Properties of cement-lime render containing perlite as lightweight aggregate

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Abstract. Lightweight renders with improved thermal performance, resistant against moisture and respecting specific behaviour of original plasters and substrates became attractive materials for surface finishing of both historical and old wall structures. In this respect, structural, mechanical and thermal properties of cement-lime based renders containing a different amount of perlite as fine silica sand substitution are researched in the presented paper. Experimental tests conducted for 28 days samples showed significant lightening of hardened renders with increased perlite content in their fresh mix. Gained strength parameters were, because of higher total open porosity of perlite enriched samples, lower compared with reference material. On the other hand, newly developed lightweight renders exhibited improved thermal insulation performance due to the highly porous perlite particles. In summary, cement-lime renders with incorporated lightweight aggregate based on expanded perlite were considered as alternative and promising materials for application in repair and restoration of historical masonry.

1. Introduction

Lime-based mortars and renders have been the most widespread used building composites not only in the historical monuments but also in buildings constructed at the beginning of 20th century [1]. As the basement of such buildings has not yet been provided with horizontal waterproof insulation or it has been already damaged there might occur a rising damp from the ground upward through permeable wall structure [2]. Advantageous property of lime-based composites, given by their pore structure with the network of capillaries, is being mentioned water vapour permeability helping to keep masonry structures breathable. However, the use of aerial lime as the main binder component provides only low mechanical strength and poor water resistance of renders in the wet or water environment respectively [3]. The incorporation of Portland cement into plaster mix helps to create denser and more durable porous structure of hardened material better resisting to water induced action due to the presence of highly stable C-S-H phases.

The compatibility between the applied repair/retrofitting render and the original substrate and all the masonry elements is very important. Gulbe et al. [4] recommend add lime binder into hydraulic based mortars in order to get conformity and comparable properties with historical mortars.

Rising damp in many cases brings difficulties with water soluble salts coming from subsoil or from agents applied for winter maintenance.

Salts nucleation and subsequent crystallization is accompanied by the creation of high volume products that fulfil porous structure of renders and cause their gradual decay [2], [5]. Consequently,
renders used for restoration should dispose high porosity exceeding 40 % according to the WTA-2-9-04 manual recommendation [6]. Their composition is often spread about the addition of light filling materials, such as perlite, polystyrene, vermiculite, etc., which are capable to store a great amount of salts [5]. In addition, highly porous aggregates enhance thermal properties of produced plasters which, like a part of building envelope, help to reduce energy demands for heating and cooling required in EU directives [7].

The effect of perlite incorporation on behaviour of cement-lime renders was examined in the paper. The analysis of experimental results revealed the reduction in unit weight and strength parameters of tested lightweight renders compared to reference material without perlite use. High open porosity, however, rapidly decreased thermal conductivity of materials with perlite-based aggregate.

2. Experimental

The experimental investigation was performed on the set of cement-lime based renders with improved thermal performance. The obtained data was compared with results assessed for reference render with silica sand aggregate. In all prepared render mixes, ordinary Portland cement (PC), type 42.5 R and hydrated lime CL 90-S were used. For the determination of chemical composition of both binders, X-ray fluorescence device ED-XRF Quant-X (Thermo Scientific) was employed. During the measurement taking place in argon atmosphere, the basic elements of tested powders were determined and subsequently by the software Uni Quant ED 6.28 recalculated to oxides. Particle size distribution of lime-hydrate and PC was accessed by the apparatus Analysette 22 NanoTec (Fritsch) equipped with the red and green lasers that enable to identify particles with diameter in the range of 0.08–2 000 µm. Specific surface was measured using Blaine device model 62 (Controls, Spa, Italy) according to the standard EN 196-6 [8]. Specific densities of both binders were determined by automatic helium pycnometer Pycnomatic ATC (Thermo Scientific).

Oxides composition (only main oxides are given) and physical properties including particle size distribution of lime hydrate and PC are summarized in Tables 1 and 2. In particular, obtained material characteristics indicated approx. 6 times higher specific surface of lime hydrate contrary to PC. That observation was also confirmed by measured particle size distribution when 50 % of hydrated lime particles were lower than 4.2 µm, 22.8 µm in the case of used cement type respectively.

| Oxides composition (mass %) | PC | LH |
|-----------------------------|----|----|
| SiO₂                        | 19.00 | 0.15 |
| Al₂O₃                       | 4.31 | 0.10 |
| Fe₂O₃                       | 2.40 | 0.12 |
| TiO₂                        | 0.28 | -   |
| CaO                         | 62.90 | 98.70 |
| MgO                         | 1.80 | 0.41 |
| K₂O                         | 0.82 | -   |
| Na₂O                        | 0.14 | -   |
| SO₃                         | 3.24 | 0.12 |

| Material               | Specific surface (m²·kg⁻¹) | Powder density (kg·m⁻³) | Specific density (kg·m⁻³) | d₁₀ (µm) | d₅₀ (µm) | d₉₀ (µm) |
|------------------------|---------------------------|-------------------------|---------------------------|---------|---------|---------|
| Hydrated lime          | 2 211                     | 232.8                   | 2 210                     | 0.8     | 4.2     | 50.3    |
| Portland cement        | 360                       | 970                     | 3 129                     | 6.0     | 22.8    | 32.4    |

