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Understanding the 16th century coastal watchtowers: Material characterisation of Torre Gregoriana (Italy)

Riccardo Cacciotti *, Veronika Petráňová [1], Dita Frankeová [1]

Institute of Theoretical and Applied Mechanics of the Academy of Sciences of the Czech Republic, Prosecká 76, 190 00 Praha 9, Czech Republic

HIGHLIGHTS

- Mortars, bricks and stone from Torre Gregoriana (1582–1585) are investigated.
- Mechanical, physical and chemical characteristics of small samples are determined.
- New insights on the technologies used by the engineers in military architecture.
- Historical events relate to care in building coastal towers in the 16th century.
- The paper opens to innovative research method for protection of coastal heritage.

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ABSTRACT

The building materials employed in Torre Gregoriana (1582–85), Terracina, have been investigated. The study focuses on the physical, chemical and mechanical characterisation of mortars, bricks and stones. The aim is to provide further insights on the knowledge of the military engineers of the time as well as to outline the material characteristics for the sake of defining compatible repair materials, details which are still missing to date. The results highlight that, due to the emergency of Turkish invasions in this period, great care was used in the building of these constructions, resulting in an accurate selection and distribution of materials by the builders (mainly hydraulic mortars and pure limestone units) and the intentional addition of reactive aggregates (such as glass particles and iron slag) for improving the durability of the structure against the aggressive marine environment.

1. Introduction

Torre Gregoriana is a masonry watchtower located in Terracina (Italy), built between 1582 and 1585. It is part of the former coastal defence system of the Pontifical States which stretched along the Tyrrhenian Sea for about 200 km. In the context of such defence system, the 16th c. typology of watchtowers (Fig. 1), also referred to as *torre pontificia* [1], constitutes the very first attempt to a standardisation of design. Being this the period of the Turkish hegemony over the Mediterranean region, the aim was clearly to establish a more reliable and organic defensive system. While previous structures present heterogeneous geometrical, material and constructive characteristics, the typology under exam, to which Torre Gregoriana belongs, follows an exact template enforced by the Papal decree "Costitutio de aedificandis turribus in oris maritimis" (Pius V, 1567). Its main features are summarised by Guglielmotti [2] as follows: square plan tower with 10 m side and 20 m height, 3–4 m thick walls, inclined façades under the cordon, tall doorway above the cordon, and external staircase with a movable bridge connecting to the entrance. Three vaulted floors: one for storage, one for living and one for shooting. Internally, a winding staircase connects the different levels. Nowadays over 15 existing structures in the Latium region alone are documented to belong to this typology [3].

Although the available historical documentation enables a satisfactorily detailed description of the morphological and structural features of the watchtowers [4–7], a lack of a formal study concerning their material characteristics is evident. The scope of this study is to characterise the physical and mechanical properties as well as the chemical and mineralogical composition of the fabric of Torre Gregoriana, whose base is the only part still standing today, by carrying out an experimental investigation in laboratory. Such investigation includes a macroscopic description of the sampled materials, an estimation of the binder/aggregate ratio in

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* Corresponding author. Tel.: +420 286885320; fax: +420 286884634.
E-mail address: cacciotti@itam.cas.cz (R. Cacciotti).

[1] Tel.: +420 286885382; fax: +420 286884634.

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Fig. 1. Examples of 16th century coastal watchtowers: from left Torre Olevola, Torre Vittoria and Torre Pesce.

mortars, binder SEM-EDS analysis, determination of basic physical characteristics, thermal gravimetric analysis and XRF, bending and compressive strength testing. The goal is twofold: firstly the historical aspect, providing insights on the technological care used during the construction phase; the aim is to underline how the turbulent period of incursions the Papal States were experiencing reflected in the selection of good quality materials and in the care paid during the execution of the works; secondly the technical aspect, deepening the knowledge concerning the materials used in such fortified structures, their durability and strength, in the perspective of individuating compatible materials that could be employed in restoration works of the many constructions of this typology surviving. The paper is structured as follows: Section 2 presents the samples available for testing, including mortars, bricks and stone units; Section 3 summarises the experimental activities carried out on the specimens, such as electron microscopy observations (BSE and EPMA), chemical analyses (XRF and TGA), bending and compression test; Section 4 is dedicated to the discussion of the results obtained during the testing; Section 5 finally concludes on the findings with respect to the previously mentioned goals set for this study as well as it proposes a comparison with available research carried out on similar objects (watchtowers, lighthouses and fortifications) for the sake of briefly outlining an adequate methodology for the analysis of these constructions.

