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THE USE OF LIME MORTARS FOR SUSTAINABLE RESTORATION OF ANCIENT BUILDINGS

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ABSTRACT

Various recent Restoration Charters recommend the use of lime-based mortars for the restoration of ancient European buildings because of their compatibility with the original masonry mortars, renders, plasters and bricks. The paper presents test results and experiences obtained with industrial and traditional lime putty-based mortars. The testing programme encompassed field studies of the behaviour of lime-based renders on the masonry walls made from solid clay bricks, and parallel tests of the characteristics of fresh and hardened lime-based mortars. The tests were carried out on five lime-based mortar mixes: traditional lime-putty:sand 1:3, industrial lime putty:sand 1:3, traditional lime-putty:sand 1:3 + 10% of metakaolin, industrial lime putty:sand 1:3 + 10% of cement and traditional lime-putty:sand 1:3 + 3% of polypropylene fibres.

The obtained results show that with mature traditional lime putty we can obtain lime mortar with superior properties in fresh and hardened state, compared to the lime mortar from industrial lime putty. The "traditional" lime render on the outside walls behaved very good and is after one winter still in the same condition. The use of plain lime mortar from industrial lime putty for rendering does not seem to be a very good decision, since this mortar needs too much water for good workability, which is a great drawback for the later process of the hardening. The addition of 10% of cement to the "industrial" lime mortar can improve some properties of the lime render in its "green" stage due to higher early strength of the render. On the basis of obtained results the addition of metakaolin to the lime mortars for rendering can not be recommended. The reason is wet spots on the render that are very unaesthetic and could also be harmful. In cases when higher ductility of the hardened lime renders is demanded, the incorporation of fine, flexible and evenly distributed fibres in the lime mortar could be a solution.

Key words: lime renders, lime-putty, additives, field studies, laboratory tests.

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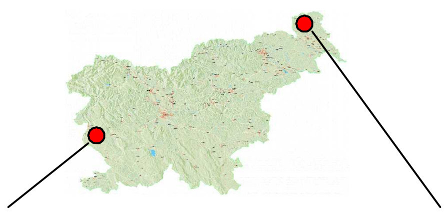
INTRODUCTION

Lime used to be traditional binder, used for a large variety of mortars for brickwork, stonework, renders and plasters in the ancient buildings of Europe. But for restoration purposes usually current materials and techniques are employed. These are often found to be ineffective and can cause damage. As a consequence there has been a renewed interest in ancient materials and technologies. These new developments are reflected in various recent Restoration Charters, which recommend the use of lime-based mortars for restoration works, because of their compatibility with the existing walls. In the same documents, the need for the redevelopment of ancient crafts is emphasized.

Before cement was introduced to the market, lime had been traditional binder for mortars for brickwork, stonework, renders and plasters also in Slovenia. Smaller-scale production, sufficient for local community needs, was typical for our country. Types of lime kilns used differ substantially between different regions of Slovenia. Two examples are presented in Fig. 1 and 2. Since the lime kiln named Frnaza from the Kras, Slovenian region near to the Italian border, was built only for a one-time use, the lime kiln from the Goricko, Slovenian region between the Austrian and Hungarian borders, was made from limestone blocks and clay bricks and was used frequently. It is interesting that this kiln was used also for burning clay bricks.