As a reference material, cement-lime render (REF) was produced. It consisted of PC and lime hydrate dosed in 1/1 wt. ratio, three kinds of silica sand providing a smooth particle size distribution curve with particles size up to 2 mm and batch water. In other renders, dense silica aggregate was substituted in the
portion of 25–100 vol.% by lightweight aggregate – a mix of commercially available perlite EP 100 (Perlite 0.0/0.5) and EP 150 PB (Perlite 0.0/2.0) mixed together in the volumetric ratio ¼. Finely particulate perlite served as a supplementary material increasing the amount of fine grains in perlite mix whose particle size distribution was thus more resembling to that of silica aggregate. Before mixing, perlite aggregate was stored in closed plastic box filled with tap water for 24 h. The amount of added batch water kept similar workability of all developed render mixtures with the value of spreading of 160 × 160 ± 5 mm. Mix proportions of reference as well as of lightweight renders are given in Table 3.

Table 3. Mix proportions of reference and lightweight renders.

| Substance          | Content (kg·m⁻³) |
|--------------------|------------------|
|                    | REF  | LR 25 | LR 50 | LR 75 | LR 100 |
| Lime hydrate       | 241.9 | 239.9 | 250.4 | 262.2 | 274.3  |
| Portland cement    | 241.9 | 239.9 | 250.4 | 262.2 | 274.3  |
| Sand 0.0/0.5       | 451.6 | 335.9 | 233.8 | 122.3 | -      |
| Sand 0.5/1.0       | 451.6 | 335.9 | 233.8 | 122.3 | -      |
| Sand 1.0/2.0       | 451.6 | 335.9 | 233.8 | 122.3 | -      |
| Perlite 0.0/0.5    | -    | 2.4   | 5.0   | 7.3   | 9.5    |
| Perlite 0.0/2.0    | -    | 40.8  | 85.6  | 123.8 | 173.4  |
| Water              | 348.3 | 263.9 | 210.3 | 157.3 | 98.8   |

Raw materials were mixed by mixer Spar D 200-B, from fresh renders prisms having dimensions of 40 × 40 × 160 mm and 70 mm cubes were casted. Filled metal moulds were than compacted by 5 hits on laboratory table. After 48 h of initial hardening in laboratory conditions at temperature (20 ± 1) °C and relative humidity (45 ± 5) %, samples were demoulded and stored in conditions with high relative humidity (~ 98 %) for overall time of 26 days.

Particle size distribution of used aggregates was assessed by sieve analysis according to the standard EN 933-1 [9]. At first, a representative sample of the particular tested aggregate was dried to constant mass at (105 ± 2) °C and naturally cooled. Then, it was placed into series of sieves with mesh size 2.0; 1.0; 0.5; 0.25; 0.125, and 0.063 mm, and mechanically shaken by vibratory sieve shaker Retsch AS 200.

Value of spreading of fresh mixtures was determined according to the standard EN 1015-3 [10] in two perpendicular directions after 15 hits on the shook table.

For the hardened 28 days cured samples, basic physical parameters, mechanical properties and thermo-physical properties were determined. The bulk density measurements were conducted according to the standard EN 1015-10 [11]. The specific densities were accessed by helium pycnometer Pycnomatic ATC (Thermo-Scientific). The total open porosity was calculated based on both the bulk and matrix density values. The relative expanded uncertainty of the applied testing method was 5 %. The mechanical properties, namely flexural and compressive strength were assessed according to the standard EN 1015 – 11 [12]. Three point bending test was carried out on prismatic specimens having size 40 × 40 × 160 mm. On the rest of broken prisms, compressive strength was tested [13]. The expanded measuring uncertainty of the both strength tests was 1.6 %. Among tested mechanical parameters, determination of dynamic Young's modulus was done using apparatus Dio 562 NLF (Starmans Electronics) [14]. The relative expanded uncertainty of the dynamic Young’s modulus measurement was 2 %.

Thermo-physical properties, represented by thermal conductivity λ (W·m⁻¹·K⁻¹), thermal diffusivity a (m²·s⁻¹) and volumetric heat capacity c (J·m⁻³·K⁻¹), were measured on 70 mm dried cubes by the portable device ISOMET 2114 (Applied Precision) equipped with circular plate probe. The measuring range of thermal conductivity was from 0.04 to 3 W·m⁻¹·K⁻¹ with the measurement accuracy 5 % of reading + 0.001 W·m⁻¹·K⁻¹. For volumetric heat capacity was the accuracy 10 % of reading and the reproducibility was 3 % of reading + 1·10³ J m⁻³·K⁻¹ [15]. Tests were performed under laboratory conditions at temperature (21 ± 2) °C.
3. Results and discussion
Basic material properties of perlite and sand fractions are introduced in Table 4. From the powder density as well as matrix density results, one can observe significantly lower unit weight of perlite compared to silica sand that led to above indicated requirement of volumetric substitutions of dense silica aggregate. Accordingly, high porosity of perlite particles expectedly help to mitigate thermal conductivity of hardened specimens. Particle size distribution of silica and perlite aggregates is shown in Figure 1. Both obtained distribution curves had practically similar shape. However, perlite aggregate contained slightly higher representation of particles with diameter size above 0.5 mm.

