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Influence of water-cement ratio and cement content on the properties of polymer-modified mortars

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Abstract

The compressive strength of modified and unmodified mortars depends on water-cement ratio and, to a lesser extent, on the cement content of the mortars. The flexural strength of unmodified mortars responds only slightly to modification of water-cement ratio or cement content. With polymer modification of the mortars, the influence of the variation is increased. There is only a minor influence of water-cement ratio and cement content on the adhesion strength of the modified mortars on concrete slabs. Only in wet conditions is there an additional effect at high cement contents and lower water-cement ratios. Shrinkage and water absorption are a function of water-cement ratio and cement content.

Keywords: Polymers; Mechanical properties; Adhesion strength; Shrinkage; Admixtures; Cement

The influence of the water-cement ratio and cement content on the compressive strength is well documented [1,2]. The compressive strength decreases with a higher water-cement ratio but is not influenced much by the cement content. Less well documented are the influences on the flexural strength of mortars, and the results are inconsistent. Wendehorst [3] claims a constant correlation between compressive strength and flexural strength. According to others [2], the flexural strength varies between 5 and 8 N/mm^2. The flexural strength decreases to a higher extent with higher water-cement ratios than does the compressive strength.

We found no literature describing systematically the influence of water-cement ratio and cement content on the adhesion strength. Results found with cementitious tile adhesives (high formulated, especially polymer-modified products) [4] show the tendency to increase adhesion strength with increasing cement content, especially after dry storage conditions. Czernin [5] describes the result of increasing cement content and water-cement ratio where the shrinkage of mortars is increased.

In this paper we present our investigations, if all the facts mentioned above are still valid, when a highly modified, especially polymer-modified mortar, is used.

The tests were carried out with modified and unmodified cement mortars. The details of the mixes are described in the experimental section. Besides a redispersible powder at a constant resin:cement ratio of 0.1, a shrinkage reducing agent at constant admixture:cement ratio of 0.005 was also incorporated. Further, a wetting agent, a defoamer, microsilica, and fly ash were used in formulation 1. Mortars following formulation 1 can be used for the repair of concrete. In a second series we investigated the contradictory results of the influences on flexural strengths of mortars described in the literature [2,3].

1. Experimental

In all experiments a portland cement CEM I 32.5 R and a sand mixture according to DIN EN 196 was used. The following were also used:

- redispersible powder Vinnapas LL 512 (styrene/acrylic powder of Wacker Polymer Systems, Burghausen, Germany)
- shrinkage reducing agent 2,5-dimethylpropanediol (BASF)
- wetting agent Emulan OG (BASF)
- defoamer Agitan P803 (Münzing)
- fly ash (EFA-Filler, Keller Dortmund)
- Microsilica (Elkem)

The sand content was always adjusted to reach 100 parts.

1.1. Formulation 1

See Table 1 for components of formulation 1. The water-cement ratios are given in the other Tables and Figs.

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Table 1
Formulation 1

Component	Percentages			
CEM I 32.5 R	20	23	26	29
Sand mixture	72.7	69.4	66.1	62.9
Vinnapas LL 512	2	2.3	2.6	2.9
Fly ash	4	4	4	4
Defoamer	0.2	0.2	0.2	0.2
Microsilica	1	1	1	1
Wetting agent	0.1	0.1	0.1	0.1
Shrinkage reducing agent	0.1	0.115	0.13	0.145

1.2. Formulation 2

In the experiments with the unmodified mortars we also followed the DIN EN 196 standards and worked with the sand mixture according to DIN; the formulation was adjusted to 100 parts by variation of the sand content. The cement content varied between 15–50% of the formulation. The mortars were mixed in accordance with DIN EN 196 in a Tony-Mixer. The data concerning workability (air content and slump characteristics) are given in Table 2, and have been measured according to DIN EN 196/DIN 1060. The water absorption was measured with 40 · 40 · 160 mm bars stored for 21 days in normal climate [23°C, 50% relative humidity (standard test condition according to ISO 554), 7 days underwater]. The modified mortars were subjected to four different curing conditions and tested at various ages for compressive strength, flexural strength, and shrinkage. Compressive and flexural strength have been measured according to DIN EN 196.