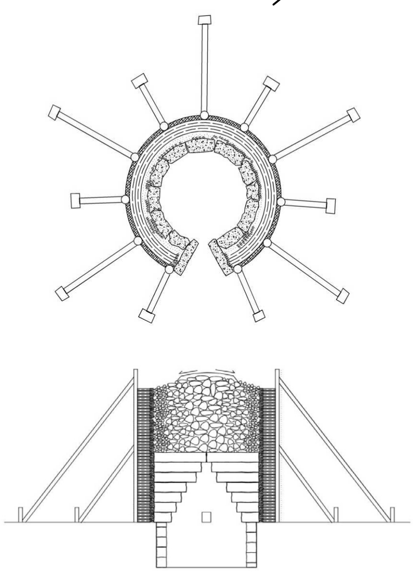


Figure 1. Lime kiln from Kras

Figure 2. Lime kiln from Goricko

In the last few years also in Slovenia the demands for the reintroduction of the lime-based mortars for restoration works are more and more frequent, although current materials and techniques are still too often used in old town centres. For this reason some public laboratories and faculties started to study and recommend lime technologies for the restoration works of ancient buildings. Our research team, Department of Research in Materials and Structures at the University of Ljubljana, has been involved in the research of lime-based mortars for clay bricklaying almost for a decade and for the last four years also in research of lime-based renders and plasters. Our main field of interest is properties and characteristics of lime-based mortars from industrial and traditional limes available on the Slovenian market, as well as the influence of possible pozzolanic additives for faster gain of strength and mikrofibres for better ductility of hardened mortars. During the research work we found out that there is lack of appropriate test methods for the evaluation of specific characteristics of lime-based mortars, particularly for mortars used for renders and for renders themselves. Therefore we developed or introduced some alternative test methods that could be appropriate for the evaluation of these characteristics.

In the sequel of the paper test results and experiences obtained with industrial and traditional lime putty-based mortars, with and without the addition of small quantities of cement or metakaolin or with polypropylene microfibres are given and discussed.

TESTING PROGRAMME

Range of tests

The testing programme encompassed field studies of the behaviour of lime-based renders on the masonry walls from solid clay bricks and parallel tests of the characteristics of fresh and hardened lime-based mortars. The chosen types of different lime-based mortars were composed as follows:

- traditional lime-putty : sand in volume proportions 1:3 (MP)
- industrial lime-putty : sand in volume proportions 1:3 (MTS)
- traditional lime-putty : sand 1:3 with 10% of metakaolin with respect to the weight of the putty (MP+met)
- industrial lime-putty : sand 1:3 with 10% of cement with respect to the weight of the putty (MTS+cem)
- traditional lime-putty : sand 1:3 with 3% of polypropylene fibres with respect to the volume of the mortar (MP+fibr).

The amount of added water was adjusted in order to obtain a flow value of about 145 mm.

The used traditional lime-putty was the 3 year old lime-putty from the village Podpeè near Ljubljana and the used industrial lime-putty was the 3 month old lime-putty produced by “Solkanska industrija apna” from Solkan, a town next to the Italian border. The type of used sand was mostly siliceous with gradation given in Fig. 3. As additives pozzolanic material metakaolin MetaStar from Great Britain and Portland cement CEMII/B-M 42.5 according to the EN 197-1 were used. Polypropylene fibres for micro reinforcement of lime-based mortar were commercial fibres “Krenit” with fibre length 12 mm, cross-section size 35x250-600 μm, ultimate stress 340-500 MPa, elastic modulus 8.5-12.5 GPa and ultimate strain 8-10%.

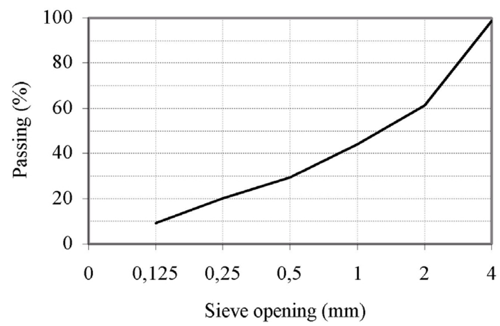


Figure 3. Particle size distribution of used sand

Fabrication of specimens and tests specifications

Figure 4. Rendered masonry walls

For the field studies of lime-based renders four masonry walls (150x200x25 cm^3) were bricklayed along the building of the Laboratory of the Faculty of Civil and Geodetic Engineering. The walls are from solid clay bricks (250x120x65 mm^3) and cement:lime:sand mortar 1:2:6 by volume and they are protected against rain with small roofs (Fig.4). Particular type of mortar was used for rendering a vertical half area of both sides of one wall. In this way it was possible to study also the possible influence of the orientation of the renders to the south and north. This means that one test field area was about 73 cm wide and almost 200 cm high. The average thickness of renders was 20 mm.

