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TECHNICAL REPORT ON THE RESEARCH ABOUT THE USE OF DENKA PRODUCT

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1. INTRODUCTION

This report includes two research programs on the use of DENKA products in concrete mixtures. The first program is devoted to DENKA CSA 20 and the second one to DENKA SC1: the results obtained will be presented and examined in the following sections 2 and 3, respectively.

All the test apparatus photographs are reported in the Annex 1.

2. RESEARCH PROGRAM ON DENKA CSA 20

This research program includes both flowing and tixotropic mortars which will discussed in section 2.1 and 2.2, respectively.

2.1 FLOWING MORTARS

Table 1 shows the composition of the dry pre-mixed mortars for flowing mixtures. They include the Denka Flowing Mortar (DFM) and the Reference Flowing Mortar (RFM) without Denka CSA 20.

Table 1 – Composition of dry flowing mortars

MIX	DFM**	RFM***
Portland Cement I 52.5 R	35.0%	35.0%
Silica Fume	3.5%	3.5%
Sand	56.5%	60.0%
PNS*	1.0%	1.0%
De-foaming agent	0.5%	0.5%
Denka CSA 20	3.5%	—

* Poly-naphthalene sulphonated (40% aqueous solution)
** Denka Flowing Mortar
*** Reference Flowing Mortar

Table 2 shows the percentage of mixing water (17% by the weight of the dry mortar), the flow table (155 % after 15 drops), the water-cement ratio (0.49 in both Denka and reference mortar)

and the water-binder ratio (0.41 in the Denka mortar vs. 0.44 in the reference mortar) where the binder includes portland cement, silica fume and Denka CSA 20.

Table 2 – Composition and properties of DFM and RFM mortars

MORTAR	DFM**	RFM***
Mixing Water*	17%*	17%*
Water/Cement	0.49	0.49
Water/Binder	0.41	0.44
Flow Table (15 drops)	155%	155%

* Referred to the weight of DFM or RFM
** Denka Flowing Mortars
*** Reference Flowing Mortar

Table 3 shows both the concrete bond strength at 28 days and the compressive strength development from 1 to 28 days of specimens cured at 20°C and 95 % of relative humidity (R.H.). The compressive strength value is about 35 MPa and 71 MPa at 1 and 28 days respectively for the DFM. Values slightly lower were obtained for the RFM: about 32 and and 65 MPa due to the lower binder content (38.5% vs. 42%) with respect to the corresponding Denka mortar.

As far as the concrete bond strength is concerned, a well cured concrete with a 28-day compressive strength class of 55 MPa (cube strength) was manufactured. The tensile strength of this concrete at 28 days was 2.6 MPa. The DFM and RFM mortars were applied on the concrete specimen according to UNI-EN 1542. The failure occurred into the concrete substrate for both DFM and RFM. Therefore, the concrete bond strength is higher than 2.6 MPa.

Table 3 – Strength of DFM and RFM

MORTAR Compressive Strength* at:	DFM**	RFM***
1 day	35.1 MPa	31.8 MPa
7 days	63.3 MPa	55.8 MPa
28 days	70.8 MPa	65.0 MPa
Concrete Bond Strength* at 28 days		
Wet substrate	> 2.7 MPa	> 2.7 MPa
Dry substate	> 2.6 MPa	> 2.6 MPa

* At 20°C and 95% R.H.
** Denka Flowing Mortar
*** Reference Flowing Mortar

Table 4 shows the restrained expansion/shrinkage of the reinforced specimens determined according to the UNI 8147 test. The initial length measurement was carried out at 6 hours after mixing, when mortar specimens were demoulded. After the demoulding, the specimens were immersed under lime-satured water for 1 day and then exposed to a 60% R.H. environment at 20°C. In the Denka mortar (DFM), after the early expansion during the first day (about 360 μm/m), the drying occurs at later ages and at 28 days there is a shrinkage of about 760 μm/m vs. a drying shrinkage of about 1300 μm/m in the corresponding reference mortar (RFM) without Denka CSA 20. In other words, a shrinkage-compensating mortar can be manufactured by using Denka CSA 20 with a shrinkage reduction of about 60% with respect to the reference mortar without Denka CSA 20.