The adhesion bond was measured by applying the mortar with a trowel in a thickness of 10 mm on a concrete block (according to DIN 485 and DIN 18500) The adhesion strength was measured according to DIN 18 156. Before the test was carried out, the samples were core-drilled through the mortar just into the substrate. A steel disc was attached to the surface of the core using an epoxy glue. The specimens were tested in direct tension at a load rate of 250 N/sec. Shrinkage was measured according to DIN 52240 with bars of 40 · 40 · 160 mm.

Table 2
Workability of formulation 1

	Water-cement ratio	Air content (%)	Slump characteristics (cm) without/with strokes
Cement 20%	0,49	7,5	10/14,5
	0,53	5,8	10/15,5
	0,57	5,0	10/17
	0,61	4,1	11/18,5
Cement 23%	0,42	6,0	10/14
	0,46	5,8	10/15
	0,50	5,6	10/17
	0,53	5,0	10,5/18
Cement 26%	0,38	7,0	10/13
	0,41	6,5	10/14
	0,44	5,8	10/15
	0,47	5,2	10/16,5
Cement 29%	0,34	7,0	10/12
	0,37	6,0	10/13
	0,39	5,2	10/14,5
	0,42	5,5	10/16
Without LL 512, cement 20%	0,49	5,0	10/12,5

2. Results

2.1. Compressive strength

Table 3 shows that a decreasing water-cement ratio leads to an increase of the compressive strength of the modified mortars at all storage conditions. The air content of the mortars was held constant as far as possible (Table 2). The results confirm that the polymer-modified mortars behave in effect like unmodified cement mortars if we compare, for example, data in Table 5 and the data in the literature [2–4].

Comparing formulation 1 with redispersible powder incorporated and without powder LL 512 at the same water-cement ratio of 0,49, in absolute values, the thermoplastic polymer reduces the compressive strength of the mortar, as was shown in the literature [6].

As Fig. 1 shows, for a storage 90 days in normal climate the cement content of the mortars in the series is not a first-order factor in respect to compressive strength. In general, at the same water-cement ratio, the modified mortar with the higher cement content seems to have a slightly lower compressive strength. We also see this result in Table 4 with the unmodified mortars.

Aspects of different workability of the mortars (influence on compaction) are not discussed in this work. The different slump properties are given in Table 2.

2.2. Flexural strength

The influence of the water-cement ratio on the flexural strength of the highly modified mortars varies under the different storage conditions. The results are given in Table 5. In always-dry condition (28 days normal climate, 90 days normal climate) there is only a small increase of the flexural strength with decreasing water-cement ratio at a constant cement level in the formulation. After storage in water and $Ca(OH)_2$, there is a pronounced increase with decreasing water-cement ratio. Fig. 2 shows this result at a 26% cement content level of formulation 1.

Also according to Table 4, the unmodified mortars show only very small increase of the flexural strength with decreasing water-cement ratios between 0,4–0,6. However the flexural strength is lower than that of the modified mortars at comparable water-cement ratios and cement contents (Fig. 2). Also by variation of the cement-content (Table 4), in formulation 2 there is only a small increase of the flexural strength with increasing cement contents.

These results do not support the findings of Wendehorst [3], who claims a constant ratio between flexural strength and compressive strength. It is well documented that the

Table 3
Compressive strength (N/mm²) of formulation 1, bars 40 · 40 · 160 mm

	Water-cement ratio	28 days in normal climate (N/mm²)	21 days in normal climate, 7 days in water (N/mm²)	28 days at normal climate* (N/mm²)
Cement 20%	0,49	51,4 ± 1,2	45,6 ± 1,9	59,0 ± 2,4
	0,53	47,0 ± 2,1	40,9 ± 2,3	56,6 ± 2,1
	0,57	43,2 ± 0,3	37,0 ± 0,9	42,3 ± 0,9
	0,61	37,2 ± 0,6	30,1 ± 1,9	43,3 ± 0,9
Cement 23%	0,42	55,6 ± 1,7	50,1 ± 0,6	64,3 ± 4,4
	0,46	51,4 ± 1,7	45,3 ± 1,3	60,6 ± 1,9
	0,50	47,1 ± 0,7	41,1 ± 0,8	55,5 ± 1,2
	0,53	44,5 ± 0,5	36,6 ± 0,6	51,5 ± 1,5
Cement 26%	0,38	61,9 ± 0,9	55,9 ± 2,2	73,4 ± 2,8
	0,41	57,3 ± 1,4	52,2 ± 1,6	68,3 ± 0,7
	0,44	53,3 ± 1,2	46,6 ± 0,7	63,6 ± 1,5
	0,47	48,9 ± 0,4	41,8 ± 2,0	59,8 ± 1,5
Cement 29%	0,34	66,8 ± 1,3	56,7 ± 2,8	80,5 ± 1,6
	0,37	61,9 ± 1,7	54,9 ± 1,4	72,6 ± 1,7
	0,39	58,9 ± 0,7	52,2 ± 0,9	69,4 ± 1,1
	0,42	52,0 ± 0,4	44,2 ± 0,5	60,1 ± 2,1
Without LL 512, cement 20%	0,49	55,7 ± 1,2	53,9 ± 1,2	67,8 ± 4,3

