Justification of Fédération International de Beton, FIB, 2000 model for elastic modulus of normal and high-performance concrete, HPC

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ABSTRACT

This article outlines an experimental and theoretical comparison between the FIB 2000 Model for Elastic Modulus of Normal Concrete, NC, and HPC and 144 laboratory tests. Two dimensions of specimen were studied (56 and 100 mm) and one climate (20 °C, sealed or with ambient relative humidity, RH, 60%). The age dependence did not seem to be well correlated between the derived and the measured elastic modulus. The FIB 2000 Model overestimated the elastic modulus of mature concrete, and in contrast, slightly underestimated the elastic modulus of young NC. However, as a whole, the derived modulus when using the FIB model was about 120% of the elastic modulus measured at loading. A relationship to strength was found for this diversity with an increasing overestimation of the E-modulus at low strength.

1. FIB 2000 MODEL FOR NC AND HPC

The model originated from European work in the field over 10 years [1-6]. The elastic modulus of concrete was derived according to the following formula:

$$E_c(t) = 21.5 \cdot (f_{cm}/f_{cm0})^{1/3} \cdot exp((1-(28/t/t_t)^{0.5} \cdot s/2)) \qquad (1)$$

f_{cm0} = 10 MPa
f_{cm} denotes 28-day strength (MPa)
t denotes age (days)
t_1 = 1 day
s denotes constant given in Table 1

Table 1. Constants in equations (1) and (2)

Type of cement and concrete strength	Notification	s
Slowly hardening, concrete strength ≤ 60 MPa	SL	0.38
Normal or rapid hardening cement, concrete strength ≤ 60 MPa	N, R	0.25
Rapid hardening high-strength cement, concrete strength ≤ 60 MPa	RS	0.20
All types of cements, concrete strength > 60 MPa	SL, N, R, RS	0.20

2. METHODS

In all 16 concretes were cast of 2 Portland cements, 1 slowly hardening (Degerhamn, SL) and 1 normal hardening (Slite, S), Table 2. w/b varied between 0.24 and 0.80 with 28-day strength varying between 24 and 141 MPa (100-mm cube). The aggregate content varied between 0.7 and 0.75 and consisted of quartzite sandstone, Table 3. Natural sand was used. The mixed proportions had silica fume, Table 4 [8-16]. After demolding at 1 day's age measurement points of steel screws were fixed into items cast in the concrete cylinders on three sides of them. Half of the specimens were sealed with adhesive aluminum foil.

For cylinders 56 mm in diameter 3 LVDT gauging devices were mounted on the side of the cylinder in order to determine the deformation. The loading for the 56-mm cylinders was applied were rapidly, after about 0.01 s, in order to obtain the "true" modulus of elasticity [17]. For the 100-mm cylinders the loading was applied in a more traditional way with a rate of about 1 MPa/s (over which period substantial creep took place, especially at young ages [8]). The observed elastic modulus was smaller at slow loading. Mechanical devices were used when the deformation was measured on the 100-mm cylinders in turn calibrated to length by an INVAR rod.

Table 2. The chemical composition of the cements [8-16].

Chemical composition (%)	Normal hardening (S)	Slowly hardening (SL)
CaO	62	65
SiO_2	20	21.6
Al_2O_3	4.4	3.5
Fe_2O_3	2.3	4.4
K_2O	1.4	0.58
Na_2O	0.2	0.05
MgO	3.5	0.78
SO_3	3.7	2.07
Ignition losses	2.4	0.47
CO_2	1.9	0.14
Clinker minerals:		
C_2S	14	21
C_3S	57	57
C_3A	8	1.7
C_4AF	7	13
Physical properties:		
Water demand	28%	25%
Initial setting time	154 min.	145 min.
Density	3122 kg/m^3	3214 kg/m^3
Specific surface	364 m^2/kg	305 m^2/kg

Table 3 - Properties of the aggregate (quartzite sandstone) [7].

Compressive strength (MPa)	Split tensile strength (MPa)	Elastic modulus (GPa)	Ignition losses (%)
333	15	60	0.3

Table 4. Mix proportions and strength of concretes, cylinder diameter, d (kg/m³, MPa, cm)

Mix	Cement, c	Cement type	Silica fume, s	w/b	Sand filler	Air (%)	28-day strength	d
1	460	SL	21	0.36		4.8	69	6
2	440	SL	44	0.34		1.1	85	6
3	445	SL	45	0.34		4	69	6
4	455	SL	23	0.3		0.9	89	6
5	495	SL	50	0.28		1.1	99	6
6	530	SL	51	0.27		1.2	106	6
7	490	SL	49	0.27		1	112	6
8	545	SL	55	0.24		1.3	114	6
27	500	SL	50	0.24	50	1.3	141	10
32	389	N		0.32	106	12	55	10
38N	360	N		0.38	68	12	42	10
38S	400	N		0.38	145	1.4	86	10
50N	285	N		0.50	33	13	30	10
50S	340	N		0.50	165	3.5	61	10
80N	250	N		0.80		1.2	24	10
80S	260	N		0.80	185	1.9	27	10

3. RESULTS AND ANALYSES (SEE ALSO APPENDICES)

3.1 Results

Evaluations according to the FIB 2000 model were plotted versus the measured laboratory results, Figures 1-2. Cylinders 56-mm with quasi-instantaneous loading were used from 1 day' age up to 500 days' age. Loading of air and sealed cured specimens showed no significant difference between the measured moduli of elasticity, Figure 1. Figure 2 shows an overestimation with the FIB Model increased with age. Figure 3 shows the ratio of derived to measured elastic modulus versus strength. Calculations according to the FIB 2000 Model at 500 days' age showed about 30% larger values compared with the measured value – independent of strength, Figure 3. At 1-3 days' age the elastic modulus was overestimated by about 20%. At 28 days' age an overestimation by about 10% of the E-modulus occurred. In Figure 4 the value of the overestimation with the FIB Model is confirmed also for a more traditional way of obtaining the E-modulus (a slow loading rate of about 1 MPa/s). The effect of strength level is clear in Figure 4. The overall overestimation with the FIB Model was about 23%. For mature HPC (high strength) the estimated value was more correct, Figure 4.

3.2 Analyses

Previously a comparison was performed between measured shrinkage of HPC and shrinkage estimated by the FIB 2000 Model [18]. In the present study on the elastic modulus two parameters may affect the overestimation and strength dependence of the FIB Model:

- Too a large exponent for the time dependence of strength, 0.5
- In contrast a too low exponent for the strength dependence, 1/3

The ratio of the elastic modulus with the FIB 2000 Model, $E_{c(t)}$, and measured, E_m, is shown in Figure 5-6. The number of specimens is given in Table 5. The following loading age, t (days), and 28-day strength, f_{cm} (MPa), dependences were calculated (GPa):

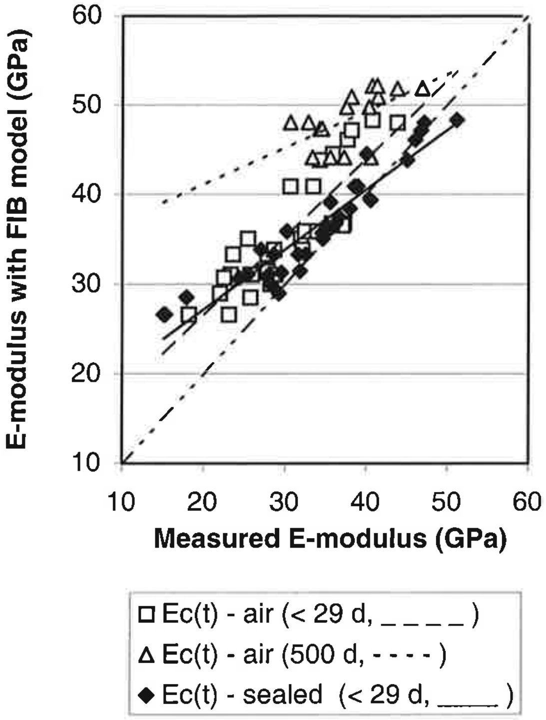

Figure 1. FIB model estimation vs measured results, 56–mm cyl., air or sealed curing.