| Material | Perlite 0.0/0.5 | Perlite 0.0/2.0 | Sand 0.0/0.5 | Sand 0.5/1.0 | Sand 1.0/2.0 |
|----------|-----------------|----------------|--------------|--------------|--------------|
| Powder density (kg·m⁻³) | 55 | 233 | 1 478 | 1 505 | 1 568 |
| Matrix density (kg·m⁻³) | 651 | 572 | 2 654 | 2 648 | 2 640 |

**Figure 1.** Sieve analysis of perlite and fine silica aggregates.

The effect of perlite dosage on basic material properties of examined renders is apparent from Table 5. It is evident that an increase of perlite content resulted in a gradual lightening of hardened renders when bulk density values dropped from initial 1 814 kg m⁻³ determined for reference sand-based material to 635 kg·m⁻³ obtained in the case of sand-free render. Total open porosity data showed corresponding trend. Moreover, tested hardened specimens containing lightweight aggregate equal or above 50 vol. % reached open porosity exceeding 40 % thereby these met requirements according to the WTA-2-2-04 [6] manual for restoration renders. According to the standard EN 998-1 [16] these materials could be also sorted as lightweight renders with dry bulk density below 1 300 kg·m⁻³.

| Render | Bulk density (kg·m⁻³) | Matrix density (kg·m⁻³) | Total open porosity (%) |
|--------|------------------------|-------------------------|-------------------------|
| REF    | 1 814                  | 2 525                   | 28.1                    |
| LR 25  | 1 536                  | 2 330                   | 34.1                    |
| LR 50  | 1 163                  | 2 090                   | 44.4                    |
| LR 75  | 908                    | 2 034                   | 55.3                    |
| LR 100 | 635                    | 1 618                   | 60.8                    |
Strength properties and dynamic Young's modulus are summarized in Table 6. Obtained experimental results are in agreement with reported basic material properties. There was recorded strength as well as Young's modulus decline proportional to the growth of perlite content. In this respect, the lowest compressive strength of 2.9 MPa was measured for LR 100. According to the EN 998-1 [16], recorded compressive strength fit in the class CS II (strength values from 1.5 N·mm² to 5.0 N·mm²) and thus can be used as lightweight render for renovation purposes as well.

| Render | Flexural strength (MPa) | Compressive strength (MPa) | Young's modulus (GPa) |
|--------|-------------------------|---------------------------|----------------------|
| REF    | 2.7                     | 8.1                       | 10.9                 |
| LR 25  | 2.3                     | 7.8                       | 8.0                  |
| LR 50  | 2.0                     | 5.2                       | 3.7                  |
| LR 75  | 1.4                     | 3.9                       | 2.5                  |
| LR 100 | 1.2                     | 2.9                       | 1.6                  |

The development of thermo-physical properties in dependence on perlite content is given in Table 7. Due to low weight and high porosity of perlite aggregate, a steep decrease in the thermal conductivity and thermal diffusivity was recorded. In porous structure entrapped air acts as an excellent thermal insulator and improves thermal insulation function of composite materials [17]. On this account, render with full silica sand substitution by perlite reached approx. 11.5 times lower thermal conductivity compared with the reference samples. Very low thermal conductivity (0.12 W·m⁻¹·K⁻¹) suggests its considerable thermal insulation function and its possible classification as a thermal insulating render meeting thermal performance demand T₂ ≤ 0.2 W·m⁻¹·K⁻¹ (EN 998-1) [16].

| Render | λ (W·m⁻¹·K⁻¹) | a × 10⁻⁶ (m²·s⁻¹) | c × 10⁶ (J·m⁻³·K⁻¹) |
|--------|---------------|-------------------|---------------------|
| REF    | 1.39          | 0.82              | 1.70                |
| LR 25  | 0.91          | 0.55              | 1.65                |
| LR 50  | 0.42          | 0.26              | 1.56                |
| LR 75  | 0.22          | 0.18              | 1.24                |
| LR 100 | 0.12          | 0.16              | 0.78                |

4. Conclusion
The paper was focused on the effect of a partial and full substitution of commonly used dense silica fine aggregate by perlite mix on properties of developed lightweight renders. Practical experiments revealed very low weight of perlite contrary to silica sand that resulted in significant decrease of bulk density and lightening of hardened render specimens. Higher representation of lightweight aggregate, however, led to mechanical resistance reduction. On the other hand, highly porous perlite particles helped to improve thermal insulation function of developed renders.

Designed renders, in particular these without silica fine aggregate, dispose of low unit weight, high open porosity, sufficient mechanical resistance, and thus meet the requirements according to the standard EN 998-1 for lightweight thermal insulating repair renders suitable for renewal purposes.

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