* $Ca(OH)_2$, 28 days at normal climate, 28 days in saturated $Ca(OH)_2$ solution at 50°C, 34 days in normal climate. Normal climate = 23°C, 50% relative humidity.

flexural strength is increased by a polymer resin modification with an emulsion or a redispersible powder [6,7]. The polymer is concentrated in the pore system of the hardened mortar and acts as a reinforcement. Fig. 3, shows this quite clearly.

With an increasing water-cement ratio of the mortar at the same polymer level, the concentration of the polymer per volume is decreased. This is true in the dry status also, because the higher water content leads to a higher pore volume in the dry mortar. Due to the lower polymer concentration in the hardened mortar, the effect of the polymer is reduced.

In wet status (storage underwater) a second effect has to be taken into consideration. Fig. 4 shows that with decreasing water-cement ratio, the water absorption of the mortars is reduced, meaning that the mortars contain less water. The forces between the polymeric material in the mortar and the mineral material in nature are more or less of van der Waals, acid/base, or of ionic character and are very much influenced by water with high dielectrical power. By decreasing the water absorption of the mortar by reducing the water-cement ratio, the weakening effect of water on the active binding forces in the modified mortar is avoided, and at a water absorption less than 2%, the difference in flexural strength between dry and wet storage becomes negligible, as demonstrated in Fig. 2 at a water-cement ratio of 0,41 and lower.

2.3. Adhesion strength

The modification of mortars with film forming thermoplastic materials, like emulsions or redispersible powders, increases the adhesional bond strength on different sub-

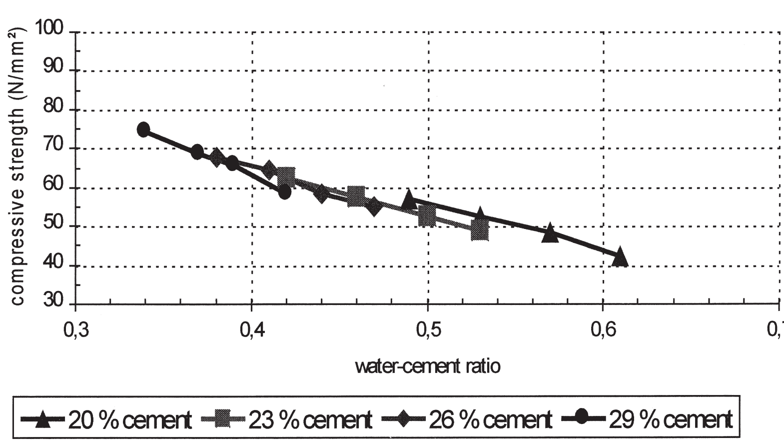

Fig. 1. Compressive strength (N/mm²) for formulation 1 at 90 days of normal climate.