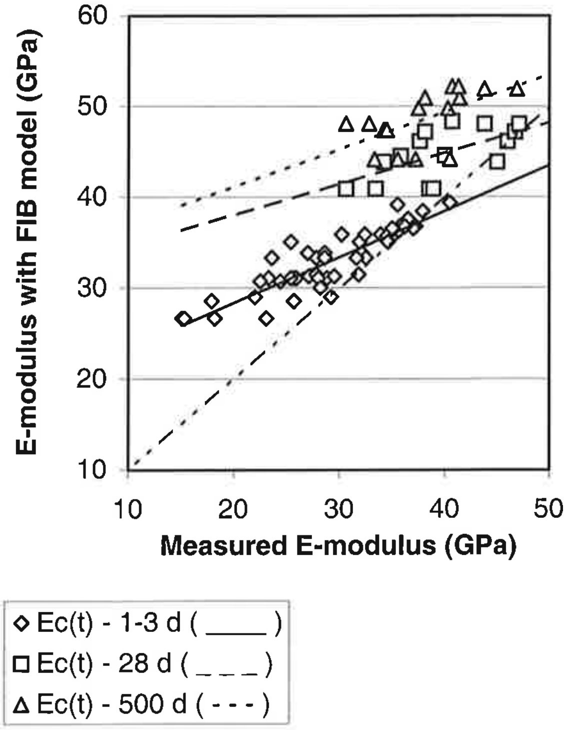

Figure 2. FIB model estimations versus the measured laboratory results, 56–mm cyl..

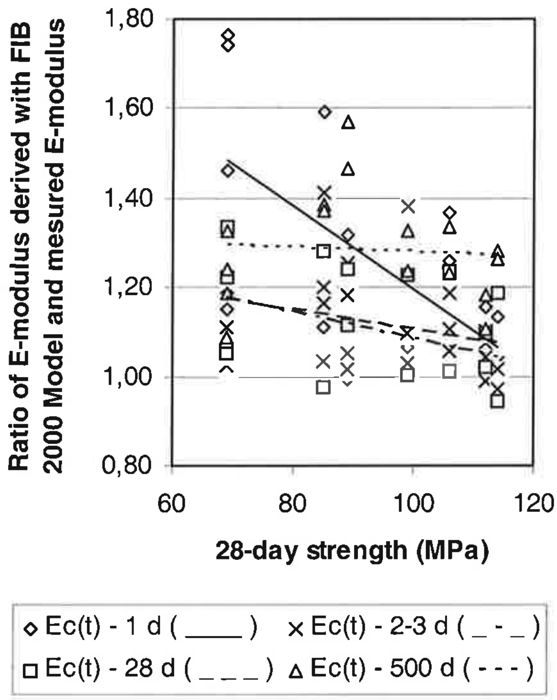

Figure 3. Ratio of derived to measured elastic modulus versus strength, 56–mm cyl..

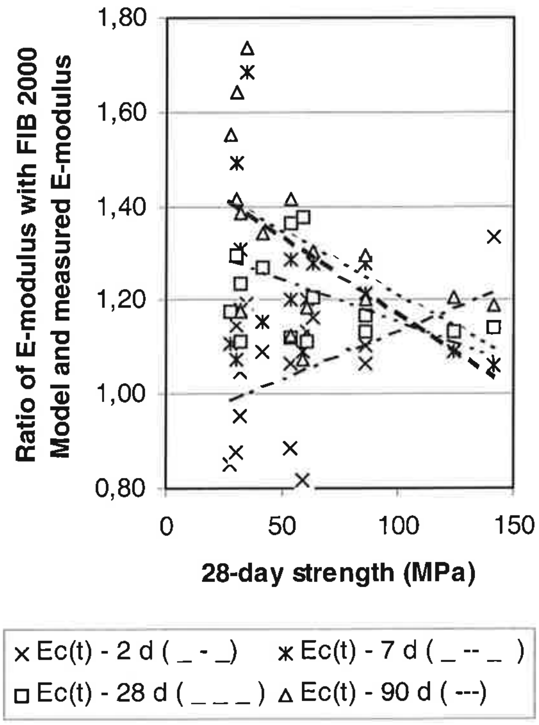

Figure 4. Ratio of derived to measured elastic modulus vs strength, 100–mm cyl..

Table 5. Elastic modulus with the FIB 2000 Model and measured- number of specimens [8,9].

d (mm)	E_m (GPa)	E_c (GPa)	f_{cm} (MPa)	$E_{c(t)\text{-}1\ d}$	$E_{c(t)\text{-}2\text{-}3\ d}$	$E_{c(t)\text{-}7d}$	$E_{c(t)\text{-}28\ d}$	$E_{c(t)\text{-}90\ d}$	$E_{c(t)\text{-}500\ d}$	$E_{c(t)\text{-total}}$
56	33	45	93	16	32	-	16	-	16	80
100	27	37	60	-	16	16	16	16	-	64
Total				16	48	16	32	16	16	144

$$E_{c(t)}/E_m = 1.14 \cdot\ t^{0.0229} \qquad (2)$$

$$E_{c(t)}/E_m = 2.67 \cdot\ f_{cm}{}^{-0.1896} \qquad (3)$$

f_{cm} denotes the 28-day strength (MPa)
t denotes the loading age (days),
$E_{c(t)}$ denotes the elastic modulus with the FIB 2000 Model (GPa)
E_m denotes the measured elastic modulus (GPa)

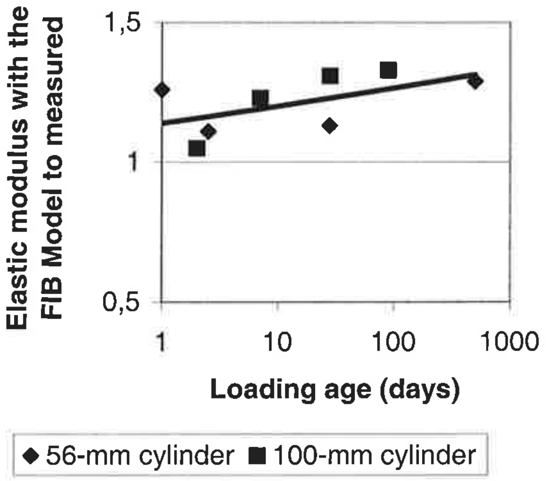

Figure 5. Elastic modulus with the FIB Model to measured vs loading age [8,9]

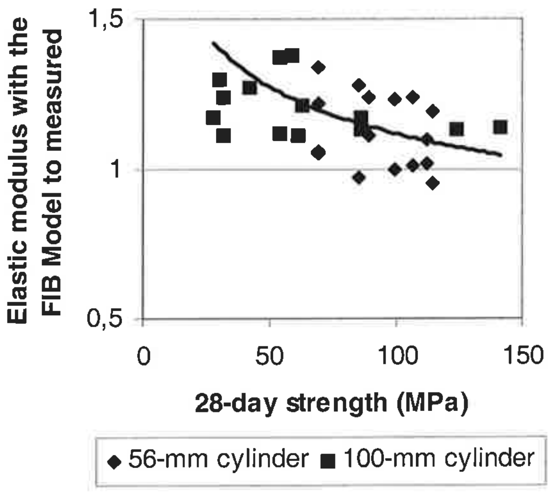

Figure 6. Elastic modulus with the FIB Model to measured vs 28-day strength [8,9].

4. SUMMARY AND CONCLUSIONS

An experimental and theoretical comparison between the elastic modulus estimated with the FIB 2000 Model for Normal and High-Performance Concrete and 144 laboratory tests on 16 concretes was performed. Two dimensions of specimen were studied (56 and 100 mm) and one climate (20 °C, sealed or relative humidity 60%). The following conclusions were drawn:

- The age dependence did not seem to be well correlated between the derived and the measured elastic modulus.
- The FIB 2000 Model overestimated the elastic modulus of mature concrete, and in contrast, slightly underestimated the elastic modulus of young NC.
- As a whole, the derived modulus with the FIB model was about 120% of the elastic modulus measured at loading.
- A relationship to strength was found for this diversity with an increasing overestimation of the E-modulus at low strength.