2. Material samples

Samples were taken onsite from the three-leaf perimeter walls and the vault. The walls consist of a stone masonry internal leaf, a rubble masonry core infill and an inclined external brick masonry leaf (Fig. 2). The sampled materials (Fig. 3) include: (M1) mortar from wall infill (samples W_N_MAL1, 2 and 3); (M2) bedding mortar of the brick masonry layer (samples W_C_MAL1, 2 and 3); (M3) bedding mortar from the resisting section of the vault (V_ER_MAL1, 2 and 3); (B) bricks from the external layer of the walls (samples W_C_MAT1, 2 and 3) and (S) stone units from the wall core and vault.

A macroscopic observation was performed in order to describe the overall appearance and consistency of the studied materials. Mortar type M1 (Fig. 4) is characterised by a greyish binder, with coarse grained aggregates and finer ceramic particles. It presents white lumps varying in size from 2–3 mm up to 10–15 mm. The cohesion and consistency of the mortar is good to slightly friable. Mortar type M2 (Fig. 5) shows a light greyish binder, fine grained particles of ceramic material and 1–2 mm large white fragments probably consisting of not well mixed binder. The mortar is friable with low consistency. Mortar type M3 (Fig. 5) is characterised by a whitish binder, coarse to fine well graded aggregates including coarse grained slag and ceramic particles and occasionally white lumps. This mortar exhibits good durability and cohesion. Brick samples (Fig. 4) are fine grained with a colour varying from pinkish to yellow exhibiting a dense structure. The limestone samples S are characterised by a compact structure without any significant structural variances. The colour varies between a bright grey and dark.

Three 20 × 20 × 20 mm specimens for each material were prepared for the experimental investigation (Fig. 6). Additional compact prism specimens of dimensions 20 × 20 × 30 mm (Fig. 7), obtained from the samples of mortars and bricks, were used for flexural testing (such specimens are denoted in the text by the addition of letter a, b, c to M1, M2, M3 and B).

3. Experimental investigation

The study of the available material is based on the application of different instrumental methods including binder SEM-EDS analysis, the determination of basic physical characteristics, the estimation of binder/aggregate ratio, thermal gravimetric (TGA) and X-ray fluorescence (XRF) analyses, bending and compressive strength testing. Specimens were investigated in the scanning electron microscope (SEM) MIRA II LMU (Tescan corp., Czech Republic) equipped with an energy dispersive X-ray detector (EDX, Bruker corp., Germany). Fragments of all samples, approximately 0.5 × 0.5 cm in size, were coated with a thin layer of gold to improve their conductivity necessary for the observation in the scanning electron device. Micrographs in secondary electrons (SE) were subsequently obtained, providing information concerning the microstructure and texture of each sample. Polished specimen sections were used for the backscattered electrons (BSE) and the electron probe microanalysis (EPMA). Sections of stone specimens S-1 and S-3, mortar specimens M1-1, M1-3, M2-1, M2-3, M3-1 and M3-3 and brick specimens B-1 and B-3 were studied. These were coated with a thin layer of carbon (approx. 15 nm) in order to determine the composition of the aggregates and binder by EMPA. The composition of the latter was determined at 10 different locations, covering an area of 50 × 50 μm, on each sample.

The water accessible porosity has been determined by a Mettler Toledo AG204 hydrostatic balance. The specimens were dried at 60 °C in order to determine the dry weight D and then they were saturated with water under vacuum. The saturated weight W and the hydrostatic weight S were measured. The water accessible porosity was calculated as $\text{Por}_w = (W - D)/(W - S) * 100$ considering the density of the water at room temperature. Bulk densities γ_s were estimated by the ratio between dried weight D and the volume of the sample. Results are summarised in Table 1.

A thermogravimetric analysis (TGA) was performed with the instrument TA SDT Q600. Samples were heated in nitrogen atmosphere up to a temperature of 1000 °C at a rate of 20 °C/min. The mass changes of specimens M1-1, M1-3, M2-1, M2-3, M3-1 and M3-3 and brick specimens B-1 and B-3 were monitored as a function of temperature, in order to identify the mineralogical phases and thus determine the composition of each sample. Mortar samples were gently hand crushed and sieved under 63 μm, brick sample was just powdered. X-ray fluorescence (XRF) measurements were carried out by a spectrometer X-Supreme (Oxford Instruments).

The flexural strength was measured on material prisms using the prosthesization method [8]. Specimens of mortars and bricks were supplemented symmetrically on both ends to the required length with two prostheses ensuring the satisfaction of the Navier's assumption of linear stress distribution along the cross section in flexure. The 20 × 20 × 30 mm prisms were glued to wooden pieces which had similar dimensions in the cross sections as the mortar specimens. The specimen part was centred in the middle of the extended specimen and loaded in the mid-span cross section in three-point flexure (Fig. 8). The span between the