Due to non-planned delay the rendering was carried out in the last week of August 2000, when the highest day temperatures were up to 34°C (relative humidity down to 30%) and the lowest night temperatures were about 18°C (relative humidity up to 80%). Although the renders were applied to the walls early in the morning or late in the afternoon, protected from sun and wind by polyethylene covering and intermittent fine mist sprayed with clean water, we were aware that environmental conditions could still be harmful for lime-based mortars. However, good behaviour of render in and after such conditions would mean that in favourable environmental conditions for rendering with lime-based mortars this behaviour would be even better.

Before and parallel to the fabrication of lime-based renders test fields, flow value (prEN 1015-3), air content (prEN 1015-7), density (prEN 1015-7) and water retentivity (prEN 1015-8) of fresh mortars were determined. Then, the specimens for the determination of characteristics of hardened lime-based mortars were prepared from the same batches as they were used for rendering. The compressive and flexural strength of the mortars were determined on prisms 4x4x16 cm^3 according to prEN 1015-11. For one lime-based mortar three prisms were cast, which means three specimens for flexural test and six specimens for compressive test. Due to earlier problems at determining the bond strength of renders by shear tests according to the recommendation of RILEM 13-MR TC, and since we have no equipment for the pull-off testing of lime-based renders, Bond Wrench test of two-stack high masonry prisms was used for the estimation of bond strength between mortars and clay bricks, although this test is designed for testing brick-mortar junction in masonry. The length of the level arm was first 540 mm and if this was not enough, the level arm with the length of 1080 mm was used. For one lime-based mortar three specimens were made. The tests on hardened lime-based mortars were carried out on 120 day old specimens.

For the measurements of the deformations of lime-based mortars due to shrinkage, the equipment developed by our research group was used. The equipment consists of five moulds 2x6x25 cm^3 and ten LVDT's (two for each specimen) with the accuracy of 10μm and it enables to measure deformations of mortar from the moment, when the filling of moulds with mortar is finished (Fig. 5). Five specimens for each mortar mix were cast. Tested were the mortar mixes with the same proportions as mixes used for rendering, but not from the same batches. During the tests the environmental conditions were as follows: temperature from 19 to 23ºC and relative humidity from 25 to 50%.

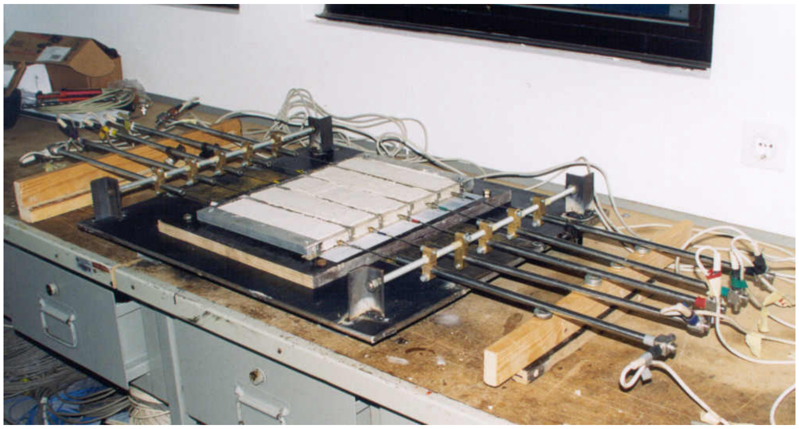


Figure 5. Test set-up for shrinkage measurements of lime-based mortars

ANALYSIS OF TEST RESULTS

Properties of fresh lime-based mortars

Table 1. Properties of fresh lime-based mortars

MIX	flow value (mm)	air content (%)	density (kg/m^3)	water retentivity (%)
MP	152	3	2048	85.6
MTS	147	3.9	2018	90.4
MP+met	138	2.8	2050	91.5
MTS+cem	152	2.7	2032	88.2
MP+fibr	135	3.2	2048	86.2

The results of tests of fresh mortars properties (Tab. 1) show that among plain lime-based mortars mix MP has about 1% lower air content, higher density and lower water retentivity than mix MTS. On this place it has to be stated that mortar MTS needs for approximately the same flow value (actually it is lower) much more water than mortar MP. The addition of metakaolin to plain lime mortar from traditional lime improves the water retentivity of fresh mortar, but has no influence on the other two properties. The addition of fibres to the same plain lime mortar results in lower flow value of fresh mortar despite almost the same workability when applying the mortar on the wall. Fibres do not influence the other properties of this mortar. The addition of cement to plain lime mortar from industrial lime lowers considerably the air content and increases the density of fresh mortar, but has almost no influence on its water retentivity.