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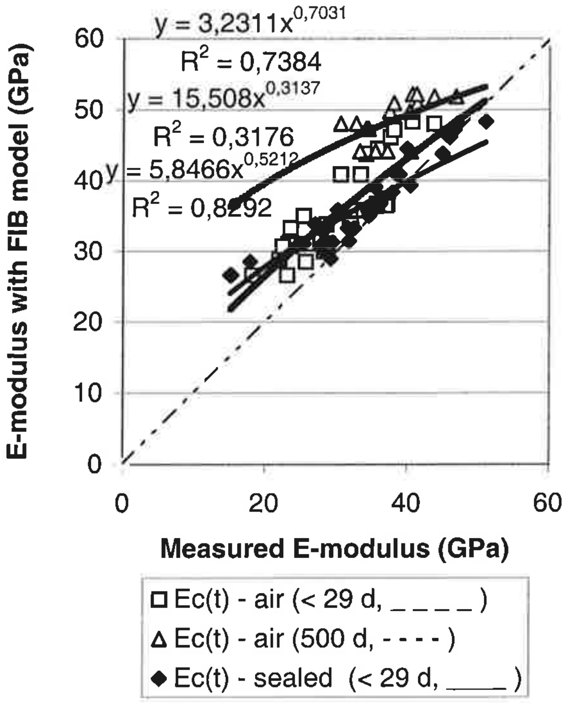
<u>Appendix fibelast</u>

fc	f_{cm}	E_m	$E_{c(t)}$ - air (< 29 d, _ _ _ _)	$E_{c(t)}$ - air (500 d, - - - -)	$E_{c(t)}$ - sealed (< 29 d, ____)	t	s	E_c	
23,00	69,00	18,20	26,63			1,00	0,20	40,90	1,00
32,00	69,00	25,70	31,10			2,00	0,20	40,90	1,00
24,00	85,00	25,70	28,55			1,00	0,20	43,85	2,00
44,00	85,00	27,80	33,33			2,00	0,20	43,85	2,00
27,00	69,00	23,10	26,63			1,00	0,20	40,90	3,00
30,00	69,00	23,30	31,10			2,00	0,20	40,90	3,00
23,00	89,00	22,00	28,99			1,00	0,20	44,52	4,00
37,00	89,00	28,60	33,85			2,00	0,20	44,52	4,00
38,00	99,00	28,20	30,03			1,00	0,20	46,13	5,00
45,00	99,00	31,90	35,07			2,00	0,20	46,13	5,00
30,00	106,00	22,50	30,72			1,00	0,20	47,19	6,00
61,00	106,00	32,40	35,88			2,00	0,20	47,19	6,00
36,00	112,00	27,10	31,29			1,00	0,20	48,06	7,00
63,00	112,00	35,80	36,54			2,00	0,20	48,06	7,00
35,00	114,00	27,80	31,48			1,00	0,20	48,35	8,00
69,00	114,00	37,20	36,76			2,00	0,20	48,35	8,00
26,00	69,00	25,90	31,10			2,00	0,20	40,90	1,00
50,00	69,00	33,40	40,90			28,00	0,20	40,90	1,00
44,00	85,00	23,60	33,33			2,00	0,20	43,85	2,00
86,00	85,00	34,20	43,85			28,00	0,20	43,85	2,00
43,00	69,00	28,80	31,10			2,00	0,20	40,90	3,00
58,00	69,00	30,60	40,90			28,00	0,20	40,90	3,00
48,00	89,00	32,10	33,85			2,00	0,20	44,52	0,00
91,00	89,00	35,80	44,52			28,00	0,20	44,52	60,00
46,00	99,00	25,40	35,07			2,00	0,20	46,13	5,00
106,00	99,00	37,60	46,13			28,00	0,20	46,13	5,00
58,00	106,00	33,90	35,88			2,00	0,20	47,19	6,00
111,00	106,00	38,10	47,19			28,00	0,20	47,19	6,00
67,00	112,00	37,00	36,54			2,00	0,20	48,06	7,00
118,00	112,00	43,80	48,06			28,00	0,20	48,06	7,00
65,00	114,00	35,70	36,76			2,00	0,20	48,35	8,00
118,00	114,00	40,70	48,35			28,00	0,20	48,35	8,00
8,5	69	15,1			26,63	1,00	0,20	40,90	1,00
24	69	25,4			31,10	2,00	0,20	40,90	
52	69	32,5			33,31	3,00	0,20	40,90	
82	69	38,5			40,90	28,00	0,20	40,90	
22	85	17,9			28,55	1,00	0,20	43,85	2,00
40	85	28,6			33,33	2,00	0,20	43,85	
64	85	34,5			35,70	3,00	0,20	43,85	
115	85	45			43,85	28,00	0,20	43,85	
15	69	15,3			26,63	1,00	0,20	40,90	3,00
35	69	28			31,10	2,00	0,20	40,90	
48	69	31,6			33,31	3,00	0,20	40,90	
90	69	38,9			40,90	28,00	0,20	40,90	
37	89	29,2			28,99	1,00	0,20	44,52	4,00
34	89	27			33,85	2,00	0,20	44,52	
56	89	35,6			36,25	3,00	0,20	44,52	
90	89	40			44,52	28,00	0,20	44,52	
38	99	28,2			30,03	1,00	0,20	46,13	5,00
66	99	34,6			35,07	2,00	0,20	46,13	
83	99	36,5			37,56	3,00	0,20	46,13	
130	99	46			46,13	28,00	0,20	46,13	
24	106	24,4			30,72	1,00	0,20	47,19	6,00
50	106	30,2			35,88	2,00	0,20	47,19	
85	106	37,9			38,43	3,00	0,20	47,19	
128	106	46,7			47,19	28,00	0,20	47,19	
42	112	29,5			31,29	1,00	0,20	48,06	7,00
58	112	35			36,54	2,00	0,20	48,06	
59	112	35,5			39,14	3,00	0,20	48,06	
117	112	47,1			48,06	28,00	0,20	48,06	
46	114	31,8			31,48	1,00	0,20	48,35	8,00
58	114	36,2			36,76	2,00	0,20	48,35	

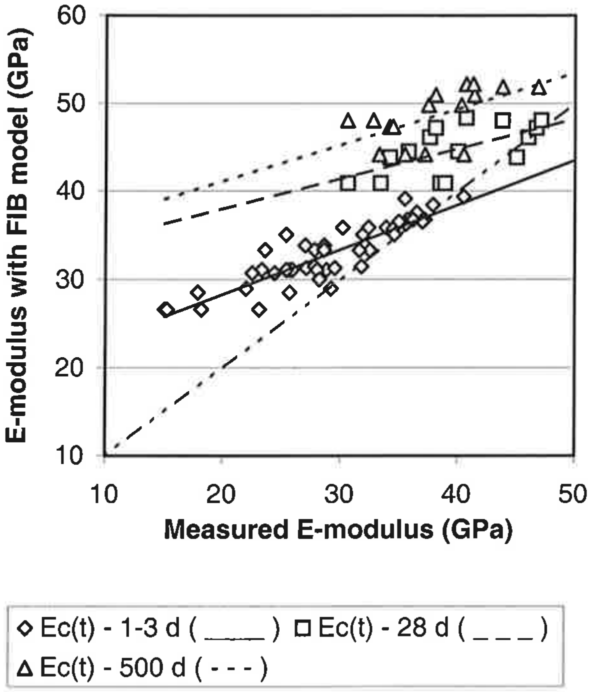
83	114	40,5			39,37	3,00	0,20	48,35	
135	114	51,1			48,35	28,00	0,20	48,35	
69	69	33,3		44,15		500,00	0,20	40,90	1
86	85	34,2		47,32		500,00	0,20	43,85	2
58	89	30,6		48,05		500,00	0,20	44,52	3
91	69	37,2		44,15		500,00	0,20	40,90	4
106	99	37,5		49,79		500,00	0,20	46,13	5
111	106	38,1		50,94		500,00	0,20	47,19	6
117	112	43,8		51,88		500,00	0,20	48,06	7
118	114	40,7		52,18		500,00	0,20	48,35	8
68	69	35,5		44,15		500,00	0,20	40,90	1
89	85	34,5		47,32		500,00	0,20	43,85	2
69	89	32,8		48,05		500,00	0,20	44,52	3
101	69	40,5		44,15		500,00	0,20	40,90	4
116	99	40,3		49,79		500,00	0,20	46,13	5
116	106	41,4		50,94		500,00	0,20	47,19	6
121	112	46,9		51,88		500,00	0,20	48,06	7
129	114	41,3		52,18		500,00	0,20	48,35	8
66,64	92,88	33,21	35,67	48,56	36,28	38,49			



