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TOPIC	Durability and Mechanical Properties of Old Concrete Test Specimens with Mowilith LDM 6880 FINAL REPORT
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This report consists of 20 pages, 9 of them text pages.
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1 OBJECTIVE OF THE TESTS

The objective of the project was to determine significant properties of 10-year-old concrete which had been modified with Mowilith LDM 6880 and to study the change of these properties up until this age. Mechanical properties such as compressive strength, splitting tensile strength and elastic modulus on the one hand and, on the other, characteristic values that decisively influence the durability of reinforced concrete components, such as carbonatisation and chloride penetration resistance, were to be determined.

2 TEST SPECIMENS

Concrete prisms of 50 cm in length were used that had been manufactured at ibac in the course of tests for the authorisation of Mowilith LDM 6880; see /1/. An overview of the test specimens remaining from this time is shown in Figure 1. Used for both types of concrete (with and without Mowilith) was a cement with a high Na_2O equivalent (1.2%): CEM I 42.5 R (old designation: PZ 45 F) of Heidelberger Zement AG, Lengfurt plant. The concrete was manufactured with 300 kg/m^3 of cement, a water/cement ratio of 0.50 and grain-size distribution A32/B32. Based on the cement content, 0.6% multi-fluid plasticiser was added to the concrete without Mowilith. The Mowilith content of the modified concrete was 60 kg/m^3, all of which was counted as part of the water portion. Please refer to /1/ concerning the fresh concrete values and the hardened concrete values calculated up to the age of one year.

3 CHARACTERISTIC VALUES

3.1 Storage and Designation of Test Specimens

The test specimens studied here were stored at 20 °C under water until the age of 7 days and then at normal climate 20/65 according to DIN 50014. The points from where the different test specimens were taken are identified in Figure 1. In the test specimen numbers specified there, which are comprised of the mixture no. (digits before the diagonal slash) and the no. of each test specimen within a mixture (digit after the diagonal slash), the first digit indicates the type of concrete. “1” stands for concrete without Mowilith and “2” for concrete with Mowilith.

3.2 Compressive Strength

For each type of concrete, the compressive strength was calculated according to DIN 1048-5 06.91 for 3 cubes with an edge length of 100 mm. In the concrete without Mowilith, an average compressive strength of 53.5 N/mm^2 was achieved at the age of 3803 days (individual values: 53.1; 53.1; 53.8). In the concrete with Mowilith, an average compressive strength of 77.9 N/mm^2 was achieved at the age of 3871 days (individual values: 71.5; 81.3; 80.3).

Table 1 lists the values from the authorisation tests /1/ and the 10-year value, whereby the 10-year value without Mowilith is equated with the 1-year value. This appears justified based on the following two assumptions:

- The smaller side length of the 10-year cube (100 mm) compared to the side length of the cubes tested in /l/ (150 mm) is compensated for by the compressive strength ratio of smaller to larger cubes, which drops to a level considerably below 1 at a high age (see /2/, page 242).

- The strength does not decrease between 1 and 10 years.

The same factor (1.02) used for multiplying with the 10-year test value (average value of the calculated individual values) of the concrete without Mowilith (53.3 N/mm^2) was also used for multiplying with the 10-year test value of the concrete with Mowilith (77.9 N/mm^2). While the increase in strength for the concrete without Mowilith is 0% according to the assumptions, there is a considerable increase in strength of 25% for the Mowilith concrete based on the same assumptions. The 46% increase in compressive strength by adding Mowilith at the age of 10 years is significantly higher than in younger concrete (between 8 and 17%; see Table 1).

3.3 Elastic Modulus

For each type of concrete, the static elastic modulus was calculated according to DIN 1048-5 06.91 in 3 cylinders with a diameter of around 95 mm and a length of around 190 mm. The cylinders had been drilled out of the concrete prisms in an axial direction. The upper test tension was 42% of the average concrete compressive strength achieved in the 100 mm cubes (see Table 1). The elongations were measured along 3 lines distributed uniformly around the circumference.

