance parameters are given in Table 1.

Double anchorage fiber in wet-process shotcrete

The DD fiber was also recently investigated in wet-process shotcrete (Law Gibb Group 2000) and the toughness plots based on ASTM C1018 are given in Fig. 8. EFNARC plates were also tested and the results of these tests are given in Table 2 along with an analysis of the C1018 beam tests. For wet-process shotcrete, since rebound is less of a concern, a fiber length of 30 mm was chosen. Note that in Fig. 8 and Table 2 the DD fiber demonstrates a superior performance over the leading commercial fibers based on both C1018 and EFNARC panel tests.

Concluding remarks

An improved reinforcing fiber for shotcrete is described. The fiber is based on a double anchoring principle where both dead and drag anchors are combined in the same fiber. The dead anchor breaks off as a result of ultimate stresses developed at a weak link in the fiber. This is then followed by the drag anchor frictionally resisting the pullout without fiber breakage. The dead anchor improves the first crack strength and the drag anchor improves the overall energy absorption capacity. The fiber is also proportioned for a reduced rebound in the dry-process shotcrete. When the low rebound aspect is combined with the novel double anchoring concept, a superior shotcrete fiber is realized.

One point worth mentioning here is the strength of the cementitious shotcrete matrix used in this investigation. Standardized shotcrete mixes were used, and these are now adopted in most countries of the world. However, it is conceivable that if a shotcrete mix of different strength were used, modifications in the fiber geometry may become necessary.

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