Exercise 5: Fiber reinforced shotcrete – analysis of test results and design

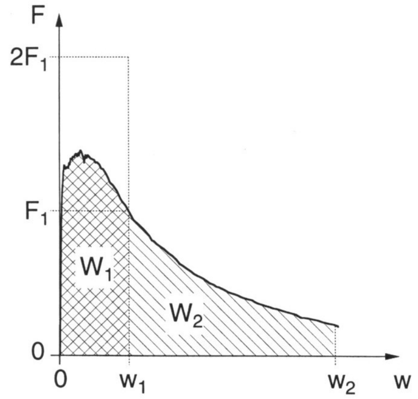
To consolidate the rock of a tunnel after excavation, a shotcrete (sprayed) layer reinforced with 35 kg/m^3 hooked metal fibers, type Dramix RC 65/35 BN, length 35 mm, diameter 0.55 mm is planned. As part of the preliminary qualification tests, 3 bending tests were carried out on square plates in accordance with SIA 162/6. The results of these tests are given in Appendix 3. In addition, a fiber count was carried out on the broken specimens after the tests to determine the actual fiber content of the plates tested. The results of these measurements are given in Appendix 4.

<u>Work to perform:</u>

Using the results given in Appendix 3 and 4 and the formulae and methods given in Appendix 1 and 2.

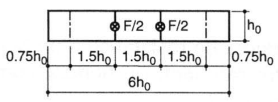
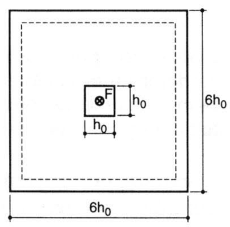
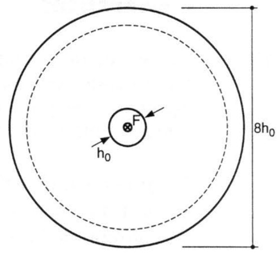
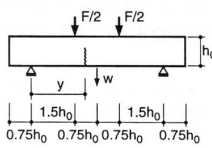
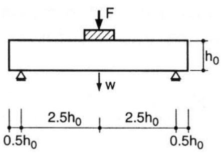
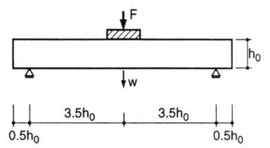
1. Determine the nominal dissipation powers W1 and W2 (Joules) for the 3 plates in accordance with SIA 162/6, using the diagrams given in Figs. 3 and 4, Appendix 3, and Appendix 1.
2. Check that the non-fragility criterion in Appendix 1 has been met.
3. Determine the design value of the breaking energy G_f (N/m=J/m^2) for the 3 plates, in accordance with SIA 162/6 (as per Appendix 1).
4. Determine for the 3 plates the effective design value of the tensile strength f_{ctf} (MPa) as per SIA 162/6 (as per Appendix 1).
5. Compare and discuss the results obtained.
6. Using the results given in Appendix 4 and the indications given in Appendix 2, determine the average orientation coefficient μ_0 of the fibers in each of the 3 plates tested.
7. From the results of the fiber counts given in Appendix 4, determine the average fiber dosage in the 3 slabs, in a plane parallel to the direction of casting.
8. Discuss the results obtained for the three different plates.
9. Calculate the maximum bending moment that a 10 cm thick section can withstand with such a fiber concrete (according to SIA 162/6 assumptions). Take the average strength f_{ctf} for the 2 slabs VC1 and VC2 as a basis. The compressive strength of the concrete is assumed to be f_{cwm}=35 MPa, and the stress distribution is that given by SIA 162/6.
10. Compare the maximum moment found above with the moment that can be absorbed by an equivalent shotcrete section reinforced with a 131 mm2/m mesh (∅ 5/s=150 mm) placed at the center of the section.
11. Discuss the results obtained.

<u>Appendix 1:</u> Analysis of bending test results according to SIA 162/6



<u>Acceptance criteria:</u>

$2F_1 w_1 \geq W_1$	(non-brittleness)
$G_f \geq 4000 N/m$	(minimal value)

Essai	Essai de traction par flexion	Essai sur dalle carrée	Essai sur dalle circulaire
Situation			
Élévation			
w_1	$\frac{l_f y}{16 h_0}$	$(0.03n + 0.06)l_f$	$(0.07n - 0.10)l_f$
W_1	$\frac{3h_0}{2y} \int_0^{w_1} F dw$	$\int_0^{w_1} F dw$	$\int_0^{w_1} F dw$
f_{ctf}	$\frac{12 W_1}{h_0^2 l_f}$	$(0.95 - 0.06n) \frac{W_1}{h_0^2 l_f}$	$\frac{3 W_1}{n h_0^2 l_f}$
w_2	—	$4w_1$	$4w_1$
W_2	—	$\int_0^{w_2} F dw$	$\int_0^{w_2} F dw$
G_f	—	$(0.107 - 0.007n) \frac{W_2}{h_0^2}$	$\frac{W_2}{3 n h_0^2}$

with n the number of yield lines in the slab test and l_f the fiber length.