Table 4 – Restrained expansion/shrinkage(UNI 8147) of reinforced mortar specimens

MORTAR Expansion/shrinkage (μm/m) at*:	DFM**	RFM***
1 day	362	-96
2 days	61	-330
7 days	-360	-858
14 days	-616	-1135
21 days	-711	-1263
28 days	-762	-1291

* Under $Ca(OH)_2$ satured water for 1 day and then at the air with R.H. = 60%; positive values indicate swelling; negative values indicate shrinkage.
** Denka Flowing Mortar
*** Reference Flowing Mortar

Table 5 shows the free length change of plain mortar specimens with respect to the initial length measured at 1 day. After the demoulding at 1 day, the length change was measured in mortar specimens kept under water for 7 days and then exposed to 60% R.H. environment at 20°C up to 28 days; in an other set of length change measurements, the mortar specimens were exposed to open air (R.H. at 60%) at 20°C immediately after their demoulding. The results indicate that:

- in Denka Flowing Mortar (DFM) there is an initial swelling of about 500 μm/m when the specimens are cured 7 days under water and then a drying shrinkage occurs which is much lower (about 55%) with respect to the corresponding Reference Flowing Mortar specimens (RFM);
- in the absence of any wet curing the difference between Denka mortar (DFM) and the reference mortar (RFM) in terms of drying shrinkage decreases: the shrinkage in the DFM specimens is about 65% with respect to that of the RFM specimens. These results indicate the importance of a wet curing at the early ages in order to take the full vantage of the Denka CSA 20 in terms of a shrinkage reduction.

Table 5 – Length change of plain mortar specimens when exposed to air with R.H. = 60%

MORTAR Curing Length Change* (μm/m) at:	DFM**		RFM***	
	7 days under water	No Curing	7 days under water	No Curing
1 day	254	-260	81	-328
2 days	326	-406	83	-409
7 days	534	-681	115	-774
14 days	-355	-868	-859	-1228
21 days	-538	-935	-1117	-1445
28 days	-740	-1057	-1338	-1607

* Positive values indicate swelling ; negative values indicate shrinkage
** Denka Flowing Mortar
*** Reference Flowing Mortar

2.2 TIXOTROPIC MORTARS

Table 6 shows the composition of the dry pre-mixed mortars for tixotropic mixtures. They include the Denka Tixotropic Mortar (DTM) and the Reference Tixotropic Mortar (RTM) without Denka CSA 20.

Table 6 – Composition of tixotropic mortars

MIX	DTM**	RTM***
Portland Cement I 52.5 R	35.0%	35.0%
Silica Fume	3.5%	3.5%
Sand	57.75%	61.25%
PNS*	0.15%	0.15%
Polymeric fibers	0.1%	0.1%
Denka CSA 20	3.5%	—

* Poly-naphthalene sulphonated (40% aqueous solution)
** Denka Tixotropic Mortar
*** Reference Tixotropic Mortar

Table 7 shows the percentage of mixing water (17.5 % by the weight of the dry mortar), the flow table (70% for DTM and 65% for RTM after 15 drops), the water-cement ratio (0.50 in both Denka and reference mortar) and the water-binder ratio (0.42 in the Denka mortar vs. 0.46 in the reference mortar) where the binder includes portland cement, silica fume and Denka CSA 20.

Table 7 – Composition and properties of DTM and RTM mortars

MORTAR	DTM**	RTM***
Mixing Water*	17.5%*	17.5%*
Water/Cement	0.50	0.50
Water/Binder	0.42	0.46
Flow Table (15 drops)	70%	65%

* Referred to the weight of DTM or RTM
** Denka Tixotropic Mortar
*** Reference Tixotropic Mortar

Table 8 shows both the concrete bond strength and the compressive strength development from 1 to 28 days of specimens cured at 20°C and 95% of relative humidity (R.H.). The compressive strength value is about 36 MPa and 72 MPa at 1 and 28 days respectively for the DFM. Values slightly lower were obtained for the RFM: about 35 and and 62 MPa due to the lower binder content (38.5% vs. 42%) with respect to the corresponding Denka mortar, and then for the higher water-binder ratio (0.46 vs 0.42).