Appendix fibelastage

fc	f_{cm}	E_m	$E_{c(t)}$ - 1-3 d (____)	$E_{c(t)}$ - 28 d (_ _ _)	$E_{c(t)}$ - 500 d (- - -)	t	s	E_c		
23,00	69,00	18,20	26,63			1,00	0,20	40,90	1,00	
32,00	69,00	25,70	31,10			2,00	0,20	40,90	1,00	
24,00	85,00	25,70	28,55			1,00	0,20	43,85	2,00	
44,00	85,00	27,80	33,33			2,00	0,20	43,85	2,00	
27,00	69,00	23,10	26,63			1,00	0,20	40,90	3,00	
30,00	69,00	23,30	31,10			2,00	0,20	40,90	3,00	
23,00	89,00	22,00	28,99			1,00	0,20	44,52	4,00	
37,00	89,00	28,60	33,85			2,00	0,20	44,52	4,00	
38,00	99,00	28,20	30,03			1,00	0,20	46,13	5,00	
45,00	99,00	31,90	35,07			2,00	0,20	46,13	5,00	
30,00	106,00	22,50	30,72			1,00	0,20	47,19	6,00	
61,00	106,00	32,40	35,88			2,00	0,20	47,19	6,00	
36,00	112,00	27,10	31,29			1,00	0,20	48,06	7,00	
63,00	112,00	35,80	36,54			2,00	0,20	48,06	7,00	
35,00	114,00	27,80	31,48			1,00	0,20	48,35	8,00	
69,00	114,00	37,20	36,76			2,00	0,20	48,35	8,00	
26,00	69,00	25,90	31,10			2,00	0,20	40,90	1,00	
50,00	69,00	33,40		40,90		28,00	0,20	40,90	1,00	
44,00	85,00	23,60	33,33			2,00	0,20	43,85	2,00	
86,00	85,00	34,20		43,85		28,00	0,20	43,85	2,00	
43,00	69,00	28,80	31,10			2,00	0,20	40,90	3,00	
58,00	69,00	30,60		40,90		28,00	0,20	40,90	3,00	
48,00	89,00	32,10	33,85			2,00	0,20	44,52	0,00	0,00
91,00	89,00	35,80		44,52		28,00	0,20	44,52	60,00	60,00
46,00	99,00	25,40	35,07			2,00	0,20	46,13	5,00	
106,00	99,00	37,60		46,13		28,00	0,20	46,13	5,00	
58,00	106,00	33,90	35,88			2,00	0,20	47,19	6,00	
111,00	106,00	38,10		47,19		28,00	0,20	47,19	6,00	
67,00	112,00	37,00	36,54			2,00	0,20	48,06	7,00	
118,00	112,00	43,80		48,06		28,00	0,20	48,06	7,00	
65,00	114,00	35,70	36,76			2,00	0,20	48,35	8,00	
118,00	114,00	40,70		48,35		28,00	0,20	48,35	8,00	
8,5264	69	15,1	26,63			1,00	0,20	40,90	1,00	
24,01	69	25,4	31,10			2,00	0,20	40,90		
51,84	69	32,5	33,31			3,00	0,20	40,90		
82,81	69	38,5		40,90		28,00	0,20	40,90		
22,09	85	17,9	28,55			1,00	0,20	43,85	2,00	
39,69	85	28,6	33,33			2,00	0,20	43,85		
64	85	34,5	35,70			3,00	0,20	43,85		
114,49	85	45		43,85		28,00	0,20	43,85		
15,21	69	15,3	26,63			1,00	0,20	40,90	3,00	
34,81	69	28	31,10			2,00	0,20	40,90		
47,61	69	31,6	33,31			3,00	0,20	40,90		
90,25	69	38,9		40,90		28,00	0,20	40,90		
37,21	89	29,2	28,99			1,00	0,20	44,52	4,00	
33,64	89	27	33,85			2,00	0,20	44,52		
56,25	89	35,6	36,25			3,00	0,20	44,52		
90,25	89	40		44,52		28,00	0,20	44,52		
38,44	99	28,2	30,03			1,00	0,20	46,13	5,00	
65,61	99	34,6	35,07			2,00	0,20	46,13		
82,81	99	36,5	37,56			3,00	0,20	46,13		
129,96	99	46		46,13		28,00	0,20	46,13		
24,01	106	24,4	30,72			1,00	0,20	47,19	6,00	
50,41	106	30,2	35,88			2,00	0,20	47,19		
84,64	106	37,9	38,43			3,00	0,20	47,19		
127,69	106	46,7		47,19		28,00	0,20	47,19		
42,25	112	29,5	31,29			1,00	0,20	48,06	7,00	
57,76	112	35	36,54			2,00	0,20	48,06		
59,29	112	35,5	39,14			3,00	0,20	48,06		
116,64	112	47,1		48,06		28,00	0,20	48,06		
46,24	114	31,8	31,48			1,00	0,20	48,35	8,00	
57,76	114	36,2	36,76			2,00	0,20	48,35		
82,81	114	40,5	39,37			3,00	0,20	48,35		

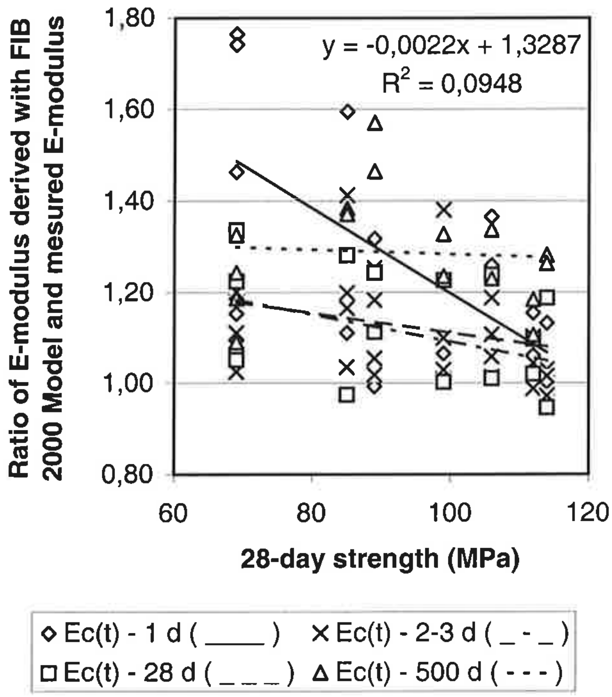
134,56	114	51,1		48,35		28,00	0,20	48,35	
69	69	33,3			44,15	500,00	0,20	40,90	1
86	85	34,2			47,32	500,00	0,20	43,85	2
58	89	30,6			48,05	500,00	0,20	44,52	3
91	69	37,2			44,15	500,00	0,20	40,90	4
106	99	37,5			49,79	500,00	0,20	46,13	5
111	106	38,1			50,94	500,00	0,20	47,19	6
117	112	43,8			51,88	500,00	0,20	48,06	7
118	114	40,7			52,18	500,00	0,20	48,35	8
68	69	35,5			44,15	500,00	0,20	40,90	1
89	85	34,5			47,32	500,00	0,20	43,85	2
69	89	32,8			48,05	500,00	0,20	44,52	3
101	69	40,5			44,15	500,00	0,20	40,90	4
116	99	40,3			49,79	500,00	0,20	46,13	5
116	106	41,4			50,94	500,00	0,20	47,19	6
121	112	46,9			51,88	500,00	0,20	48,06	7
129	114	41,3			52,18	500,00	0,20	48,35	8
66,63		33,21	32,97	44,99	48,56	38,49		44,99	



Appendix fibelaststrength

f_c	E_m	f_{cm}	$E_{c(t)}$ - 1 d (____)	$E_{c(t)}$ - 2-3 d (_ - _)	$E_{c(t)}$ - 28 d (_ _ _)	$E_{c(t)}$ - 500 d (- - -)	t
23,00	18,20	69,00	1,46				1,00
32,00	25,70	69,00		1,21			2,00
24,00	25,70	85,00	1,11				1,00
44,00	27,80	85,00		1,20			2,00
27,00	23,10	69,00	1,15				1,00
30,00	23,30	69,00		1,33			2,00
23,00	22,00	89,00	1,32				1,00
37,00	28,60	89,00		1,18			2,00
38,00	28,20	99,00	1,07				1,00
45,00	31,90	99,00		1,10			2,00
30,00	22,50	106,00	1,37				1,00
61,00	32,40	106,00		1,11			2,00
36,00	27,10	112,00	1,15				1,00
63,00	35,80	112,00		1,02			2,00
35,00	27,80	114,00	1,13				1,00
69,00	37,20	114,00		0,99			2,00
26,00	25,90	69,00		1,20			2,00
50,00	33,40	69,00			1,22		28,00
44,00	23,60	85,00		1,41			2,00
86,00	34,20	85,00			1,28		28,00
43,00	28,80	69,00		1,08			2,00
58,00	30,60	69,00			1,34		28,00
48,00	32,10	89,00		1,05			2,00
91,00	35,80	89,00			1,24		28,00
46,00	25,40	99,00		1,38			2,00
106,00	37,60	99,00			1,23		28,00
58,00	33,90	106,00		1,06			2,00
111,00	38,10	106,00			1,24		28,00
67,00	37,00	112,00		0,99			2,00
118,00	43,80	112,00			1,10		28,00
65,00	35,70	114,00		1,03			2,00
118,00	40,70	114,00			1,19		28,00
8,5264	15,1	69	1,76				1,00
24,01	25,4	69		1,22			2,00
51,84	32,5	69		1,02			3,00
82,81	38,5	69			1,06		28,00
22,09	17,9	85	1,59				1,00
39,69	28,6	85		1,17			2,00
64	34,5	85		1,03			3,00
114,49	45	85			0,97		28,00
15,21	15,3	69	1,74				1,00
34,81	28	69		1,11			2,00
47,61	31,6	69		1,05			3,00
90,25	38,9	69			1,05		28,00
37,21	29,2	89	0,99				1,00
33,64	27	89		1,25			2,00
56,25	35,6	89		1,02			3,00
90,25	40	89			1,11		28,00
38,44	28,2	99	1,07				1,00
65,61	34,6	99		1,01			2,00
82,81	36,5	99		1,03			3,00
129,96	46	99			1,00		28,00
24,01	24,4	106	1,26				1,00
50,41	30,2	106		1,19			2,00
84,64	37,9	106		1,01			3,00
127,69	46,7	106			1,01		28,00
42,25	29,5	112	1,06				1,00
57,76	35	112		1,04			2,00
59,29	35,5	112		1,10			3,00
116,64	47,1	112			1,02		28,00
46,24	31,8	114	0,99				1,00
57,76	36,2	114		1,02			2,00

