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Design and testing of artificial stone for the restoration of stone elements in monuments and historic buildings

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HIGHLIGHTS

- The analysis of authentic stones gives the guidelines for designing the artificial stones.
- Utilization of local materials (binders and aggregates) for sustainable mortar mixtures.
- Each site requires a unique approach based on the authentic stones and on the local environment.
- The design of the artificial stone is based on principles of compatibility.

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ABSTRACT

Different structural parts of monuments and historic buildings were based on stone as the main building material, such as masonry and foundation, while many types of stones were also used for decorative, architectural elements, such as reliefs, cornices, corbels, colonnettes. The preservation of stone elements is crucial for the continuity of these structures. Mortar on the other hand is an artificial building material which serves different construction needs, according to the selection and combination of binders and aggregates. By the design of a mortar with similar properties to the specific stone type, a low cost and environmental friendly product of adjustable dimensions, texture and high reproducibility can be achieved. In an effort to re-produce a specific type of stone by an artificial material, many studies have been performed based on polymer resins and fillers. Despite the fact that the results of such research seem promising, the restrictions in the case of monumental structures focusing on using compatible repair materials, renders them inappropriate for restoration works. The development of repair mortars based on inorganic binders for stone restoration receives a lot of attention as a compatible solution.

The aim of this study is to present the philosophy of the design, production and testing of artificial stones by the mortar technique, based on principles of compatibility and utilization of the local resources. Repair mortars specially designed for the needs of each site look like the natural stone, present durability and adjustability to the local environment without causing side effects.

1. Introduction

Different types of stones have been employed in the construction of monuments and historic buildings, based on their significance and structural requirements, as well as the availability of raw materials. Nowadays, many difficulties arise during restoration works, when filling of missing parts or replacement of stone elements is required. This is mainly attributed to the availability of specific stone types, the high cost of quarrying and transportation, as well as the high environmental impact.

An environmentally friendly alternative is the use of artificial stones which are designed using guidelines and criteria based on the recorded properties of the authentic stones [1]. Surface treatment of the final product could also add specific properties such as brightness and hardness for imitating natural stone.

The definition of the term "artificial stone" as given in the Encyclopedic Dictionary of Polymers is [2]: "Special concretes and tiles, artificially colored to simulate natural stone, obtained by mixing stone dust aggregate and chips with Portland cement".

The capability to produce a light weight material of high strength and resistance, which at the same time could be aesthetically elegant, imitating natural stones, is nowadays an extensive research field, leading to the domination of epoxy resin technology [3–6]. Many patents have been developed producing mainly

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artificial marble, as it is an expensive and widely used stone, based on fillers and polymer resin materials [7,8]. Recently, nanoparticles were also incorporated in mixtures as modifiers, in order to improve mechanical properties [9,10].

Despite the fact that the results of these studies are promising, the main restriction for their application in restoration works of monuments and historic buildings has been their incompatibility with the authentic stones. This is because polymers such as epoxies or acrylics due to their completely different chemical composition, they behave and weather differently than stone. Therefore, research focused on the design of artificial stones based on inorganic binders [11–16] which however, have been used for millennia in construction (i.e. reliefs, cornices, corbels, colonnettes). Such construction refers to mixtures of binders and aggregates, in such types and proportions in order to achieve specific properties (color hue, texture, physico-mechanical properties, etc.) [13,14]. Generally, the use of artificial stone was adopted diachronically in construction, due to the advantages it offered in comparison to natural stones (lower cost related to mining and transport, easiness in manufacture, application and reproduction).

Historically, the first attempt to produce decorative ornaments with mud mortars dated during the Neolithic period in Çatal Hüyük (7th–6th millennium BC) [17]. During the Minoan and Mycenaean civilizations (2nd millennium BC) the manufacture of architectural elements (reliefs, epistyles, moldings, entablatures) with mortars based on gypsum and lime was systematic [18] and continued throughout the Classic and Hellenistic period [19]. In Roman times, the constructional tradition was applied in several public and private buildings, due to the low cost and ease of reproduction [20,21]. During Renaissance and until the beginning of the 20th century, the manufacture of architectural elements with mortars for the external and internal decoration of buildings dominated [12–15].