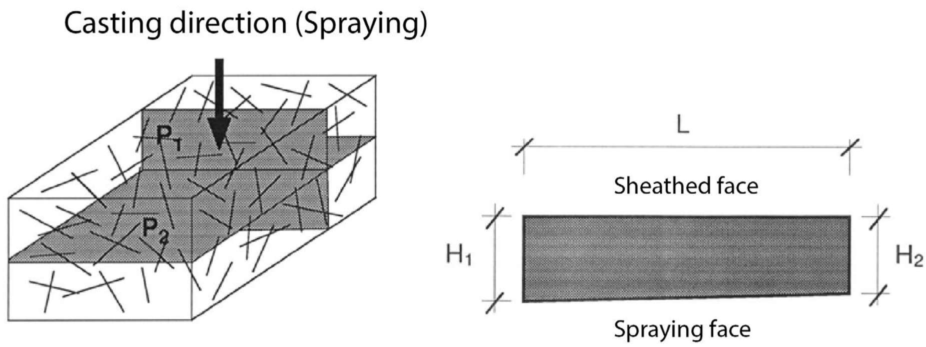
<u>Ref:</u> Recommandation SIA 162/6: "Béton renforcé de fibres métalliques", édition de 1999.

<u>Appendix 2:</u> determination of fiber dosage by counting of fibers on cut planes

The % vol. of fibers V_f in a discontinuous fiber reinforced composite is given by:

$V_f = \frac{N_f}{\mu_0} \cdot \frac{\pi d_f^2}{4}$ and the fiber dosage by : $M_f = V_f \cdot \rho_f$ (ρ_f : specific weight of fibers)

The fiber diameter d_f is known. The number of fibers per unit area N_f can be determined by counting them on a given cut surface. The orientation coefficient μ_0 can be estimated by counting the number of fibers N_{f1} and N_{f2} passing through 2 perpendicular cutting planes P_1 and P_2 (see figure 1 below); P_1 parallel to the casting direction (projection, for shotcrete) and P_2 perpendicular to P_1, and therefore perpendicular to the casting direction (projection).



a) b)

Figure 1: definition of the cutting planes a) and their geometry b).

The orientation coefficient μ_0 for the pure two-dimensional case is 0.637. For the pure three-dimensional case, according to the authors, the coefficient μ_0 ranges from 0.405 to 0.50. According to the literature, in the 3D case, the coefficient μ_0 is closer to 0.50. In what follows, this value will be taken as a basis. In the case of three-dimensional fiber orientation (μ_0=0.5), no direction is favored. The number of fibers crossing the 2 perpendicular planes P_1 and P_2 must be the same: N_{f1}=N_{f2}. In the case of pure two-dimensional fiber orientation (μ_0=0.637), the number of fibers crossing the P_2 plane becomes negligible, all fibers are perpendicular to the casting direction, and N_{f2}= 0. It can be assumed that when the effect of fiber orientation changes from the two-dimensional to the three-dimensional case, the orientation coefficient μ_0 ranges from 0.637 to 0.50 and the ratio N_{f2}/N_{f1} varies between 0 and 1. By simplification, based on literature results, the following linear relationship is assumed, illustrated in figure 2 below:

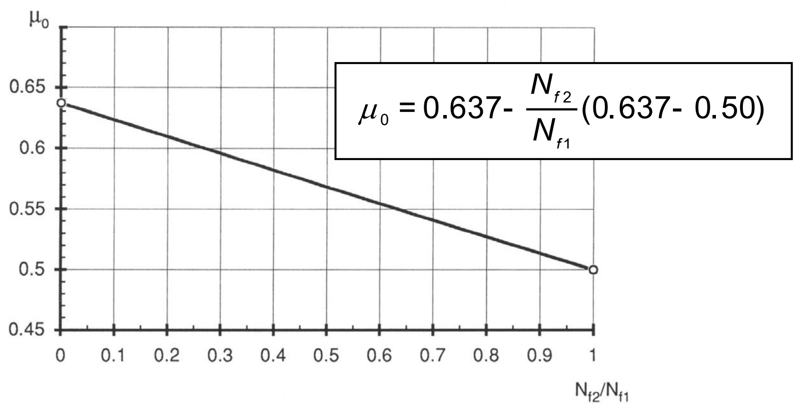


Figure 2: orientation coefficient as a function of the ratio of the number of fibers crossing two perpendicular planes.