Table 4
Flexural and compressive strength (N/mm^2) of formulation 2, bars 40 · 40 · 160 mm*

Cement content (%)	Water-cement ratio	Air content (%)	Flow characteristics (cm)	Flexural strength (N/mm^2)	Compressive strength (N/mm^2)
15	0,7	8	10/15	6,0 ± 0,7	21,9 ± 2,6
20	0,55	5,5	10/17	6,6 ± 0,5	28,9 ± 2,8
25	0,5	5	10/18	6,7 ± 0,7	32,6 ± 2,8
30	0,45	4	11/20	6,9 ± 0,6	39,7 ± 2,3
35	0,42	3	10/18	6,9 ± 0,6	40,3 ± 2,5
40	0,38	3	10/18,5	7,4 ± 0,9	45,1 ± 1,6
45	0,35	3,6	11/21	7,6 ± 0,6	49,0 ± 2,8
50	0,35	3	10,5/21	7,3 ± 0,2	49,3 ± 2,3
25	0,41	3,6	10/10	7,1 ± 0,8	52,1 ± 2,1
25	0,44	3,8	10/13,5	7,5 ± 0,6	46,3 ± 1,1
25	0,47	4,1	10/15	7,2 ± 0,5	41,3 ± 1,2
25	0,50	4,0	10/16,5	7,1 ± 0,7	37,0 ± 1,4
25	0,55	2,1	10,5/20	6,7 ± 0,5	30,1 ± 1,3
25	0,60	1,3	14/22,5	6,9 ± 1,0	26,7 ± 1,2

* Both series were produced with different cement lots. Storage 28 days normal climate.

strates considerably. This is the main reason for the widespread use of this product worldwide [8].

Because of the low adhesion and the limited inherent strength of an unmodified mortar in thin layer on concrete slabs, we could not measure the bond strength after $Ca(OH)_2$ storage condition because the mortar was already destroyed during core-drilling of the samples. According to our internal experience, the adhesion strength of such mortars, following the pull-off test we used, is about 0.1–0.3 N/mm^2.

With a polymer modification the adhesion strength is remarkably increased, as shown in Table 6. Table 6 also shows that the adhesion strength of the modified mortar in dry state (storage for 28 or 90 days at normal climate) at the same cement level is more or less independent from the water-cement ratio of the formulation (for example, at the level of 20 or 23% of cement and taking into consideration the standard deviation of the measurement). With higher amounts of cement, the adhesion strength is increased, but the influence of the polymer is much higher than the influence of the cement content.

In wet state (storage for 21 days in normal climate and then 7 days in water) the adhesion strength of the modified mortar is lower than in the dry state, but still much higher than the adhesion of the unmodified mortar (Fig. 5). There is no influence of the water-cement ratio above a water-cement ratio >0.4. Below a water-cement ratio of 0.4 the

Table 5
Flexural strength (N/mm^2) of formulation 1, bars 40 · 40 · 160 mm

	Water-cement ratio	28 days normal climate (N/mm^2)	21 days normal climate, 7 days water (N/mm^2)	90 days normal climate (N/mm^2)	28 days normal climate* (N/mm^2)
Cement 20%	0,49	12,1 ± 0,3	9,3 ± 0,8	12,6 ± 1,5	9,5 ± 1,3
	0,53	10,9 ± 0,9	8,3 ± 1,7	11,5 ± 1,1	9,4 ± 1,4
	0,57	10,9 ± 0,7	7,0 ± 0,8	10,4 ± 0,9	8,7 ± 0,7
	0,61	9,6 ± 0,3	7,0 ± 0,8	10,4 ± 0,9	6,4 ± 2,6
Cement 23%	0,42	12,7 ± 1,1	10,2 ± 0,6	12,9 ± 1,4	9,8 ± 1,3
	0,46	12,3 ± 0,6	9,3 ± 0,9	12,3 ± 0,6	9,6 ± 0,9
	0,50	11,1 ± 1,6	8,1 ± 0,8	11,2 ± 1,0	8,6 ± 1,5
	0,53	11,0 ± 1,6	7,4 ± 0,7	11,5 ± 0,6	7,6 ± 2,9
Cement 26%	0,38	13,2 ± 1,0	12,7 ± 0,5	12,9 ± 2,5	11,6 ± 1,6
	0,41	12,8 ± 1,5	11,1 ± 0,9	11,8 ± 1,2	11,5 ± 1,4
	0,44	12,3 ± 1,5	10,0 ± 0,8	11,0 ± 0,3	10,0 ± 1,2
	0,47	11,5 ± 0,2	8,3 ± 1,5	11,6 ± 0,9	10,0 ± 1,3
Cement 29%	0,34	13,3 ± 1,0	13,1 ± 0,8	13,1 ± 0,8	12,0 ± 1,8
	0,37	12,6 ± 1,8	11,3 ± 1,4	12,1 ± 1,6	11,8 ± 0,8
	0,39	13,0 ± 1,7	11,1 ± 0,6	13,6 ± 1,3	10,9 ± 1,3
	0,42	12,6 ± 1,8	9,1 ± 1,0	13,0 ± 1,5	9,3 ± 0,9
Without LL 512, cement 20%	0,49	7,3 ± 0,4	7,8 ± 0,2	7,4 ± 0,5	6,7 ± 0,4