82,81	40,5	114		0,97			3,00
134,56	51,1	114			0,95		28,00
69	33,3	69				1,33	500,00
86	34,2	85				1,38	500,00
58	30,6	89				1,57	500,00
91	37,2	69				1,19	500,00
106	37,5	99				1,33	500,00
111	38,1	106				1,34	500,00
117	43,8	112				1,18	500,00
118	40,7	114				1,28	500,00
68	35,5	69				1,24	500,00
89	34,5	85				1,37	500,00
69	32,8	89				1,47	500,00
101	40,5	69				1,09	500,00
116	40,3	99				1,24	500,00
116	41,4	106				1,23	500,00
121	46,9	112				1,11	500,00
129	41,3	114				1,26	500,00
66,63	33,21	92,88	1,26	1,11	1,13	1,29	1,20



Appendix fibelaststrength

s	E_c		
0,20	40,90	1,00	
0,20	40,90	1,00	
0,20	43,85	2,00	
0,20	43,85	2,00	
0,20	40,90	3,00	
0,20	40,90	3,00	
0,20	44,52	4,00	
0,20	44,52	4,00	
0,20	46,13	5,00	
0,20	46,13	5,00	
0,20	47,19	6,00	
0,20	47,19	6,00	
0,20	48,06	7,00	
0,20	48,06	7,00	
0,20	48,35	8,00	
0,20	48,35	8,00	
0,20	40,90	1,00	
0,20	40,90	1,00	
0,20	43,85	2,00	
0,20	43,85	2,00	
0,20	40,90	3,00	
0,20	40,90	3,00	
0,20	44,52	4,00	
0,20	44,52	4,00	
0,20	46,13	5,00	
0,20	46,13	5,00	
0,20	47,19	6,00	
0,20	47,19	6,00	
0,20	48,06	7,00	
0,20	48,06	7,00	
0,20	48,35	8,00	
0,20	48,35	8,00	
0,20	40,90	1,00	
0,20	40,90		
0,20	40,90		
0,20	40,90		
0,20	43,85	2,00	
0,20	43,85		
0,20	43,85		0,50
0,20	43,85		1,50
0,20	40,90	3,00	
0,20	40,90		
0,20	40,90		
0,20	40,90		
0,20	44,52	4,00	
0,20	44,52		
0,20	44,52		
0,20	44,52		
0,20	46,13	5,00	
0,20	46,13		
0,20	46,13		
0,20	46,13		
0,20	47,19	6,00	
0,20	47,19		
0,20	47,19		
0,20	47,19		
0,20	48,06	7,00	
0,20	48,06		
0,20	48,06		
0,20	48,06		
0,20	48,35	8,00	
0,20	48,35		

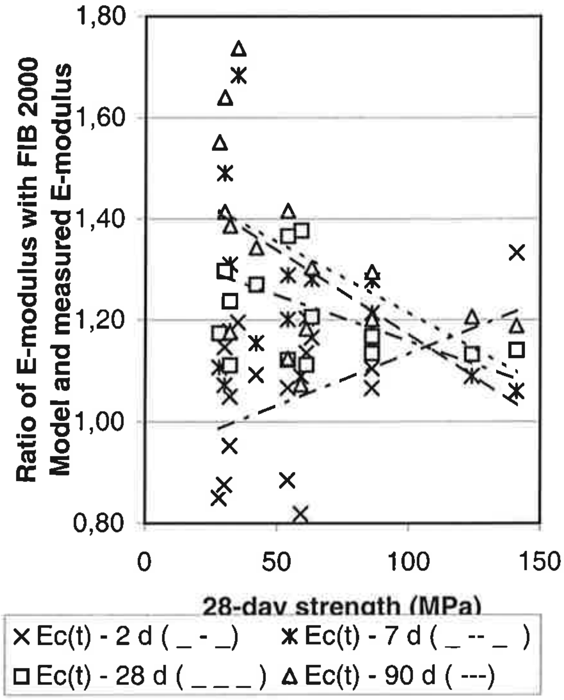
Appendix fibelaststrength

0,20	48,35	
0,20	48,35	
0,20	40,90	1
0,20	43,85	2
0,20	44,52	3
0,20	40,90	4
0,20	46,13	5
0,20	47,19	6
0,20	48,06	7
0,20	48,35	8
0,20	40,90	1
0,20	43,85	2
0,20	44,52	3
0,20	40,90	4
0,20	46,13	5
0,20	47,19	6
0,20	48,06	7
0,20	48,35	8
	44,99	

Appendix fibelast100

fc	E-modul (försegling)	fcm	$E_{c(t)}$ - 2 d (_ - _)	$E_{c(t)}$ - 7 d (_ -- _)	$E_{c(t)}$ - 28 d (_ _ _)	$E_{c(t)}$ - 90 d (---)	
63,00	29,60	141,00	1,33				27S
63,00	27,70	124,00	1,09				
110,00	40,80	141,00		1,06			
103,00	38,80	124,00		1,09			
141,00	45,50	141,00			1,14		
124,00	43,90	124,00			1,13		
158,00	47,40	141,00				1,19	
134,00	44,20	124,00				1,21	
36,00	23,90	59,00	0,82				32N
36,00	22,10	54,00	0,89				
50,00	27,90	59,00		1,09			
50,00	25,30	54,00		1,20			
59,00	28,20	59,00			1,38		
54,00	33,60	54,00			1,12		
61,00	39,80	59,00				1,07	
64,00	38,60	54,00				1,12	
45,00	19,30	42,00	1,09				38N
46,00	19,90	54,00	1,07				
46,00	25,60	42,00		1,15			
56,00	24,50	54,00		1,29			
42,00	27,30	42,00			1,27		
54,00	27,60	54,00			1,37		
43,00	28,30	42,00				1,34	
60,00	30,00	54,00				1,42	
65,00	27,60	86,00	1,10				38S
65,00	28,60	86,00	1,07				
76,00	29,90	86,00		1,28			
79,00	31,90	86,00		1,21			
86,00	38,80	86,00			1,13		
86,00	37,70	86,00			1,17		
98,00	40,00	86,00				1,20	
94,00	36,60	86,00				1,29	
23,00	14,70	30,00	1,15				50N
23,00	14,10	35,00	1,20				
27,00	16,60	30,00		1,49			
27,00	14,70	35,00		1,68			
30,00	16,40	30,00			1,89		
35,00	15,20	35,00			2,15		
38,00	25,80	30,00				1,41	
38,00	21,00	35,00				1,74	
43,00	23,40	61,00	1,14				50S
43,00	22,80	63,00	1,17				
52,00	28,00	61,00		1,20			
55,00	26,80	63,00		1,28			
61,00	35,30	61,00			1,11		
63,00	32,90	63,00			1,21		
67,00	35,80	61,00				1,18	
67,00	32,50	63,00				1,30	
14,00	16,80	28,00	0,85				80N
14,00	16,30	30,00	0,88				
24,00	21,50	28,00		1,11			
24,00	22,20	30,00		1,07			
28,00	25,80	28,00			1,17		
30,00	23,90	30,00			1,30		
32,00	22,20	28,00				1,55	
26,00	19,60	30,00				1,64	
18,00	16,30	32,00	0,95				80S
18,00	14,80	32,00	1,05				
27,00	21,00	32,00		1,18			
27,00	18,90	32,00		1,31			
32,00	28,50	32,00			1,11		
32,00	25,60	32,00			1,24		
34,00	29,90	32,00				1,18	
35,00	25,60	32,00				1,39	
	27,43	59,81	1,05	1,23	1,31	1,33	1,23