Properties of hardened lime-based mortars

The average results of compressive, flexural and Bond Wrench tests of hardened lime-based mortars are given in Fig. 6 and information on failure modes of Bond Wrench test specimens are given in Tab. 2. From these results we can see that plain lime mortar from traditional lime (MP) has by 72% higher compressive strength, 23% higher flexural strength and probably more than 131% higher bond strength than plain lime mortar from industrial lime (MTS). These results confirm statements (Gibbons, 1995) that with mature traditional lime-putty considerably better lime mortar could be obtained than with industrial limes. The addition of metakaolin to MP extremely increases the compressive strength of mortar, even by 342%. Also the flexural strength of the mortar is considerably increased, by 147%. These results are more or less expected, although higher increase in flexural (tensile) strength would be preferred. On the other hand, the bond strength is much lower, more than 40%, which indicates that very small metakaolin particles probably fill the surface pores of clay bricks and thus hinder the formation of a bond between mortar and brick.

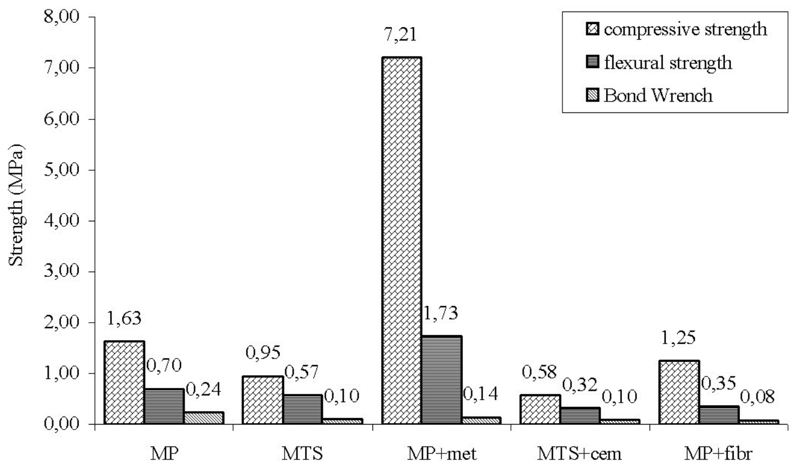


Figure 6. The average compressive, flexural and Bond Wrench strengths of hardened lime-based mortars

The addition of cement to MTS has negative influence on the properties of hardened mortar. This was not expected despite some information that the addition of small amount of cement to lime mortar worsens its properties (Holmström, 1995). The compressive strength of the mortar MTS+cem is by 39% lower, flexural strength is by 44% lower and bond strength is approximately the same as for the mortar MTS. The incorporation of polypropylene micro fibres in the mortar results in lower compressive strength (by 23%), lower flexural strength (by 49%) and lower strength obtained at Bond Wrench test (by 67%), compared to the mortar MP. Due to fact that failure at Bond Wrench test was not only in the mortar joint but also in the mortar-brick junction we can conclude that also bond strength is lower at MP+fibr than at MP. Since the properties of fresh mortar mix were almost not changed due to the addition of small amount of fibres (Tab. 1), lower strengths could be the result of compaction of fibre-reinforced mortar that was not so effective as at plain lime mortar MP. Unfortunately, none of the used tests for strengths characteristics of lime-based mortars can estimate improvement in ductility of the mortar due to incorporated fibres. However, already not instantaneous but progressive failure obtained at Bond Wrench test indicates that ductility of such mortar is highly improved.