As far as the concrete bond strength is concerned, a well cured concrete with a 28-day compressive strength class of 55 MPa (cube strength) was manufactured. The tensile strength of this concrete at 28 days was 2.6 MPa. The DTM and RTM mortars were applied on the concrete specimen according to UNI-EN 1542. The failure occurred into the concrete substrate for both DTM and RTM. Therefore, the concrete bond strength is higher than 2.60 MPa.

Table 8 – Strength of DTM and RTM

MORTAR Compressive Strength* at:	DTM**	RTM***
1 day	35.8 MPa	34.5 MPa
7 days	61.1 MPa	56.7 MPa
28 days	72.4 MPa	62.1 MPa
Concrete Bond Strength* at 28 days		
Wet substrate	> 2.65 MPa	> 2.65 MPa
Dry substate	> 2.60 MPa	> 2.60 MPa

* At 20°C and 95% R.H.
** Denka Tixotropic Mortar
*** Reference Tixotropic Mortar

Table 9 shows the restrained expansion/shrinkage of the reinforced specimens determined according to the UNI 8147 test. The initial length measurement was carried out at 6 hours after mixing, when mortar specimens were demoulded, immersed under lime-satured water for 1 day and then exposed to a 60% R.H. environment at 20°C. In the Denka mortar (DTM), after the early expansion during the first day (about 520 μm/m), the drying occurs at later ages and at 28 there is a shrinkage of about 380 μm/m vs. a drying shrinkage of about 830 μm/m in the corresponding reference mortar (RTM) without Denka CSA 20. In other words, a shrinkage-compensating mortar can be manufactured by using Denka CSA 20 with a shrinkage of about 45% with respect to the reference mortar without Denka CSA 20.

Table 10 shows the free length change of plain mortar specimens with respect to the initial length measured at 1 day. After the demoulding at 1 day, the length change was measured in mortar specimens kept under water for 7 days and then exposed to 60% R.H. environment at 20°C up to 28 days; in an other set of shrinkage measurements, the mortar specimens were exposed to open air (R.H. at 60%) at 20°C immediately after their demoulding. The results indicate that:

- in Denka Tixotropic Mortar (DTM) there is an initial expansion of about 500 μm/m when the specimens are cured 7 days under water and then a drying shrinkage occurs which is much lower, (about 30%) with respect to the corresponding Reference Tixotropic Mortar specimens (RTM);
- in the absence of any wet curing the difference between Denka mortar (DTM) and the reference mortar (RTM) in terms of drying shrinkage decreases:the shrinkage in the DTM specimens is about 70% with respect to that of the RTM specimens. These results again indicate the importance of a wet curing at the early ages in order to take the full vantage of the Denka CSA 20 in terms of a shrinkage reduction.

Table 9 – Restrained expansion/shrinkage (UNI 8147) of reinforced mortar specimens

MORTAR Expansion/Shrinkage (μm/m) at*:	DTM**	RTM***
1 day	520	50
2 days	298	-115
7 days	34	-373
14 days	-237	-683
21 days	-301	-743
28 days	-381	-834

* Under $Ca(OH)_2$ satured water for 1 day and then at the air with R.H. = 60%; positive values indicate swelling; negative values indicate shrinkage.
** Denka Tixotropic Mortar
*** Reference Tixotropic Mortar

Table 10 – Length change of plain mortar specimens when exposed to air with R.H. = 60%

MORTAR Curing Length Change* (μm/m) at:	DTM**		RTM***	
	7 days under water	No Curing	7 days under water	No Curing
1 day	240	-176	60	-188
2 days	430	-399	67	-500
7 days	499	-511	118	-660
14 days	-122	-719	-346	-959
21 days	-272	-793	-532	-1041
28 days	-347	-817	-561	-1122

* Positive values indicate swelling ; negative values indicate shrinkage
** Denka Tixotropic Mortar
*** Reference Tixotropic Mortar

3. RESEARCH PROGRAM ON DENKA SC1

This research program includes both rapid hardening and selflevelling mortars which will discussed in section 3.1 and 3.2 respectively.