For the concrete without Mowilith, an average E-modulus of 40,800 N/mm^2 was achieved at the age of 3849 days (individual values: 40,700; 40,800). For the concrete with Mowilith, an average E-modulus of 40,400 N/mm^2 was determined at the age of 3917 days (individual values 41,800 (test specimen 207/4); 39,700; 39,700). In addition, an E-modulus of 41,300 N/mm^2 was calculated in a second cylinder of test specimen 207/4 (see Figure 1) at a load level of 30%. This minimal difference shows that the E-modulus is not significantly influenced by the different load level. The average E-modulus values at the age of 28 days (see /1/) and 10 years are compiled in Table 2.

If the 10-year values are compared with the 28-day values, this largely confirms the extremely minimal difference of 1% between the concrete with and without Mowilith. The fact that the 10-year value is 9% (without Mowilith) and 8% (with Mowilith) over the 28-day value is presumably attributable in part to the different test specimen sizes.

3.4 Splitting Tensile Strength

The splitting tensile strength was determined in the E-modulus test specimens according to DIN 1048-5 06.91. For the concrete without Mowilith, an average splitting tensile strength of 3.41 N/mm^2 was achieved at the age of 3852 days (individual values: 3.52; 3.29). For the concrete with Mowilith, an average splitting tensile strength of 5.11 N/mm^2 was achieved at the age of 3920 days (individual values: 5.08; 5.94; 4.18; 5.25).

Table 3 lists the values from the authorisation tests /1/ and the 10-year value. The fact that the 10-year values are lower compared to the 1-year values may well be attributable to the very different test specimens – at least in part. As with the compressive strength, the improvement in the splitting tensile strength by adding Mowilith became more considerable with increasing age, reaching 50% at the age of nearly 11 years; see Table 3.

3.5 Carbonatisation

For each type of concrete, the carbonatisation depth was determined parallel to the fracture surfaces of the three test specimens and perpendicular to the longitudinal axis of the prisms. Table 4 lists the values from the approval tests /1/, the measurements taken afterwards and the 10.5-year value.

After more than 10 years, the carbonatisation depth is reduced to 1/3 by adding Mowilith.

3.6 Chloride Penetration Resistance

3.6.1 Preparation of Test Specimens

Cylindrical test specimens with a diameter of 100 mm and a length of 50 mm were used for the tests. To obtain these from the existing concrete prisms, cubes with an edge length of 100 mm were sawn off the prisms and embedded in mortar before drilling out the cylinders. From 3 prisms each of mixtures 118 and 218, a core was cut perpendicular to the surface not covered by the casing (filling side), which then was cut into two halves each approx. 50 mm long. These two test specimens are differentiated below by the suffix “E” for filling side [German: “Einfüllseite”] and “S” for casing side [German: “Schalungsseite”]. Only 1 test specimen each was obtained from the prisms of mixtures 107 and 207. The end surfaces of all test specimens were ground plane-parallel before starting the tests, with the cement paste layer having been removed from the casing side and the filling side. The designations of the test specimens, their position in the prism and their dimensions are shown in Tables 5 and 6.

3.6.2 Two-Electrode Method (TEM)

The two-electrode method is a method for determining the level of electrolytic resistance of concrete. To do this, alternating current at a frequency of 100-1000 Hz is applied and the resulting current is measured. The quotient of the two parameters is the associated alternating current resistance. This alternating current resistance is a close approximation of the electrolytic resistance of the concrete for said frequency range.

The cylindrical test specimens (diam. = 100 mm, l = 50 mm) are placed between the electrodes as indicated above, thereby enabling the electrolytic resistance of water-saturated test specimens to be measured. In order to convert the calculated absolute resistance values to specific resistance values later on, the test specimen length needs to be determined beforehand at a precision of 0.5 mm.

The absolute resistance values determined are converted to specific electrolytic resistance values using equation (1).

$$\rho_{TEM,0} = R_{el} \cdot \frac{A}{l}$$

whereby

$\rho_{TEM,0}$:	specific electrolytic resistance (TEM) in [Ωm]
R_{el}:	measured resistance in [Ω]
A:	test specimen cross section [m^2]
l:	test specimen length (height) in [m]

3.6.3 Rapid Chloride Migration Test

The rapid chloride migration test is a method for determining the chloride migration coefficient of mortar and concrete. The test set-up can be seen in Figure 3.