* $Ca(OH)_2$, 28 days at normal climate, 28 days in saturated $Ca(OH)_2$ solution at 50°C, 34 days in normal climate. Normal climate = 23°C, 50% relative humidity.

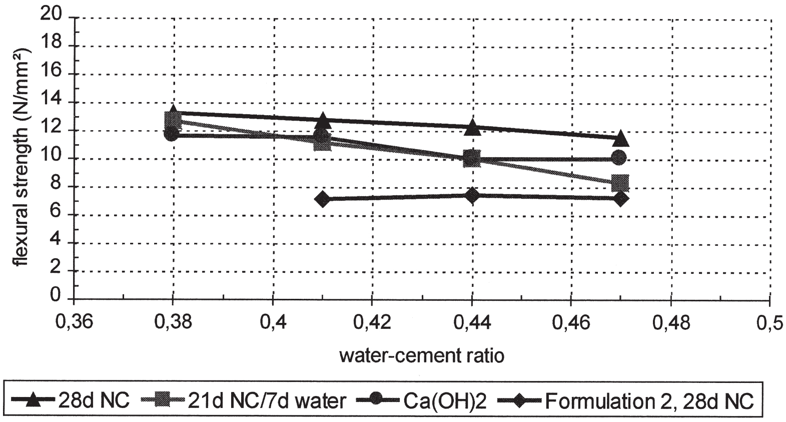

Fig. 2. Flexural strength (N/mm^2) for formulation 1 with 26% cement and formulation 2 with 25% cement.

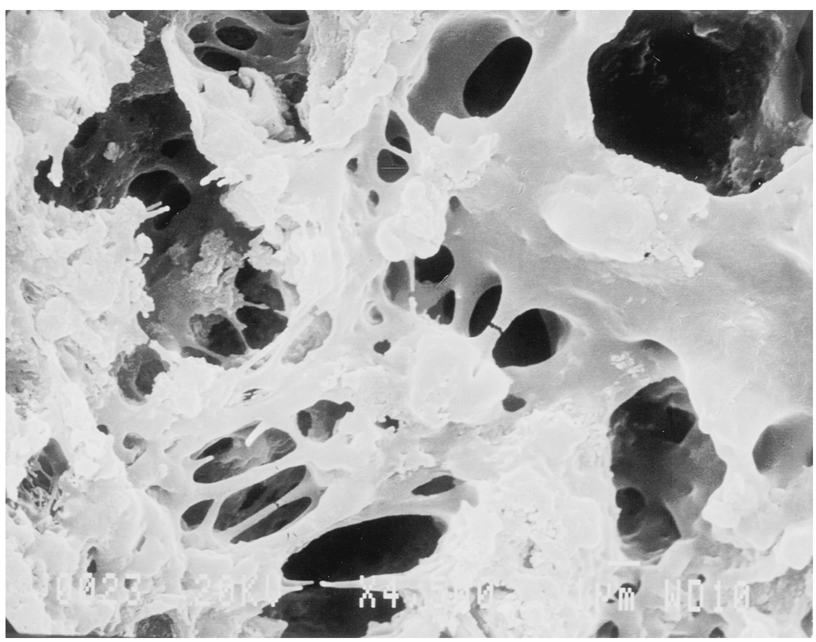

Fig. 3. SEM photograph of formulation 1 with Vinnapas LL 512 after 90 days in normal climate. (Magnification 4500×)