3.1 RAPID HARDENING MORTARS

Table 11 shows the composition of the dry mixtures for fast hardening mortars. They include the Denka Rapid Hardening Mortar (DRHM) and the Reference Alumina Cement Mortar (RACM) without Denka CSA 20.

Table 12 shows the percentage of mixing water (16.7% by the weight of the dry mortars), the flow table (80% after 15 drops), the water-cement ratio (0.48 in Denka mortar and 0.37 in the reference mortar), and the water-binder ratio (0.37 in both Denka and reference mortar) where the binder includes portland cement, alumina cement and Denka SC1.

Table 13 shows the compressive strength development at 1 hr, 3 hr and 7 days of specimens cured at 20°C and 95% of relative humidity (R.H.). The compressive strength value is 8.0, 23.4 and 65.8 MPa at 1 hr, 3 hr and 7 days respectively for the Denka fast hardening mortar. Values significantly lower were obtained for the reference mortar with alumina cement instead of SC1.

Table 11 – Composition of fast hardening mortars

MIX:	DRHM*	RACM**
Portland Cement I 52.5R	35.0%	35.0%
Sand	54.6%	54.7%
Denka SC1	10.0%	—
Citric acid	0.4%	0.3%
High Alumina Cement	—	10.0%

* DRHM Denka Rapid Hardening Mortar
** RACM Reference Alumina Cement Mortar

Table 12 – Composition and properties of DRHM and RCAM

MORTAR	DRHM**	RACM***
Mixing Water*	16.7%	16.7%
Water/Cement	0.48	0.37
Water/Binder	0.37	0.37
Flow Table (15 drops)	80	80

* Referred to the weight of DRHM or RCAM
**DRHM Denka Rapid Hardening Mortar
*** RACM Reference Alumina Cement Mortar

Table 13 – Compressive strength of DRHM and RACM

MORTAR Compressive Strength* at:	DRHM**	RACM***
1 hour	8.0 MPa	–
3 hours	23.4 MPa	2.9 MPa
7 days	65.8 MPa	52.8 MPa

* At 20°C and 95% R.H.
**DRHM Denka Rapid Hardening Mortar
*** RACM Reference Alumina Cement Mortar

3.2 SELF-LEVELLING MORTARS

Table 14 shows the composition of the dry mixtures mortars for self-levelling mortars. They include the Denka Self-Levelling Mortar (DSLM1) with Denka SC1 (7.5%) + Denka CSA 20 (0.7%), Denka Self-Levelling Mortar (DSLM2) with Denka SC1 (10%), and the Reference Self-Levelling Mortar (RSLM) with alumina cement + anydrous $CaSO_4$ instead of Denka products.

Table 15 shows the percentage of mixing water (16% by the weight of the dry mortars), the flow table (155-150% without any drop table in all mortars), the water-cement ratio (0.56 in DSLM1; 0.59 in DSLM2; 0.52 in the reference mortar) and the water-binder ratio (0.43 in the Denka mortars and 0.45 in the reference mortar), where the binder includes portland cement, alumina cement, anhydrite ($CaSO_4$) and Denka products.

Table 16 shows the compressive strength development from 1 hr to 7 days of specimens cured at 20°C and 95% of relative humidity (R.H.). The compressive strength value at 1 hour is 6.3 MPa for DSLM1, 9.9 MPa for DSLM2 and only 0.9 for the reference mix. At 7 days the compressive strength are 70.6, 78.3 and 59.6 for DSLM1, DSLM2 and reference mortar, respectively. These results show the extra-ordinary accelerating effect of SC1 and SC1 + CSA 20 on the early strength.