The test specimens must be completely saturated with water to prevent Cl ions from being transported due to any other cause. The differences in concentration of the pending solutions on the one hand and the application of an electrical field on the other bring about chloride transport within the test specimen via diffusion and migration.

The test specimens are enclosed in a rubber seal to ensure that the pending chloride-free (0.2 N KOH) and chloride-containing solutions (0.2 N KOH + 10% NaCl) do not mix. The sealed test specimens are then placed on a holding device. Thus prepared, the positioned electrodes are used to generate the electrical field, which accelerates the penetration of the chlorides considerably. To ensure sufficiently deep penetration of the chlorides, the test duration is selected according to the current I_o measured at the start of testing. When testing is over, the test specimens are removed and split. A suitable indicator solution (e.g. $AgNO_3$) is used to visually determine and record the penetration depth x_d of the chlorides.

The chloride migration coefficients are calculated with the equations (2) to (4)

$$D_{RCM,0}\Big| = \frac{R\ T\ L}{zFU} \cdot \frac{x_d - \alpha\sqrt{x_d}}{t} \qquad (2)$$

:

whereby

$$\alpha = 2\left|\sqrt{\frac{RTL}{zFU}} \cdot \mathrm{erf}^{-1} \cdot \left(1-\frac{2c_d}{c_0}\right)\right| \tag{3}$$

$$\xi = \mathrm{erf}^{-1}\left(1-\frac{2 \cdot c_d}{c_0}\right) \tag{4}$$

D_{RCM0}: chloride migration coefficient, $[m^2/s]$

z: load number, for chloride: z = 1

F: Faraday constant, $F = 9.648 \cdot 10^4$ $[J\ (V \cdot mol)^{-1}]$

U: voltage, [V]

R: universal gas constant, $R = 8.314$ $[J\ (K \cdot mol)^{-1}]$

T: temperature, [K]

L: test cylinder length, [m]

x_d: chloride penetration depth, [m], determined with indicator solution $AgNO_3$

t: test duration in [s]

erf^{-1}: inverse of error function

c_d: chloride concentration at which the indicator solution causes a colour change, $c_d = 0.07$ $mol \cdot l^{-1}$

c_0: chloride concentration in the chloride-contaminated test chamber $[mol \cdot l^{-1}]$

ξ: auxiliary variable (see Table 7)

3.6.4 Presentation and Discussion of the Results

Figure 4 shows the electrolytic resistance values determined from the two-electrode measurements for the water-saturated test specimens. The graphed values each represent average values from four individual measurements. The results of the individual measurements are found in Tables 8 and 9. It is evident that the specific electrolytic resistance values of the test specimens with Mowilith are multiple times higher than those of the test specimens without Mowilith. No influence due to the original position of the test specimens in the concrete prism on the electrolytic resistance values can be determined. However, there is influence because of the concrete batch. Despite the same concrete composition, the electrolytic resistance values of mixtures 107 and 207 and considerably higher than those of mixtures 118 and 218, respectively.

For the rapid chloride migration tests conducted, the penetration depths determined for the chloride front (determined with silver nitrate solution) are listed in Tables 10 and 11. Since the side seal (rubber seal) did not completely prevent the accelerated penetration of chlorides, greater penetration depths can be found on some of the edges. The increased penetration depths on the edges were not factored in when assessing the tests.

The test parameters for the rapid chloride migration tests conducted and the chloride migration coefficients calculated with equations (2) to (4) are listed in Tables 12 and 13. Image 5 shows a comparison of the calculated chloride migration coefficients. It is evident that the chloride migration coefficients are markedly reduced by adding Mowilith. In other words, the chloride penetration resistance is noticeably increased.

The results of the rapid chloride migration test are also right in line with the results of the electrolytic resistance measurements. /3/ shows the functional relationship between the results of the rapid chloride migration tests and the results of the two-electrode measurement. In Figure 6, the measuring results obtained are depicted in a diagram summarising the results found in the literature. It can be clearly seen that there is close agreement between the results found in the literature and the values determined here.

Both the results of the two-electrode measurement as well as the results of the rapid chloride migration tests indicate that adding Mowilith to the concrete recipes tested here results in considerable sealing of the concrete pore structures and thus markedly increases the level of chloride penetration resistance.

