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Development and testing of repair mortars for floor mosaic substrates

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ABSTRACT

Mosaics were diachronically used as a mean to decorate floors of historic constructions. Their durability and resistance to loading and environmental parameters, was mostly attributed to their substrate, which composed of three to four very well compacted mortar layers. The construction of these substrates usually followed specific requirements and criteria, concerning both the selection of raw materials and the application techniques followed. This paper concerns a systematic study of double-layered mortars, designed and manufactured according to the characteristics found in ancient floor mosaic substrates. Specific parameters were taken into account, such as the binding system, the aggregates' type and gradation, the Binder/Aggregate (B/A) and Water/Binder (W/B) ratio, as well as the layers' thickness and the application technique. A series of test were performed at the age of 28, 90 and 180 days. The properties measured concerned porosity, apparent specific gravity, water permeability, capillary absorption, dynamic modulus of elasticity, flexural, compressive strength, while bond strength by pull off and tensile bond strength were conducted. From the evaluation of the results, it was concluded that good compaction and low W/B ratio ensured relatively high compressive strength (5–10 MPa), as well as increased adhesion between the mortar layers, while the addition of brick dust and crushed brick enhanced the layered mortars' performance.

1. Introduction

The use of mosaics as a mean to decorate the floors of ancient structures started during the 2nd millennium BC [1–3]. From the 4th century BC their construction was systemized and specific criteria started to be followed, regarding both their materials and application techniques [4–7].

The substrate of floor mosaics played a fundamental role in their structure, ensuring their durability and resistance to loading and environmental factors [5]. Vitruvius [8] categorized floor mosaics according to their application (i.e. outdoor, indoor), giving specific technical details on the construction of the substrate of each case. Diachronically, the floor mosaic substrates consisted of three to four very-well compacted layers, concerning [5,8–14]:

1. 'statumen', a layer of pebbles (dimensioned around 6 × 8 cm), put above a very well compacted sub-ground,
2. 'rudus' a mortar layer (4–8 cm thick) based on lime and pozzolan, consisting of a high proportion of coarse aggregates (0–16 mm),
3. 'nucleus'(2–4 cm thick) consisting of lime, pozzolan, often brick dust and aggregates of gradation 0–6 mm to 0–8 mm (natural, as well as ceramic) and
4. 'supra nucleus' (0.5–1 cm thick) consisting of lime, pozzolan, often brick dust and fine aggregates (0–2 mm).

Synoptically, mortar layers were mainly based on lime and pozzolan, while in nucleus and supra nucleus brick dust was also added [5–8]. Their thickness was reduced towards the surface, as well as the aggregates' maximum size, while the B/A ratio was increased [5,6]. As a result, porosity was usually decreased towards the upper layers [5].

A significant parameter taken into account during their application was the good compaction of the layers, usually made with wooden tools (i.e. mallets, rammers) [5,8]. This resulted on reducing the pores and voids of each layer and therefore on enhancing their mechanical properties, whilst it had a significant impact on the adhesion of the layers, ensuring the durability of the substrate [5]. To this direction, a synergy of other factors contributed, such as the individual characteristics of each layer (i.e. low W/B ratio, aggregates' gradation, B/A ratio), as well as the scoring of the fresh subjacent layer forming a relief of lines (random or ordered) [5,8,15,16].

Nowadays, the conservation of ancient floor mosaics depends on the pathology symptoms encountered, which are usually interrelated with the stability of the mosaics' substrate. Multiple techniques maybe applied, such as the consolidation of the tesserae's through grouting [17],

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Fig. 1. Cracking of repaired ancient floor mosaic edges and tesserae loosening.

Table 1
Stratigraphy and characteristics of ancient floor mosaic substrates.