Table 14 – Composition of Self-Levelling mortars

MIX:	DSLM1**	DSLM2***	RSLM****
Portland Cement I 52.5R	28.8%	27.0%	15.0%
Sand	62.6%	62.6%	64.6%
Denka SC1	7.5	10%	–
Denka CSA	0.7%	–	–
High Alumina Cement	–	–	15.0%
Anhydrous $CaSO_4$	–	–	5.0%*****
Citric acid	0.3%	0.3%	–
PC*	0.1%	0.1%	–

* Polycarboxylate superplasticizer (30% aqueous solution)
** Denka Self-Levelling Mortar 1
*** Denka Self-Levelling Mortar 2
**** Reference Self-Levelling Mortar
*****Because of an excessive expansion with the anhydrite dosage of 7% as was defined in the original program, this component was reduced to 5.0%

Table 15 – Composition and properties of Self-Levelling mortars

MIX:	DSLM1**	DSLM2***	RSLM****
Mixing Water*	16%	16%	16%
Water/Cement	0.56	0.59	0.52
Water/Binder	0.43	0.43	0.45
Flow Table without any drop	155	150	155

* Referred to the weight of dry mortar
** Denka Self-Levelling Mortar 1
*** Denka Self-Levelling Mortar 2
**** Reference Self-Levelling Mortar

Table 16 – Compressive strength of Self-Levelling mortars

MORTAR Compressive Strength* at:	DSLM1**	DSLM2***	RSLM****
1 hour	6.3 MPa	9.9 MPa	0.9 MPa
3 hours	16.9 MPa	23.9 MPa	3.6 MPa
7 days	70.6 MPa	78.3 MPa	59.6 MPa

* At 20°C and 95% R.H.
** Denka Self-Levelling Mortar 1
*** Denka Self-Levelling Mortar 2
**** Reference Self-Levelling Mortar

Table 17 shows the free length change of plain mortar specimens with respect to the initial length measured at 1 day. After the demoulding at 1 day, the length change was measured in mortar specimens kept under water for 7 days and then exposed to 60% R.H. environment at 20°C up to 28 days; in an other set of shrinkage measurements, the mortar specimens were exposed to open air (R.H. at 60%) at 20°C immediately after their demoulding. The results indicate that:

- in Denka Self-Levelling mortars DSLM1 or DSLM2 there is an initial expansion of 400- 500 μm/m when the specimens are cured 7 days under water and then a drying shrinkage occurs which is 25-35% with respect to the corresponding reference mortar specimens;
- in the absence of any wet curing the difference between Denka mortars and the reference mortar in terms of drying shrinkage significantly decreases. These results again indicate the importance of a wet curing at the early ages in order to take the full advantage of the Denka SC1 and Denka CSA 20 in terms of a shrinkage reduction.

Table 17 – Shrinkage of plain mortar specimens

MORTAR Curing Shrinkage* (μm/m) at:	DSLM1**		DSLM2***		RSLM****	
	7 days under water	No Curing	7 days under water	No Curing	7 days under water	No Curing
1 day	267	-144	293	-225	6	-334
2 days	291	-402	338	-411	70	-639
7 days	516	-649	400	-603	84	-996
14 days	-108	-745	-48	-668	-400	-1100
21 days	-245	-802	-159	-708	-607	-1206
28 days	-306	-897	-203	-748	-830	-1420

* Positive values indicate swelling ; negative values indicate shrinkage
** Denka Self-Levelling Mortar 1
*** Denka Self-Levelling Mortar 2
**** Reference Self-Levelling Mortar

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ANNEX 1

Fig. 1 – Mortar mixing apparatus UNI EN 196/1.

Fig. 2 – Mortar flow table (UNI 7044).

Fig. 3 – Mortar come for flow test (UNI 7044).