According to the depth and volume of the cast architectural members, the traditional way of application varied within two main categories [20,21]:

- In the case of large members the production was carried out in situ with cast material and specific formworks.
- Smaller elements were precast, usually produced in a laboratory, transferred and placed on site while they were still fresh.

Nowadays, the advantages of artificial stone in comparison to natural stone are highlighted under the principles of sustainability in construction, related to reducing raw materials and energy resource consumption [22]. However, this research field is very interesting, as the reports of using stone repair mortars in stone conservation are based on ready to mix products not designed specifically for the needs of a worksite [23,24].

The use of artificial stone in heritage structures, which is the topic of this research, presents several benefits including the following options:

- Designing a mortar of similar physical (color hue, texture, porosity, apparent specific gravity, etc.) mechanical and microstructure properties with the original stone, under the prism of compatibility.
- Determining specific properties of the final product according to the specific needs of the monument and the wider environmental aspects (water retentivity, frost action, durability).
- Flexibility in manufacture, application and reproduction process.
- Cost effectiveness and preservation of raw materials resources, under the prism of sustainability.
- Revival of a diachronic constructional technique which prevailed in constructions from the Neolithic period, until the beginning of the 20th century.

The present study focuses on designing, manufacturing, testing and applying a series of artificial stone compositions for the restoration of three monuments in Greece. In all cases, the main challenge was to design effective artificial stone mixtures for replacing or filling deteriorated stones, by maintaining the physico-mechanical properties of the authentic stones and enhancing their durability under the existing environmental conditions. The artificial stones were based on inorganic binders such as white cement, lime and clay, natural aggregates of different gradation (preferably from local origin) and inorganic pigments. The studied monuments were:

- Archaeological site of Pella (4th century BC): The aim of the study was to produce cast pieces of artificial stone in order to reconstruct the low walls of the Ancient Agora, highlighting the ground plan of the site.
- Ancient Theatre of the Archaeological site of Maronia (3rd century BC): The aim of the study was to fill the lacunas of the deteriorated stone domes of the Ancient Theatre.
- The Fortress of Saint Nicolaos of the Medieval city of Rhodes (14th century AD): The aim of the study was either to replace or fill the deteriorated stones of the stone masonry.

2. Materials and methods

First, a systematic analysis of the old stones was made, by taking an adequate number of samples from sound and problematic specimens. In this way, the process of deterioration and the differences in physical and mechanical properties between sound and degraded stones were recorded.

Micro-structure observation was performed by stereoscope (Leica Wild M10) assisted by image analysis (ProgRes). When necessary for mineralogical characterization, thin sections were produced and the observation was performed using polarized microscope (Leica Laborlux 12 POLS). Porosity and apparent specific gravity were determined according to RILEM CPC 11.3 absorption of water under vacuum. Dynamic Modulus of Elasticity and compressive strength was recorded according to ASTM C597-71 and ASTM C191-81, respectively. The pore size distribution of the specimens was calculated using the BJH method after nitrogen adsorption (Nova 2000, Quantachrome).

Then, mortar mixtures for artificial stones were designed, based on the characteristics of the existing old stones and taking into account the aim of the intervention and the environmental aspects of each site.

Raw materials available in the market were tested in order to check their suitability (specific gravity and average particle size using particle size analysis, pozzolanicity index according to ASTM C593-06, aggregates granulometry (EN1015-1:1998), soluble salt content (using HPLC) (Tables 1 and 2). In each site, an effort was made to reclaim local materials such as clay and aggregates from the excavation or from a nearby river. When this was possible, the materials were tested in the laboratory to check their suitability according to relevant regulations

Table 1
Characteristics of the binders used for the artificial stone compositions.

Binders	Specific gravity (g/ml)	Avg. particle size (μm)	Specific surface area (m^2/g)	Pozzolanicity index (MPa) (ASTMC31:77)
Properties				
White cement (CEM II/A-LL42.5N)	2.644	17	1.03	–
Clay	2.573	85.7	0.64	1.5
Hydrated lime (Type N)	2.471	10.8	2.25	–
Natural pozzolan	2.403	11.6	1.82	10.5