<u>Appendix 3:</u> Bending test results on square slabs 60/60/10 cm

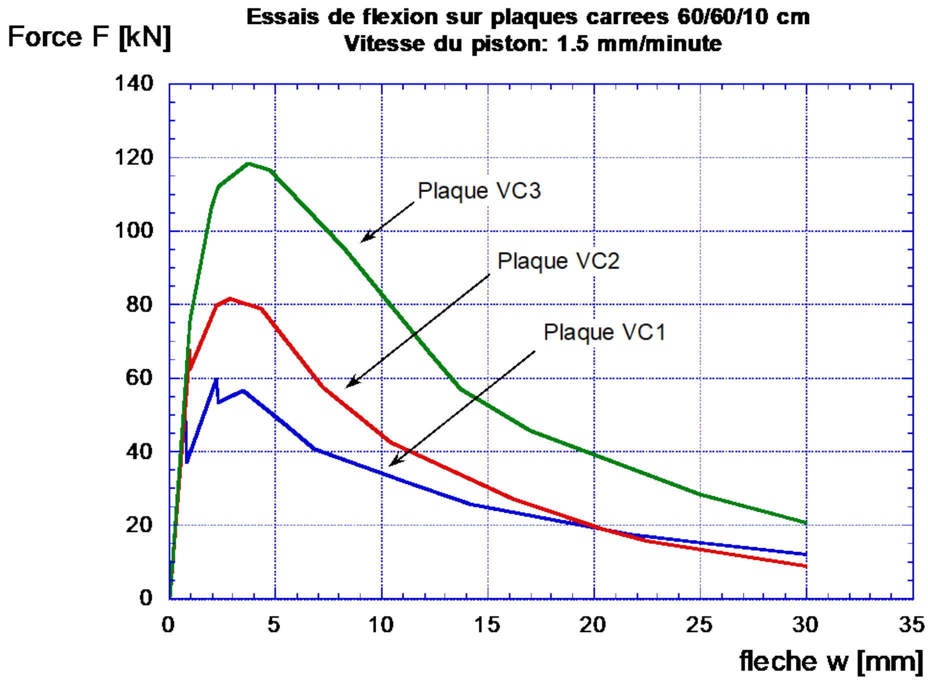


Figure 3: experimental Force-deflection curves

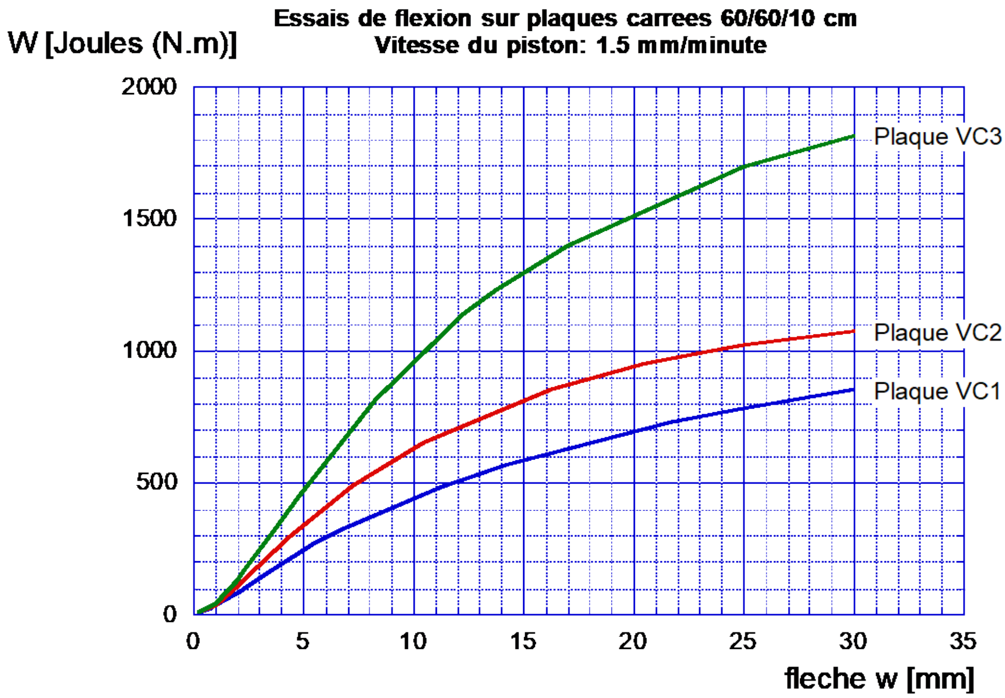
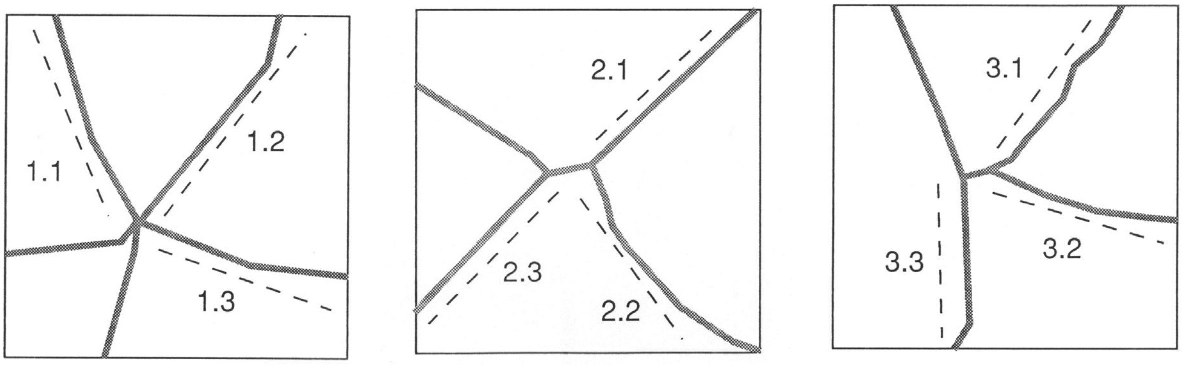


Figure 4: dissipated power W vs deflection for the 3 slabs (integral of the curves given on Figure 3).

Appendix 4: Fiber counting results



Plaque VC1 Plaque VC2 Plaque VC3

Figure 5: Yield lines patterns at the end of the tests (lower face of the slabs), solid lines, and fiber counting planes (sawn) in dashed lines.

NB: For plates VC2 and VC3, the number of yield lines is assumed to be n = 4. The small crack at the center of these plates contributes little to energy dissipation, which is dominated by that of the cracks running to the ends of the plates.

Plaque	L	H1	H2	Section	n_{f2}	N_{f2}
	[cm]	[cm]	[cm]	[cm2]	[fibres]	[fibres/cm2]
VC1	20.00	10.00	10.00	200.00	122.00	0.61
VC2	20.00	10.00	10.00	200.00	94.00	0.47