1,80

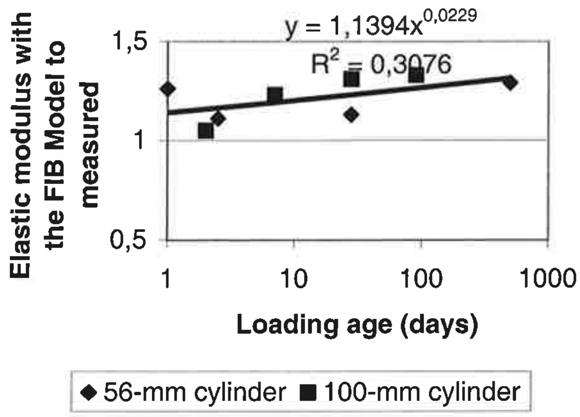

1,80
1,60
1,40
1,20
1,00
0,80
Ratio of E-modulus with FIB 2000 Model and measured E-modulus
0
50
100
150
28-day strength (MPa)
Ec(t) - 2 d (_ - _)
Ec(t) - 7 d (_ -- _)
Ec(t) - 28 d (_ _ _)
Ec(t) - 90 d (---)

Appendix fibelast100

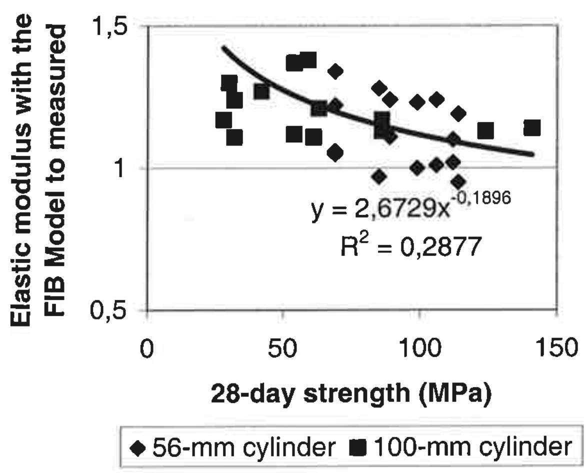
t	s	E_c
2,00	0,20	51,90
2,00	0,20	39,68
7,00	0,20	47,78
7,00	0,20	46,74
28,00	0,20	51,90
28,00	0,20	49,72
90,00	0,20	53,90
90,00	0,20	51,02
2,00	0,38	32,94
2,00	0,38	32,94
7,00	0,38	36,74
7,00	0,38	36,74
28,00	0,38	38,83
28,00	0,38	37,70
90,00	0,38	39,26
90,00	0,38	39,89
2,00	0,38	35,48
2,00	0,38	35,74
7,00	0,38	35,74
7,00	0,38	38,16
28,00	0,38	34,67
28,00	0,38	37,70
90,00	0,38	34,94
90,00	0,38	39,04
2,00	0,20	40,10
2,00	0,20	40,10
7,00	0,20	42,24
7,00	0,20	42,79
28,00	0,20	44,02
28,00	0,20	44,02
90,00	0,20	45,97
90,00	0,20	45,34
2,00	0,38	28,37
2,00	0,38	28,37
7,00	0,38	29,93
7,00	0,38	29,93
28,00	0,38	31,00
28,00	0,38	32,63
90,00	0,38	33,54
90,00	0,38	33,54
2,00	0,20	34,94
2,00	0,20	34,94
7,00	0,20	37,23
7,00	0,20	37,93
28,00	0,20	39,26
28,00	0,20	39,68
90,00	0,20	40,51
90,00	0,20	40,51
2,00	0,38	24,05
2,00	0,38	24,05
7,00	0,38	28,78
7,00	0,38	28,78
28,00	0,38	30,29
28,00	0,38	31,00
90,00	0,38	31,67
90,00	0,38	29,55
2,00	0,38	26,15
2,00	0,38	26,15
7,00	0,38	29,93
7,00	0,38	29,93
28,00	0,38	31,67
28,00	0,38	31,67
90,00	0,38	32,32
90,00	0,38	32,63
		36,64

Appendix fibelasttime

	56-mm cylinder	100-mm cylinder
1	1,26	
2,5	1,11	
28	1,13	
500	1,29	
2	1,05	1,05
7	1,23	1,23
28	1,31	1,31

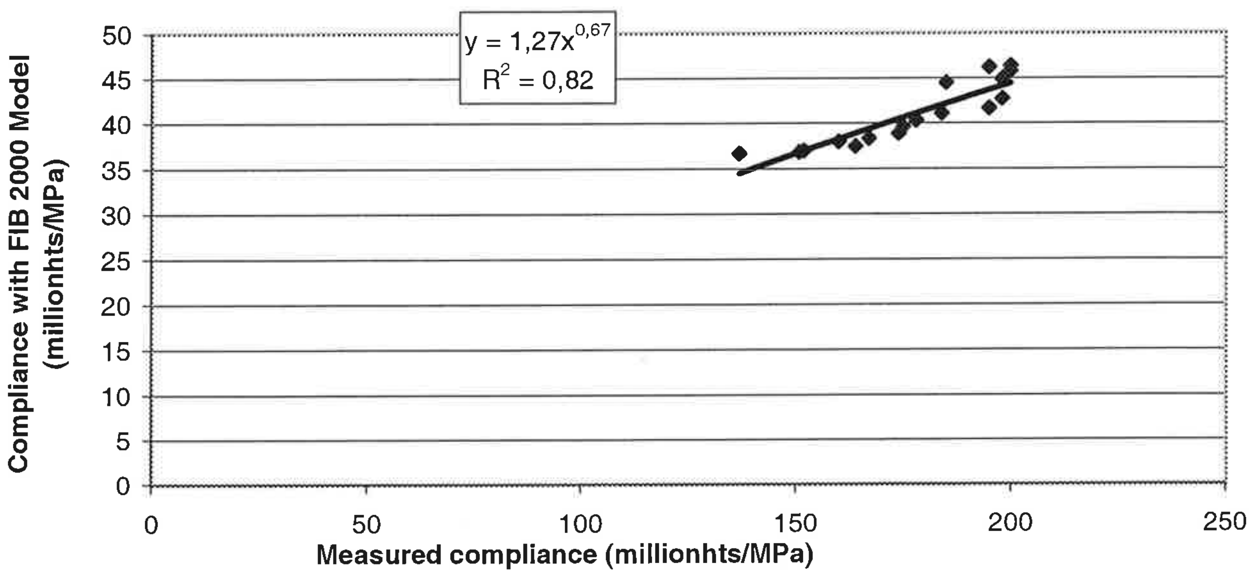


fcm	56-mm cylinder	100-mm cylinder
69	1,22	
85	1,28	
69	1,34	
89	1,24	
99	1,23	
106	1,24	
112	1,1	
114	1,19	
69	1,06	
85	0,97	
69	1,05	
89	1,11	
99	1	
106	1,01	
112	1,02	
114	0,95	
141	1,14	1,14
124	1,13	1,13
59	1,38	1,38
54	1,12	1,12
42	1,27	1,27
54	1,37	1,37
86	1,13	1,13
86	1,17	1,17
30	1,89	1,89
35	2,15	2,15
61	1,11	1,11
63	1,21	1,21
28	1,17	1,17
30	1,3	1,3
32	1,11	1,11
32	1,24	1,24
76,34375	1,215625	