Table 2. Failure modes of Bond Wrench test

MIX	Failure modes of Bond Wrench test
MP	always in the mortar joint
MTS	partial in the mortar joint, partial in the mortar-brick junction
MP+met	always in the mortar-brick junction
MTS+cem	always in the mortar-brick junction
MP+fibr	mostly in the mortar joint

Shrinkage of lime-based mortars

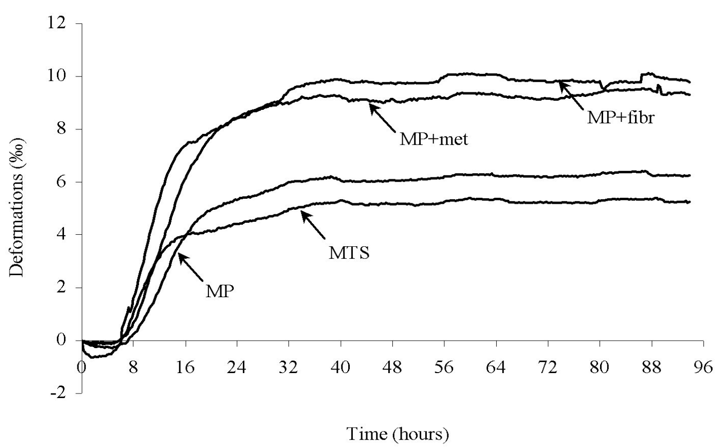


Figure 7. Average deformations due to shrinkage of lime-based mortars

The results of shrinkage measurements of lime-based mortars show (Fig. 7) that in three days most of the deformations due to shrinkage occur. According to JUS B.C8.029, former Yugoslav standard, we have to leave the lime-mortar specimens for standard shrinkage measurements in moulds 4x4x16 at least that long, before we can start the test. After three days we can expect gain in deformations due to shrinkage for pure lime mortars only up to 0.02% in two months (Bosiljkov, 2000). From Fig. 7 we can see that shrinkage of the lime-based mortars starts in three to five hours after mixing the mortar. Deformations due to shrinkage after the first four days are the lowest at pure lime mortars from industrial (about 5‰) and traditional (about 6‰) limes. The addition of metakaolin to mortar from traditional lime increases the shrinkage deformations after four days by about 50% and accelerates the start of shrinkage. Surprising, incorporation of polypropylene micro fibres in the mortar results in even higher increase of shrinkage (about 67%). Since the fibres do not influence the process of lime hardening (at least not importantly) the obtained results could be the consequence of smaller amount of micro cracks in the mortar. Obviously the fibres increase also the strain capacity at the "green" state of the mortar. This limits the formation and growth of micro cracks and can results in higher shrinkage deformations. An important information at this stage is that almost no visible cracks could be detected on the tested specimens after demoulding.