VC3	20.00	10.00	10.00	200.00	402.00	2.01

Figure 6: Fiber counting results on cutting planes perpendicular to spraying direction (P_2).

Plaque n° 1

Coupe	L	H1	H2	Section	n_{f1}	N_{f1}
	[cm]	[cm]	[cm]	[cm2]	[fibres]	[fibres/cm2]
1.1	37.00	10.00	9.40	358.90	273.00	0.76
1.2	31.30	10.00	9.51	305.33	263.00	0.86
1.3	33.60	10.00	9.30	324.24	273.00	0.84
					Moyenne	**0.82**

Plaque n° 2

Coupe	L	H1	H2	Section	n_{f1}	N_{f1}
	[cm]	[cm]	[cm]	[cm2]	[fibres]	[fibres/cm2]
2.1	34.50	10.50	10.11	355.52	311.00	0.87
2.2	32.40	10.71	10.61	345.38	230.00	0.67
2.3	27.10	10.21	10.21	276.69	260.00	0.94
					Moyenne	**0.83**

Plaque n° 3

Coupe	L	H1	H2	Section	n_{f1}	N_{f1}
	[cm]	[cm]	[cm]	[cm2]	[fibres]	[fibres/cm2]
3.1	30.50	10.00	9.00	289.75	1'005	3.47
3.2	32.20	8.81	10.21	306.22	1'102	3.60
3.3	24.70	10.41	10.00	252.06	732	2.90
					Moyenne	**3.32**

Figure 7: Fiber counting results on cutting planes parallel to spraying direction (P_1).