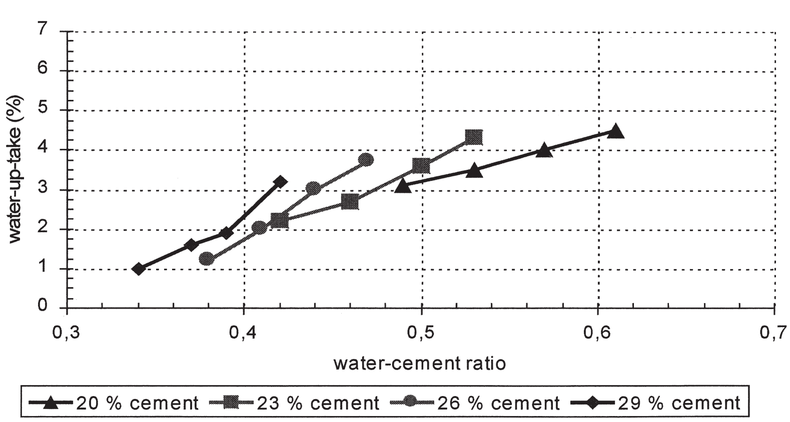

Fig. 4. Water absorption at 7 days (%) for formulation 1 at 21 days of normal climate, bars 160 × 40 × 40 mm.

Table 6
Adhesion strength (N/mm^2) of formulation 1, bars 40 · 40 · 160 mm

	Water-cement ratio	28 days at normal climate (N/mm^2)	21 days at normal climate, 7 days in water (N/mm^2)	90 days at normal climate (N/mm^2)	28 days at normal climate* (N/mm^2)
Cement 20%	0,49	1,32 ± 0,08	0,83 ± 0,03	1,40 ± 0,06	1,88 ± 0,15
	0,53	1,33 ± 0,07	0,93 ± 0,16	1,39 ± 0,07	1,66 ± 0,13
	0,57	1,36 ± 0,07	1,04 ± 0,05	1,36 ± 0,03	1,69 ± 0,14
	0,61	1,34 ± 0,07	0,95 ± 0,17	1,36 ± 0,03	1,74 ± 0,05
Cement 23%	0,42	1,37 ± 0,11	0,96 ± 0,06	1,63 ± 0,05	1,78 ± 0,25
	0,46	1,51 ± 0,08	0,96 ± 0,04	1,57 ± 0,04	1,94 ± 0,20
	0,50	1,43 ± 0,05	0,95 ± 0,09	1,42 ± 0,05	1,72 ± 0,08
	0,53	1,45 ± 0,04	1,09 ± 0,06	1,45 ± 0,06	1,74 ± 0,08
Cement 26%	0,38	1,52 ± 0,12	1,37 ± 0,09	1,70 ± 0,07	1,75 ± 0,18
	0,41	1,60 ± 0,14	1,06 ± 0,05	1,71 ± 0,06	1,65 ± 0,14
	0,44	1,54 ± 0,10	0,92 ± 0,08	1,67 ± 0,12	1,64 ± 0,15
	0,47	1,57 ± 0,07	0,86 ± 0,10	1,57 ± 0,10	1,67 ± 0,13
Cement 29%	0,34	1,73 ± 0,33	1,47 ± 0,33	2,09 ± 0,28	1,71 ± 0,26
	0,37	1,72 ± 0,15	1,43 ± 0,11	1,91 ± 0,16	1,80 ± 0,17
	0,39	1,52 ± 0,15	1,13 ± 0,02	1,72 ± 0,06	1,57 ± 0,30
	0,42	1,58 ± 0,13	1,04 ± 0,19	1,68 ± 0,08	2,13 ± 0,23
Without LL 512, cement 20%	0,49	0,50 ± 0,08	0,31 ± 0,18	0,37 ± 0,15	destroyed

* $Ca(OH)_2$, 28 days at normal climate, 28 days in saturated $Ca(OH)_2$ solution at 50°C, 34 days in normal climate. Normal climate = 23°C, 50% relative humidity.

adhesion strength is increased. We compare this to the flexural strength with the low water absorption of the mortars. The effect is probably the same as explained earlier for flexural strength.

2.4. Shrinkage

According to Czernin [5] the shrinkage of cement mortars is a function of the water-cement ratio and the cement content. With an increasing water-cement ratio, as well as a higher cement content of the mortar, the shrinkage of the hardening mortar is increased. Following Fig. 6, this statement is also valid for the highly modified mortars.