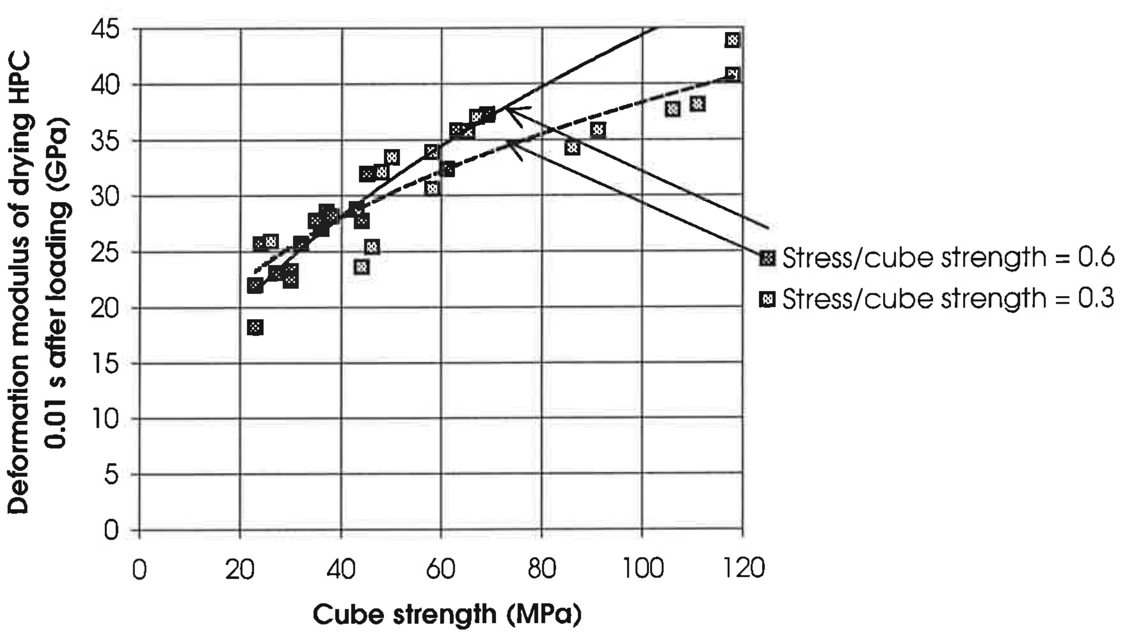


Appendix 1B01

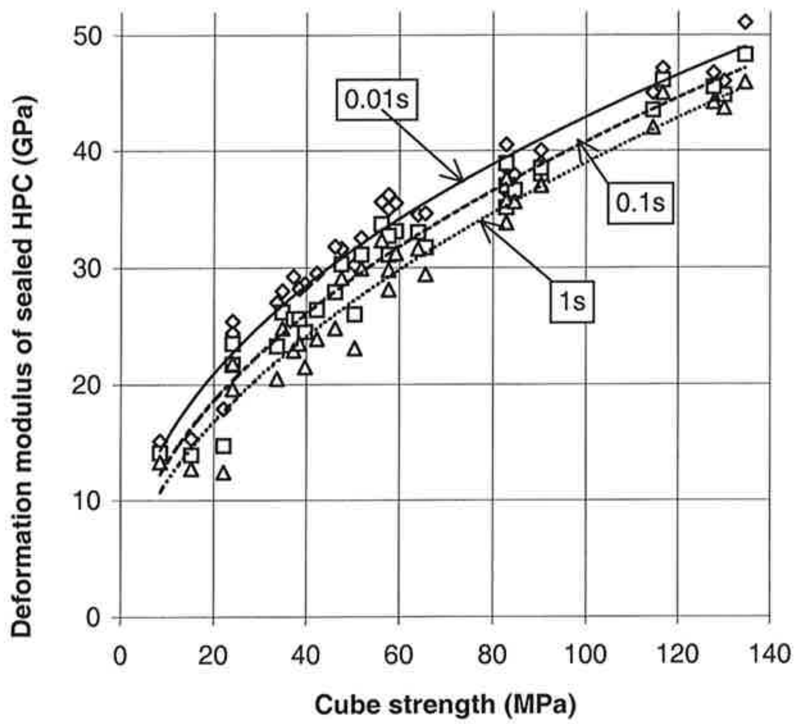
tage	tload	J(t,t0)m	J(t,t0)	n(t0)	fi0	fiRH	RH	d	alfa1	alfa2	beta(fcm)	beta(t0)	t0	beta(t,t0)	betaH	fi(t,t0)	Ec	Ec(t0)	s	fcm0	fcm
4	3	137	37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
11	10	151	37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,02	604,60	0,01	0,042	0,027	0,20	14	82
19	18	152	37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,03	604,60	0,02	0,042	0,027	0,20	14	82
42	41	164	37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,06	604,60	0,04	0,042	0,027	0,20	14	82
71	70	160	38	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,10	604,60	0,06	0,042	0,027	0,20	14	82
91	90	167	38	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,13	604,60	0,07	0,042	0,027	0,20	14	82
130	129	174	39	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,18	604,60	0,10	0,042	0,027	0,20	14	82
178	177	175	40	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,23	604,60	0,13	0,042	0,027	0,20	14	82
241	240	178	40	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,28	604,60	0,16	0,042	0,027	0,20	14	82
317	316	184	41	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,34	604,60	0,19	0,042	0,027	0,20	14	82
382	381	195	42	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,39	604,60	0,21	0,042	0,027	0,20	14	82
522	521	198	43	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,46	604,60	0,26	0,042	0,027	0,20	14	82
901	900	185	44	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,60	604,60	0,33	0,042	0,027	0,20	14	82
1041	1040	198	45	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,63	604,60	0,35	0,042	0,027	0,20	14	82
1381	1380	200	46	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,70	604,60	0,39	0,042	0,027	0,20	14	82
1611	1610	195	46	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,73	604,60	0,40	0,042	0,027	0,20	14	82
1721	1720	200	46	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,74	604,60	0,41	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82
1			37	1,54	0,55	1,35	94	56	0,70	0,90	0,45	0,91	1	0,00	604,60	0,00	0,042	0,027	0,20	14	82



	Stress/cube strengt	Stress/cube strength = 0.3				
23	18,2					
32	25,7					
24	25,7					
44	27,8					
27	23,1					
30	23,3					
23	22					
37	28,6					
38	28,2					
45	31,9					
30	22,5					
61	32,4					
36	27,1					
63	35,8					
35	27,8					
69	37,2					
26		25,9				
50		33,4				
44		23,6				
86		34,2				
43		28,8				
58		30,6				
48		32,1				
91		35,8				
46		25,4				
106		37,6				
58		33,9				
111		38,1				
67		37				
118		43,8				
65		35,7				
118		40,7				



fc0.5	fc	em0.01	em(	em1	
2,92	8,53	15,1	14	13,3	50
4,9	24	25,4	24	21,8	
7,2	51,8	32,5	31	29,9	
9,1	82,8	38,5	37	35,7	
4,7	22,1	17,9	15	12,4	90
6,3	39,7	28,6	25	21,5	
8	64	34,5	33	31,6	
10,7	114	45	44	42	
3,9	15,2	15,3	14	12,7	90L
5,9	34,8	28	26	24,8	
6,9	47,6	31,6	30	29,1	
9,5	90,3	38,9	38	37,1	
6,1	37,2	29,2	26	22,9	90R
5,8	33,6	27	23	20,5	
7,5	56,3	35,6	34	32,3	
9,5	90,3	40	39	37	
6,2	38,4	28,2	26	23,5	110
8,1	65,6	34,6	32	29,4	
9,1	82,8	36,5	35	33,8	
11,4	130	46	45	43,7	
4,9	24	24,4	22	19,6	130
7,1	50,4	30,2	26	23,1	
9,2	84,6	37,9	37	35,6	
11,3	128	46,7	46	44,2	
6,5	42,3	29,5	26	23,9	130F
7,6	57,8	35	31	28,1	
7,7	59,3	35,5	33	31,2	
10,8	117	47,1	46	45	
6,8	46,2	31,8	28	24,8	150
7,6	57,8	36,2	33	29,8	
9,1	82,8	40,5	39	37,6	
11,6	135	51,1	48	45,9	

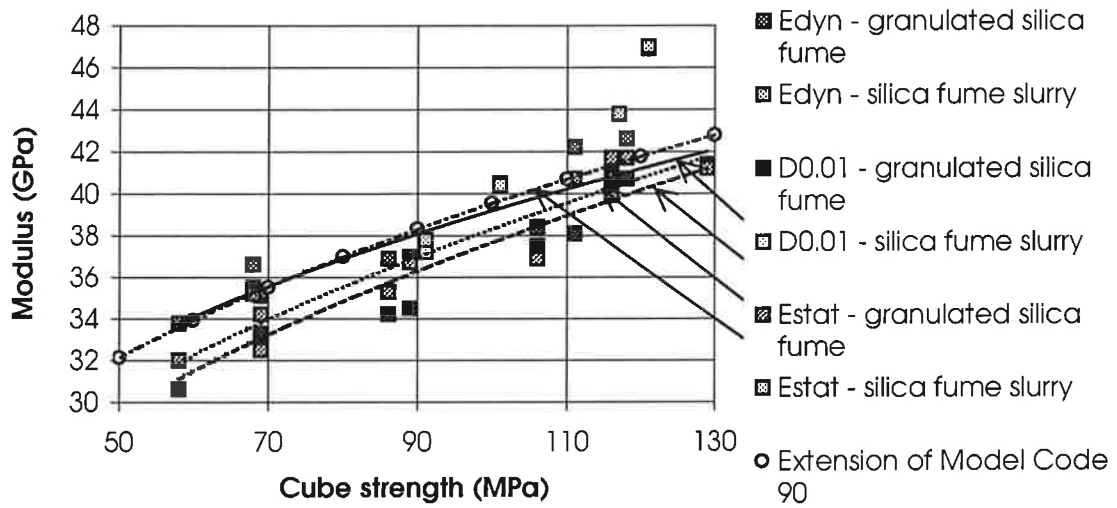


	a	b
0,01	5,5	0,447
0,1	4,3	0,489
1	3,5	0,524

Appendix cdynage1

Cdynage1

	Edyn - granulated silica fume	Edyn - silica fume slurry	D0.01 - granulated silica fume	D0.01 - silica fume slurry
69	35,1		33,3	
86	36,9		34,2	
58	33,8		30,6	
91				37,2
106	38,4		37,5	
111	42,2		38,1	
117				43,8
118	42,6		40,7	
68	36,6		35,5	
89	37		34,5	
69	35,3		32,8	
101		40,5		
116	40,4		40,3	
116	40,7		41,4	
121		48,9		46,9
129	41,4		41,3	