Field studies of the behaviour of renders

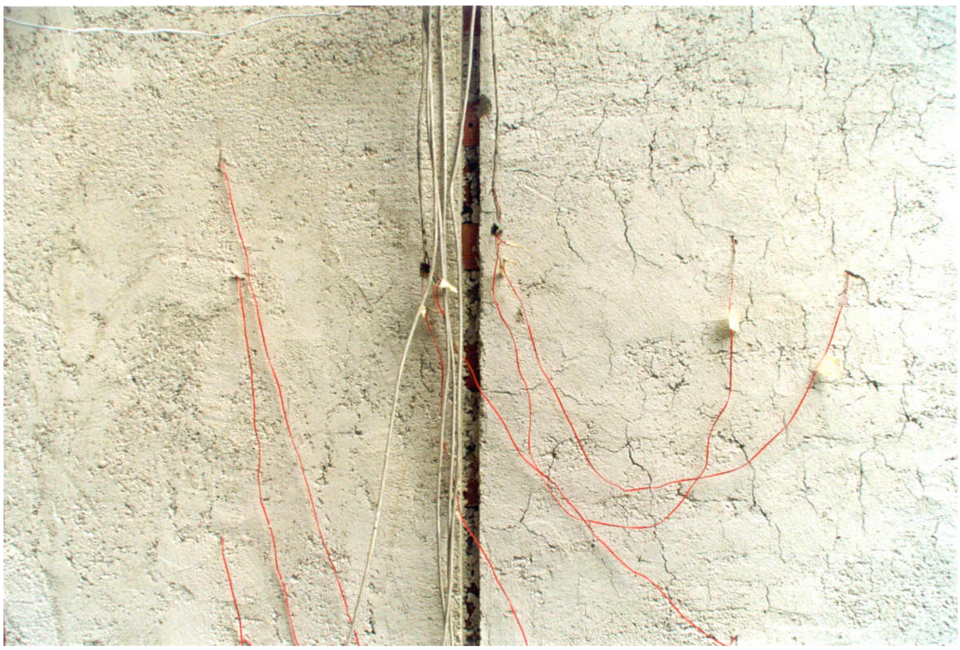


Figure 8. Visual appearance of renders MP (on the left) and MTS (on the right)

Visual examination of rendered test fields on outside walls show that cracking is most extensive for plain lime render from industrial lime (MTS). For this render not only the formation of maximum number of cracks occurred but also the average width of the cracks is the highest, 2.5 mm. Since the most of the cracks were formed almost instantly after the rendering of test field was finished, the most probable reason for cracking of the render is too faster evaporation of water from the render due to unfavourable environmental conditions. Just the opposite is the behaviour of plain lime render from traditional lime (MP). The cracks did not form instantly after rendering but within the first day, the number of cracks is low and the average width of the cracks is about 1.4 mm. The visual appearance of the render MP is after one winter still very good. Since the mortar MP has lower water retentivity (Tab. 1) and little higher shrinkage (Fig. 7) than the mortar MTS, the observed behaviour of both renders on the outside walls could not be directly connected with the two properties of the mortars. The fact is that for approximately the same workability the mortar MTS requires much more water than the mortar MP. Due to higher amount of water in the mortar plastic shrinkage of the render MTS at higher temperatures (around 35ºC) could be much higher than that of the render MP. Fig. 8 shows the visual appearance of both plain lime renders.

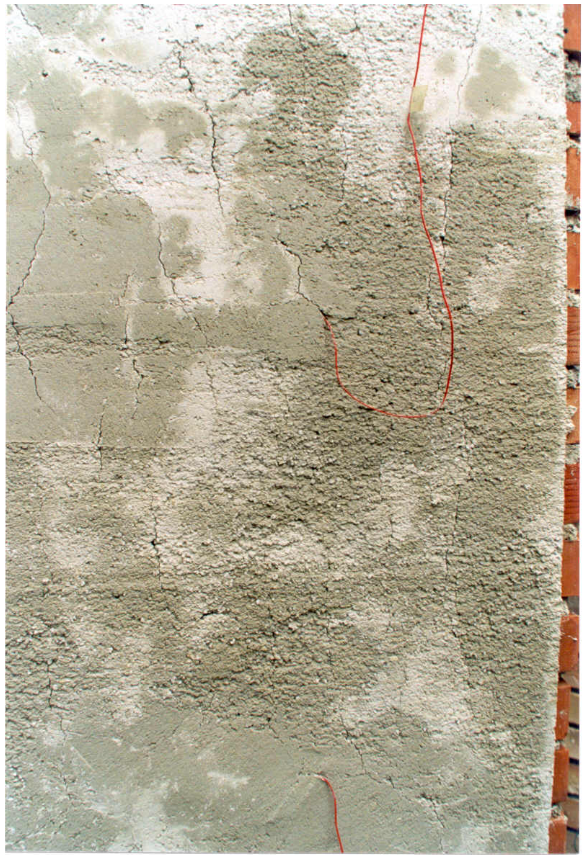


Figure 9. Visual appearance of render MP+met

The addition of metakaolin to the plain lime mortar MP significantly worsens the properties of the lime-based render. First of all, the cracking of the render is extensive (Fig. 9), the average width of the cracks is 2.1 mm and the maximum width is 2.5 mm. The reason for extensive cracking could be higher plastic shrinkage of the mortar with small amount of metakaolin (Fig. 7). Another unfavourable influence of the metakaolin is very visible and extensive wet spots on the rendered test fields (Fig. 9), which are at least disturbing (if not also harmful) due to the aesthetic function of the render. The results of the tests of wetting/drying behaviour of the renders (Kosovel, 2000) show, that the addition of metakaolin to the plain lime mortar MP slightly worsens the resistance of the render to water absorption due to capillary action, but at the same time the ability of the render to dry out is much wors. The described behaviour is probably the reason for wet spots, which could also be very harmful to the lime-based renders during the winter period (deterioration by frost). This render (MP+met) is also one example that in case of renders higher compressive and flexural strength of the used mortars alone do not necessarily mean better behaviour of the render.