4 LITERATURE

/1/ ibac; AG 1; Rössler, G.; Vannahme, S.; A 2449/3): Zulassungsversuche für den organischen Zusatzstoff "Mowilith LDM 6880" als Betonzusatzstoff nach DIN 1045 (Authorisation Tests for the Organic Additive "Mowilith LDM 6880" as a Concrete Additive according to DIN 1045). Aachen: Institute for Construction Research, 1993. Test Report No. A 2449/3

/2/ Wesche, K: Baustoffe für tragende Bauteile. Bd. 2: Beton, Mauerwerk (Building Materials for Load-Bearing Components. Vol. 2: Concrete, Masonry). 3rd ed., Wiesbaden: Bauverlag, 1993

/3/ Gehlen, C.; Ludwig, H.-M.; Brite Euram: Compliance Testing for Probalistic Design Purposes. Brussels: European Union – Brite EuRam, 1999. – Contract BRPR-CT95-0132, Project BE95-1347, Document BE95-1347/R8, March 1999

Table 1: Compressive Strength; Average Values

Age	Compressive Strength		
	Concrete without Mowilith	Concrete with Mowilith	Concrete with Mowilith compared to concrete without Mowilith
d	N/mm^2		-
1	2	3	4
3	32.6*	35.3*	1.08
7	33.9*	39.8*	1.17
28	42.4*	48.7*	1.15
90	50.8*	55.7*	1.10
360	54.4*	63.4*	1.17
3803 [1]	54.4 [2]	79.5 [2]	1.46

* See ibac Test Report A 2449/3 dated 22/12/1993
[1] with Mowilith 3871 days
[2] calculated value = test value * factor (factor: 360-d value / test value = 54.4/53.3)

Table 2: Elastic Modulus; Average Values

Age	Elasticity Modulus		
	Concrete without Mowilith	Concrete with Mowilith	Concrete with Mowilith compared to concrete without Mowilith
d	N/mm^2		-
1	2	3	4
28	37,500*	37,300*	0.99
3849 [1]	40,800	40,400	0.99

* See ibac Test Report A 2449/3 dated 22/12/1993
[1] with Mowilith 3917 days

Table 3: Spitting Tensile Strength; Average Values

Age	Splitting Tensile Strength		
	Concrete without Mowilith	Concrete with Mowilith	Concrete with Mowilith compared to concrete without Mowilith
d	N/mm^2		-
1	2	3	4
3	3.01*	3.72*	1.24
7	3.26*	4.20*	1.29
28	3.55*	4.42*	1.25
90	4.19*	5.05*	1.21
360	4.36*	5.95*	1.36
3852 [1]	3.41 [2]	5.11 [2]	1.50

* See ibac Test Report A 2449/3 dated 22/12/1993; values calculated for prisms with a cross-section side length of 100 mm
[1] with Mowilith 3920 days
[2] values calculated using cylinders with a diameter of 95 mm and a length of 190 mm

Table 4: Carbonatisation Depths; Average Values

Age	Carbonatisation	
	Without Mowilith	With Mowilith
	mm	
1	2	3
14 d	0.1*	0.0*
28 d	0.6*	0.1*
56 d	1.4*	0.3*
98 d	3.8*	0.9*
140 d	4.7*	1.0*
1 a	5.5*	1.8
2 a	6.0	2.2
3 a	7.8	2.9
5 a	9.1	2.7
7 a	10.6	4.2
10.5 a	12.7	4.3

* See ibac Test Report A 2449/3 dated 22/12/1993

Table 5: Test Specimens of Concrete without Mowilith

Test Designation	Position in Prism	Diameter	Length
-	-	mm	mm
1	2	3	4
118-4E	near filling side	100.3	48.0
118-5E		100.3	49.3
118-6E		100.3	47.8
118-4S	near casing side	100.3	48.2
118-5S		100.3	47.1
118-6S		100.3	48.2
107-1		100.5	47.8

Table 6: Test Specimens of Concrete with Mowilith

Test Designation	Position in Prism	Diameter	Length
-	-	mm	mm
1	2	3	4
218-4E	near filling side	100.3	49.5
218-5E		100.3	45.4
218-6E		100.3	48.0
218-4S	near casing side	100.3	49.0
218-5S		100.3	48.5
218-6S		100.3	48.6
207-5		100.5	50.6
207-6		100.5	47.7