Historic period	Substrate layer / thickness (cm)	Binding system L: lime P: Pozzolan B: Brick dust	B/A ratio	Aggregates gradation (mm) / type	Compr. strength (MPa)	Porosity (%)
Hellenistic	Supra nucleus / 0.2–0.8	L:P:B	1/1	0–2 / siliceous, crushed brick	–	11–18
	Nucleus / 2–4	L:P	1/2	0–4 to 0–8 / siliceous	1.5–4	12–19
	Rudus/ 3–8	L:P	1/2.5 – 1/3	0–8 to 0–16 / siliceous	3–5	16–25
Roman	Supra nucleus / 0.3–1	L:P:B	1/1	0–2 / siliceous, crushed brick	–	18–20
	Nucleus / 2–5	L:P:B	1/1.5–1/2	0–8 / siliceous, crushed brick	2.5–3.5	26–31
	Rudus/ 4–7	L:P	1/2.5 – 1/3	0–16 / siliceous	2–4	28–33

the reinforcement of the mosaic edges with repair mortars [17], as well as the detachment of the mosaic and its backing in a new substrate (portable or on site) [18].

Although there is accumulated research knowledge on the stratigraphy and characteristics of ancient floor mosaic substrates [5,7,10,11,13], restoration projects mainly focus on specific mortar layer that need to be conserved or substituted by repair materials [17,18]. Consequently, the functional role of the substrate as a composite system is not taken into account, neither the interrelating properties of each layer. This maybe attributed to the lack of information regarding the extend to which each layer influences or even determines the final properties and performance of the substrate.

As a result, past interventions conducted with incompatible repair materials or improper techniques have resulted in secondary problems that aggravated the preservation state of floor mosaics (i.e. cracking of the repaired and neighboring mosaic edges, loosening of tesserae) (Fig. 1).

In the present study, an effort has been made to simulate the structure of the two main mortar layers of ancient floor mosaic substrates (rudus and nucleus). The goal was to identify the key elements of their performance, focusing on the following aspects:

- Understand the impact of the mortar layer's properties on the performance of the composite system.
- Define the parameters (type and proportion of raw materials, application technique) that influence the substrates' characteristics.
- Propose a methodological approach regarding the design and testing of multilayer mortar systems, for the restoration of ancient floor mosaic substrates.

To this direction, four mortar compositions and three double-layered mortar series, were manufactured and tested, taking into account specific constructional aspects, found in ancient floor mosaic substrates. All mortars were based on lime and natural pozzolan, while specific parameters (i.e. layer's thickness, B/A ratio, aggregates' type and gradation), varied according to the layer (rudus or nucleus). Special attention was given to the compaction technique followed, in order to enhance the adhesion between the layers. At the age of 28, 90 and 180 days the physical and mechanical properties of the specimens were tested, in order to estimate the early and long-term properties of the specimens and mainly the strength development throughout time.

2. Materials and methods

The design of the mortar layer series followed the test results of a representative number of ancient floor mosaic substrates, analyzed during the last two decades in the Laboratory of Building Materials, School of Civil Engineering, Aristotle University of Thessaloniki and dated during Hellenistic and Roman times [5,6]. The monuments from where the mortars were sampled concerned Aiges Palace (350-340 BCE), the archaeological site of Pella (325-300 BCE), the archaeological site of Dion (3rd cent. AD) and the Galerius complex in Thessaloniki (3rd cent. AD).

According to Table 1, the ancient mortar layers were based on lime and pozzolan, while brick dust and crushed brick (as aggregates) were often detected in nucleus and supra nucleus. The B/A ratio of the mortars was decreased to the upper layers (rudus: 1/2.5-1/3,nucleus: 1/1.5–1/2), as well as the aggregates maximum size (0–16 to 0–8 mm for rudus and 0–4 to 0–8 mm for nucleus).

In order to simulate in laboratory scale the constituents and characteristics of the ancient floor mosaics' layers (nucleus and rudus), a series of mortar compositions were designed [19]. In all cases, the binding system was based on lime and natural pozzolan, while a short proportion of brick dust (10% w/w of binders) was added in some compositions.

The characteristics of the binding agents are presented in Table 2. The aggregates followed the gradation found in the ancient mortar layers, according to Fig. 2 and their characteristics are shown in Table 3. The B/A ratio was decided to be 1/3 for rudus and 1/2 for nucleus, following the analysis results of the ancient substrates (Table 1) [5,6].

The amount of water was adjusted for attaining a generally low workability of 12 ± 1 cm [20]. This was imposed by the diachronic requirement of minimizing the water quantity in this type of mortars, in