The addition of cement to the lime mortar MTS considerably improves the properties of the render, compared to the plain lime render. The cracking of the render is medium and also the width of the cracks is slightly smaller. Since we have had no results of the shrinkage of the mortar MTS+cem yet, realistic explanation of the described behaviour is not possible. It could be connected with higher early strength of the mortar due to the hydration process of cement. Such mortar can in the "green" stage of the lime-based render take over higher tensile stresses due to shrinkage. However, also in this case we can see that lower strength characteristics of the lime-based mortar for rendering do not automatically mean worse behaviour of the render itself. The presence of cement in the lime-based render obviously influences also the properties of the render regarding its orientation, since only in this case the cracking of the northern test field was relatively more extensive than the cracking of the southern one.

The best behaviour of the lime-based renders was obtained with lime mortar from the traditional lime micro-reinforced with polypropylene fibres. The number of visible cracks is very low, the cracks are on average hair-thin and short. It is obviously that the fibres improved the ductility of the render. They could take over a part of the tensile stresses in the render due to restrained shrinkage, but they certainly distributed these stresses evenly in the render. Thus, higher number of evenly distributed micro cracks, not visible with unaided eye, can be expected in this render.

CONCLUSIONS

Several conclusions can be drawn from the analysis of the test results. The first one is that with mature traditional lime putty we obtained lime mortar with superior properties in fresh and hardened state, compared to the lime mortar from industrial lime putty. The necessary amount of water for the same workability of fresh lime mortar is much lower than at the industrial lime putty, and compressive, flexural and bond strengths are much higher. Despite the possibly harmful environmental conditions under which the rendering was carried out and in the first weeks of hardening of the mortar, the "traditional" lime render behaved very good and is after one winter still in the same condition. We believe that this render does not need any pozzolanic addition for the improvement of its properties.

The use of plain lime mortar from industrial lime putty for rendering does not seem to be a very good decision. It is true that very bad results obtained at the field studies could be only the consequence of unfavourable environmental conditions. But this mortar simply needs too much water for good workability, which is a great drawback for later process of hardening of lime. The addition of 10% of cement to "industrial" lime mortar was chosen because in Slovenia craftsmen in practice usually make lime mortar for rendering in this way. Obviously, small addition of cement can improve the properties of "industrial" lime render. Since the strength characteristics of the mortars were determined only on 120 days old specimens, where worsening of the strength properties due to addition of the cement was established, it is very realistic to believe that soon after mixing of the mortar the hydration of cement results in higher gain in strength characteristics of the mortar. Such mortar can in the “green” stage of the lime render take over higher tensile stresses due to shrinkage.

On the basis of obtained results the addition of metakaolin as pozzolanic material to the lime mortars for rendering can not be recommended. The reason is wet spots on the rendered test fields that are very unaesthetic and could also be harmful for the lime-based render. The formation of extensive cracks in the render MP+met could only be due to unfavourable environmental conditions, but it could also be due to higher shrinkage of the render. The obtained gain in compressive and flexural strength could be useful in case of masonry mortars when the demands for the compatibility of properties of restoration mortar to the properties of original lime-based mortar have to be met.

In cases when higher ductility of the hardened lime renders is demanded, the incorporation of fine, flexible and evenly distributed fibres in the lime mortar could be a solution. The used polypropylene fibres behaved good as far as the properties of lime-based renders discussed in the paper are concerned. However, for the final assessment of the influence of the fibres on the properties of lime-based renders all key characteristics (short-term and long-term) of the renders have to be studied.

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