Table 7: Auxiliary Variable ξ as a Function of Chloride Concentration c_0

c_0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
	$mol \cdot l^{-1}$								
ξ	0.764	1.044	1.187	1.281	1.351	1.407	1.452	1.491	1.554

<u>Table 8:</u> Specific Resistance Values of Mowilith-Free Test Specimens Calculating Using the Two-Electrode Method

Test Specimen Designation	Test Date	Specific Resistance Value				
		Measurement				Average
		1	2	3	4	
		Ωm				
1	2	3	4	5	6	7
118-4E	29/10/2002	235.39	240.33	241.97	245.27	**240.74**
118-5E		246.81	250.02	250.02	248.41	**248.81**
118-6E		231.42	234.72	233.07	233.07	**233.70**
118-4S	04/11/2002	245.89	240.97	244.25	247.53	**244.66**
118-5S		249.95	254.98	260.02	249.95	**253.73**
118-6S		249.17	252.44	250.80	250.80	**250.80**
107-1	12/02/2003	320.30	330.25	336.89	320.30	**326.93**

<u>Table 9:</u> Specific Resistance Values of Mowilith-Containing Test Specimens Calculating Using the Two-Electrode Method

Test Specimen Designation	Test Date	Specific Resistance Value				
		Measurement				Average
		1	2	3	4	
		Ωm				
1	2	3	4	5	6	7
218-4E	29/10/2002	716.69	716.69	721.48	724.67	**719.88**
218-5E		678.74	685.7	689.18	692.66	**686.57**
218-6E		767.07	776.95	786.83	788.47	**779.83**
218-4S	04/11/2002	749.81	757.87	756.26	759.48	**755.85**
218-5S		684.23	680.97	689.11	692.37	**686.67**
218-6S		726.71	731.59	721.84	733.22	**728.34**
207-5	12/02/2003	1194.61	1199.31	1186.77	1188.34	**1192.26**
207-6		1150.83	1155.82	1164.13	1172.45	**1160.80**

Table 10: Chloride Penetration Depths in Test Specimens without Mowilith after RCM (Rapid Chloride Migration Test) Measured with $AgNO_3$ Solution

Test Specimen	Test Surface	Chloride Penetration Depth at Measuring Point											Average Chloride Penetration Depth
		1	2	3	4	5	6	7	8	9	10	11	
-	-	mm											
1	2	3	4	5	6	7	8	9	10	11	12	13	14
118-4E	left	48[1)]	36[1)]	10.5	not det.	9	9	10	12	11	11.5	48[1)]	10.30
	right	48[1)]	10	9.5	not det.	9	9.5	11	11.5	10	11	48[1)]	
118-5E	left	12[1)]	7	7.5	7	9	5.5	7.5	5.5	6.5	13	15.5[)]	7.97
	right	13[1)]	6.5	8.5	7	7	8	9.5	7	9	12.5	13[1)]	
118-6E	left	47[1)]	10	9.5	10	8	8.8	8	9	8	12.5	29[1)]	9.08
	right	47[1)]	10	8.5	10	6.5	9	8	9.5	9	20[1)]	29.5[1)]	
118-4S	left	18[1)]	13	16	7.5	10	16	8	15.5	10	33[1)]	48[1)]	11.97
	right	18[1)]	11.5	12	7.5	13	14	8	12.5	13	16	48[1)]	
118-5S	left	47[1)]	47[1)]	9	13	13	12	8	9	8	47[1)]	47[1)]	10.82
	right	47[1)]	47[1)]	13	10.5	15	17	6	10	8	47[1)]	47[1)]	
118-6S	left	48[1)]	48[1)]	12	12	12	10.5	9.5	8.0	7.0	48[1)]	48[1)]	10.39
	right	48[1)]	48[1)]	9.5	15	12	12	11	8	7	48[1)]	48[1)]	
107-1	left	10[1)]	9	8.5	10	6.5	6	5	7.5	11	20[1)]	47[1)]	7.91
	right	11[1)]	7	6.5	9.5	5	7.5	6	9	9	11.5	47[1)]	

1) Values with a large edge inflow are not factored in
not det.: not determinable