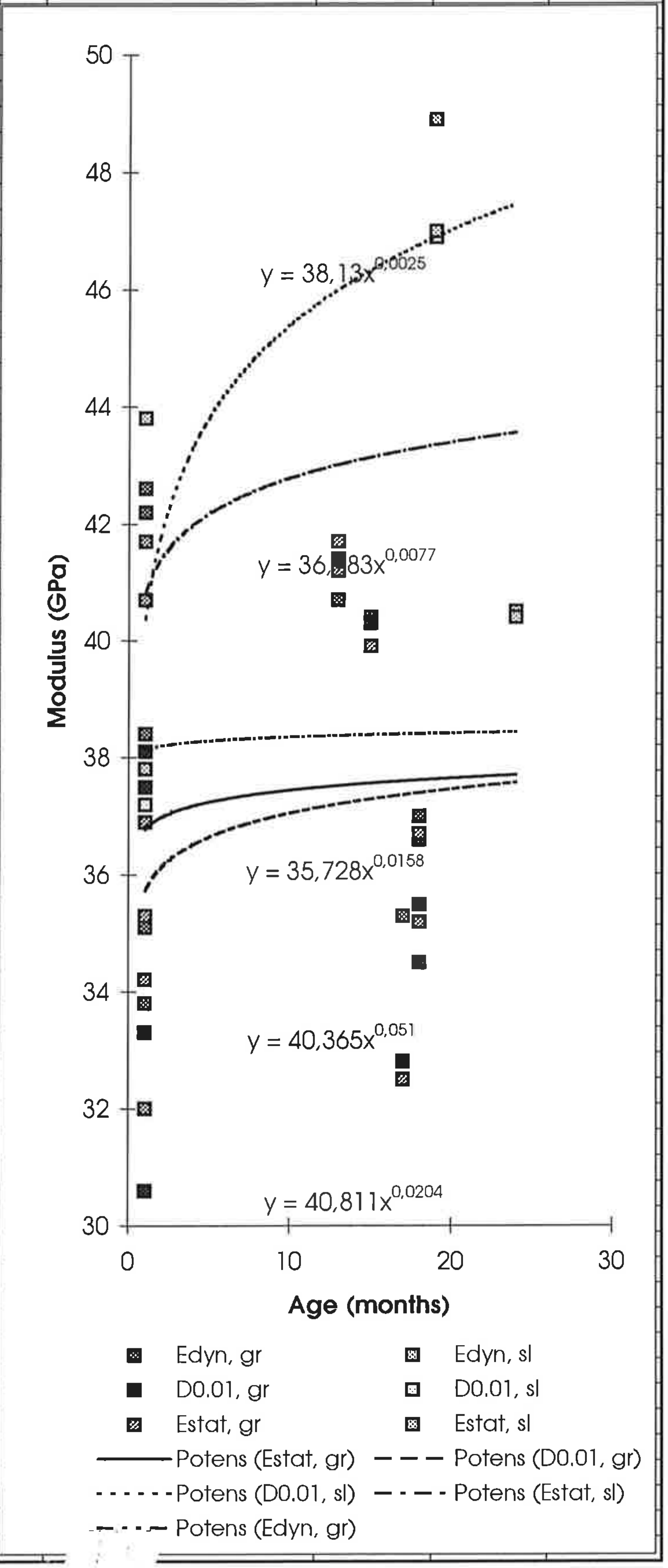


	Edyn, gr	Edyn, sl	D0.01, gr	D0.01, sl
1	35,1		33,3	
1	36,9		34,2	
1	33,8		30,6	
1				37,2
1	38,4		37,5	
1	42,2		38,1	
1				43,8
1	42,6		40,7	
18	36,6		35,5	
18	37		34,5	
17	35,3		32,8	
24		40,5		
15	40,4		40,3	
13	40,7		41,4	
19		48,9		46,9
13	41,4		41,3	

Appendix cdynage1 Cdynage1

Estat - granulated silica fume	Estat - silica fume slurry			Extension of Model Code 90			
34,2		1	50	32,11			
35,3		2	60	33,92			
32		3	70	35,52			
	37,8	4	80	36,97			
36,9		5	90	38,3			
40,7		6	100	39,53			
	43,8	7	110	40,68			
41,7		8	120	41,75			
35,2		1	130	42,77			
36,7		2					
32,5		3					
	40,4	4					
39,9		5					
41,7		6					
	47	7					
41,2		8					

Estat, gr	Estat, sl
34,2	
35,3	
32	
	37,8
36,9	
40,7	
	43,8
41,7	
35,2	
36,7	
32,5	
	40,4
39,9	
41,7	
	47
41,2	



Appendix bfrcem

Bfrcem

	fc	fc/fc28	ó/fc	B02	D02	B07	D07	B28	D28	B90	D90	fc	E-modul (försegling	E-modul (uttorkning
27S	63	0,45	0,4	0,78								63	29,6	
	63	0,51	0,4		0,95							63	27,7	27,7
	110	0,78	0,31			0,81						110	40,8	
	103	0,83	0,4				0,84					103	38,8	38,8
	141	1	0,18					0,62				141	45,5	
	124	1	0,2						0,62			124	43,9	43,9
	158	1,12	0,19							0,29		158	47,4	
	134	1,08	0,22								0,36	134	44,2	44,2
32N	36	0,85	0,68	1,79								36	23,9	
	36	0,93	0,7		3,7							36	22,1	22,1
	50	0,92	0,59			1,83						50	27,9	
	50	0,97	0,55				3,45					50	25,3	25,3
	59	1	0,53					1,23				59	28,2	
	54	1	0,65						3,25			54	33,6	33,6
	61	1,1	0,35							1,13		61	39,8	
	64	1,1	0,35								1,99	64	38,6	38,6
38N	45	0,98	0,79	1,47								45	19,3	
	46	0,83	0,78		2,82							46	19,9	19,9
	46	1	0,78			1,84						46	25,6	
	56	0,93	0,62				3,26					56	24,5	24,5
	42	1	0,7					1,73				42	27,3	
	54	1	0,7						3,09			54	27,6	27,6
	43	1,1	0,35							0,93		43	28,3	
	60	1,1	0,35								1,35	60	30	30
38S	65	0,76	0,4	1,1								65	27,6	
	65	0,76	0,4		1,79							65	28,6	28,6
	76	0,88	0,41			1,13						76	29,9	
	79	0,92	0,39				2,28					79	31,9	31,9
	86	1	0,2					1,05				86	38,8	
	86	1	0,2						1,71			86	37,7	37,7
	98	1,14	0,21							0,57		98	40	
	94	1,1	0,2								1,11	94	36,6	36,6
50N	23	0,77	0,69	2,12								23	14,7	
	23	0,66	0,69		3,64							23	14,1	14,1
	27	0,9	0,71			1,56						27	16,6	
	27	0,77	0,7				3,63					27	14,7	14,7
	30	1	0,7					1,42				30	16,4	
	35	1	0,6						3,02			35	15,2	15,2
	38	1,27	0,35							1,27		38	25,8	
	38	1,09	0,35								1,53	38	21	21
50S	43	0,7	0,4	1,29								43	23,4	
	43	0,66	0,4		2,28							43	22,8	22,8
	52	0,85	0,41			1,17						52	28	
	55	0,77	0,39				2,45					55	26,8	26,8
	61	1	0,2					1,3				61	35,3	
	63	1	0,19						2,15			63	32,9	32,9
	67	1	0,2							1,04		67	35,8	
	67	1	0,2								1,5	67	32,5	32,5
80N	14	0,5	0,7	1								14	16,8	
	14	0,47	0,7		3							14	16,3	16,3
	24	0,85	0,47			1,02						24	21,5	
	24	0,8	0,47				2,15					24	22,2	22,2
	28	1	0,39					0,89				28	25,8	
	30	1	0,36						1,67			30	23,9	23,9
	32	1,14	0,56							1,6		32	22,2	
	26	1,15	0,6								2,13	26	19,6	19,6
80S	18	0,56	0,4	1,29								18	16,3	
	18	0,56	0,4		2,7							18	14,8	14,8
	27	0,84	0,4			1,33						27	21	
	27	0,86	0,3				3,13					27	18,9	18,9
	32	1	0,2					1,71				32	28,5	
	32	1	0,2						3,74			32	25,6	25,6
	34	1,06	0,2							0,98		34	29,9	
	35	1,09	0,19								1,44	35	25,6	25,6