2.5. Water absorption

Water penetrates into the pore structure of the mortar. Therefore a cement mortar with a lower pore volume will have a lower water absorption. We do not discuss a change in the transportation mechanism in the mortar. For the modified mortars we see in Fig. 4, with respect to the unmodified mortars, the water absorption is reduced with a lower water-cement ratio. With an increasing cement content and constant water-cement ratio, the water absorption increases.

3. Conclusions

The influence of water cement-ratio and cement content on the properties of polymer-modified mortars (as they are formulated for mortars used in concrete repair in general) has the same influence as in unmodified mortars. Compressive strength is decreased with increasing water cement ratio and the cement content is of minor influence. Shrinkage

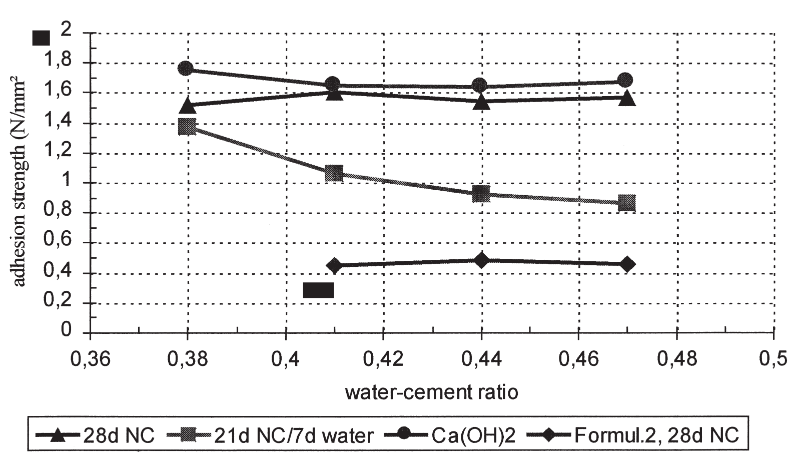

Fig. 5. Adhesion strength (N/mm^2) of formulation 1 with 26% cement and formulation 2 with 25% cement.

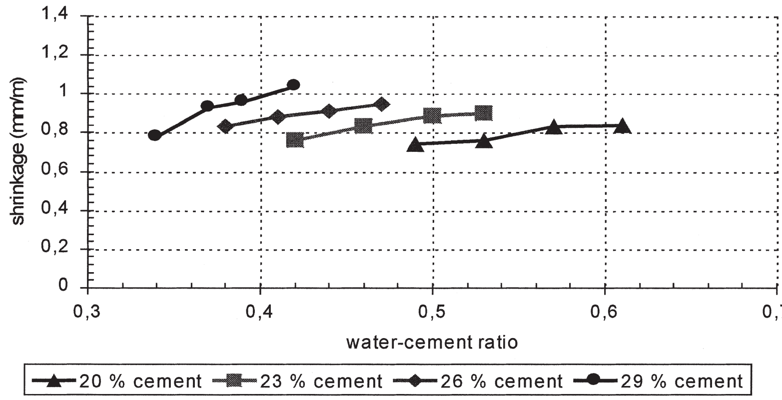

Fig. 6. Shrinkage (mm/m) of formulation 1 at 56 days of normal climate.

and water absorption are increased with a higher water cement ratio and a higher cement content.

The flexural strength of unmodified mortars at water-cement ratios of 0.4–0.6 is nearly independent of water cement ratio and cement content. This is in contradiction to some previously published work [3], but confirms other data [2].

With polymer-modified mortars the flexural strength is increased in comparison to the unmodified one. With increasing water-cement ratios of the modified mortar, the flexural strength is decreased only slightly after 28 and 90 days of normal climate storage, but after storage underwater there is a significant reduction with increasing water-cement ratios. The influence of the cement content on the flexural strength of the mortars is not of first order.

The adhesion bond strength of a polymer-modified mortar is much higher than that of the unmodified one; there is only a small effect of the water-cement ratio and a higher cement content increases the adhesion.

The results of this study fit quite well into the picture of the composite material, as the polymer-modified mortars show. Both binders act in synergy: the cement as the inorganic binder is responsible for mechanical stability as compressive strength and the redispersible powder as the organic one is acting as a reinforcement and is responsible for the internal tensile strength and at interfaces for the adhesion-bond strength [4]. With both binders creating synergism, the modern composite material reaches a performance the historic unmodified mortars cannot reach.

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