Fig. 4 A – Flow table measurement for tixotropic mortar.

Fig. 4 B – Flow table measurement for flowing mortar.

Fig. 4 C – Flow table measurement for self leveling mortar.

Fig. 5 – Concrete substrate for bond strength test (UNI EN 1766).

Fig. 6 – Bond strength test by pull-out (UNI EN 1542).

A B

Fig. 7 A-B – Pull-Off apparatus for bond strength measurement (UNI EN 1542).

A B

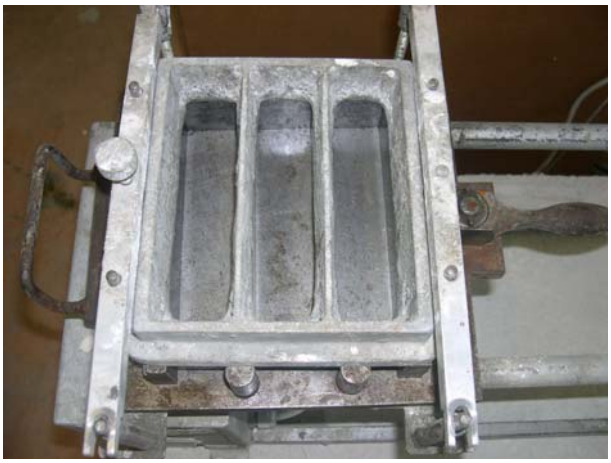
Fig. 8 A-B – Specimens for pull-off test (UNI EN 1542).

Fig. 9 – Restrained expansion specimen (UNI 8147).

Fig. 10 – Restrained expansion measurement (UNI 8147).

Fig. 11 – Shrinkage measurement (UNI 6687).

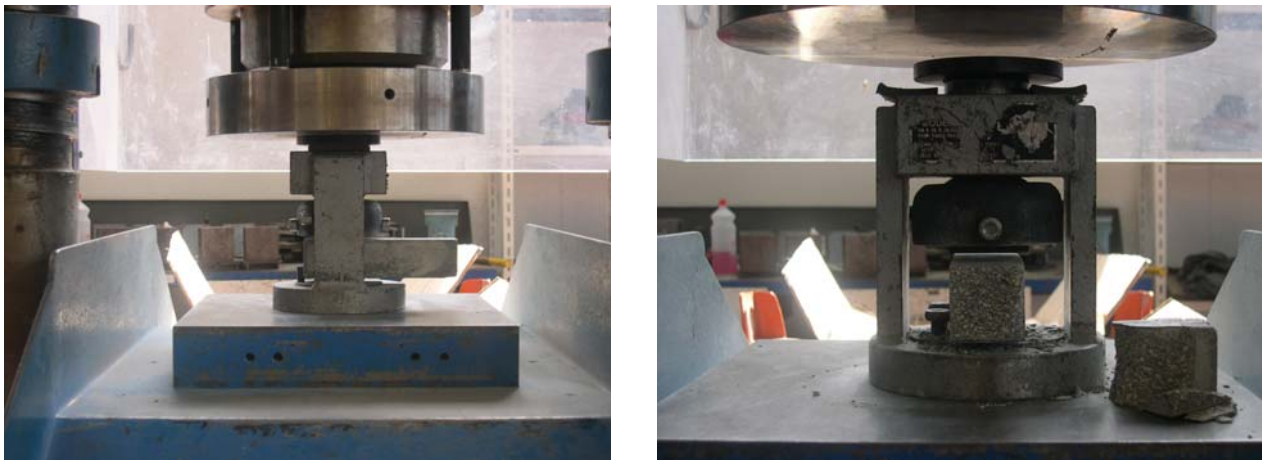
A



B

Fig. 12 A-B – Casting apparatus for mortar specimens(UNI EN 196/1).

Fig. 13 – Casting apparatus for mortar specimens (UNI EN 196/1).



A **B**

Fig. 14 A-B – Compressive strength test on mortar specimen (UNI EN 196/1).