Mortars and their compatibility for the conservation of masonry walls in Tróia Archaeological Site

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SUMMARY:

Due to a very long exposure since the first excavations, the Tróia archaeological site shows conservation problems of different types and grades. Most of them are directly connected to the geographical location facing the sea and also reflect the lack of due conservation care.
Four mortar typologies were studied in the laboratory and were subsequently applied in limited areas of the archaeological site as testing trials. Results on the composition, preparation procedure, application and on site monitoring are presented.
The Incompatibility Degree, developed under the *PRODOMEA* project, was used to assess the expected compatibility of the four typologies in relation to the main ancient mortars found on the site. This Degree may integrate information of different kinds, namely, chemical and physical parameters, social-cultural constraints and the environmental context. Its application to the new mortar formulations based on physical and chemical indicators is presented and discussed.

KEY-WORDS: repair mortar; compatibility, conservation of archaeological site, Prodomea, Troia site

INTRODUCTION

The archaeological site of Tróia is located by the Sado estuary, facing the harbour city of Setúbal, some 60km south of Lisbon, Portugal. The structures point out the importance reached by this industrial centre in Roman times when it constituted a profitable and dynamic industrial village for about four hundred years.

Among other constructions, several fish factories were discovered, one of them in the actual shore and others located some tens of meters to the interior. The fish-salting tanks (*cetariae*) have different sizes and are separated by slim masonry walls. The products of fishery were sorted, washed and prepared for salting and then stored in the *cetariae*. Herbs and spices were mixed with fish viscera and submitted to a maceration and fermentation process to obtain a sauce called *garum*, used to season food. Bottled in amphorae, *garum* was exported for several parts of the Roman World were it was much appreciated, and sometimes sold at very high prices.

Figure 1 - Map of Portugal with location of Tróia peninsula. The main fish plant is located at its centre

The remnants of the fish salting tanks located along the harbour are the most threatened archaeological structures in the whole site and some of them were almost completely destroyed by the progression of the sea erosion. In the stretches still standing the plasters are deformed or bulging, fissuring is frequent and in some areas detachment has lead to total or partial losses, exposing the masonry wall to the external severe environment conditions. Drying-wetting cycles induce the formation of salt efflorescences, cause disintegration and lead to the progressive erosion of the building materials.

The fish salting factory located some tens of meters inland constitutes the central and best preserved nucleus of the excavated area. It is the largest industrial factory identified in this site and consists of several sets of tanks with different sizes, and was originally covered by some roofing structures as suggested by the presence of several square pillars identified throughout the factory. The masonry walls are covered with a thick impermeable plaster, originally composed of two layers.

The main decay agents relevant for the site are the nearby estuary and the direct hydraulic erosion, the presence of salts, the frequent strong winds, the large thermohygrometric variations, the growth of plants, bushes and trees and finally the human presence, as normal visiting loads and as vandalism acts.

A first sampling campaign was carried out with the purpose of characterizing the Roman mortars of the site. In a second step, and based on the results obtained in the first campaign, four types of mortars were prepared as potential candidates to be used in future intervention actions. These mortars were characterized in the laboratory and tested on site trials for direct assessment of their compatibility towards the damaged archaeological substrates. The mortar compositions were selected with the aim of producing types with different properties considering that they could be needed for different situations. Slaked lime, white cement and fly ash were the materials used to produce the four mortar types.

The concept of compatibility recently developed under the framework of the *Prodomea* project [1,2,3] was tentatively applied to the four mortar types vis-à-vis different substrates and the results are here presented and discussed.

COMPATIBLE TECHNOLOGIES FOR CONSERVATION TREATMENTS

Based on the characterization results of samples collected in a first sampling campaign[4] and on the specificities of the structures, four types of mortars were prepared to serve as basis for the present study. They were firstly characterized in the laboratory and subsequently applied in some on site trials aiming at assessing the compatibility behaviour of these mortars in relation with the archaeological substrates where they are expected to be applied. The constituents, composition and properties of the selected mortars are described below.

Mortars composition

Four mortars, designated as T1, T2, T3 and T4, were prepared with slaked lime, white cement and fly ash in different proportions. As aggregates, washed Tróia sand, Corroios sand (clay sand) and calcareous gravel with a maximum dimension of 4.5mm were utilized. The mass of each constituent necessary for preparing three kilograms of mortar is presented on Table 1. The water content was determined in order to obtain a consistency similar for all the fresh mortars; the corresponding flow values were 17.3cm for T1, 18.4cm for T2, 17.8cm for T3 and 17.6cm for T4.

Table 1- Composition of the selected mortars

Constituents	Mortar T1	Mortar T2	Mortar T3	Mortar T4
Slaked lime (g)	273	128	105	200
White cement (g)	-----	----	123	158
Fly ash (g)	-----	309	124	-----
Tróia sand (g)	1449	1362	454	1405
Corroios sand (g)	1278	1201	400	1237
Calcareous gravel (g)	-----	-----	1795	-----
Water (ml)	560	500	470	505

The chemical elements that could contribute to carry soluble salts into the mortar were determined on the cement, fly ash and slaked lime according to current chemical standards[5, 6] and the results are presented on Table 2.

Table 2 – Potential soluble salts expressed in equivalent weight.

Soluble salts	Slaked lime	White cement	Fly ash
Sodium, Na^{+}	0.002	0.004	0.012
Potassium, K^{+}	0.0	0.017	0.06
Sulphates, SO_4^{2-}	0.005	0.065	0.027
Chlorides, Cl^{-}	0.0	0.001	0.0
Total	0.007	0.087	0.099

As expected, the content of soluble ions of slaked lime is very low, while the white cement and fly ash present similar contents.

Mortar properties

Twelve prisms with 160mm x 40mm x 40mm were moulded[7] from mortars T1, T2, T3 and T4. The moulds were filled with fresh mortar in two layers and the mortar compacted by hand into the mold after applying 8 jolts in order to obtain homogeneous specimens. Afterwards the finished surface was smoothed and the mortars cured inside the moulds in a room stabilized at (20±1)ºC and 60 % relative humidity. After 8 days in these conditions the mortar prisms were withdrawn from the moulds and returned to the conditioned room for 22 days more.

The following properties were tested: absorption coefficient by capillarity[8], elasticity modulus[9], flexural and compressive strengths[10] and total porosity[11].

The pozzolanicity test was performed in two mixtures; the first mixture consisted of 10.0g of slaked lime and 10.0g of fly ash and the second one of 5.0g of fly ash, 5.0g of white cement and 10.0g of slaked lime. These mixtures correspond to the proportions of binder in the T2 and T3 mortars. The pozzolanicity test was assessed by comparing the concentration of calcium, expressed as calcium oxide, present in the aqueous solution in contact with the mixture, with the quantity of calcium necessary to saturate a solution with the same alkalinity[12]. The results are presented in Table 3.

Table 3 – Results of the characterization of the mortars

Property	Mortar T1	Mortar T2	Mortar T3	Mortar T4
Elasticity modulus (MPa)	2609	2505	3393	3832
Bending strength (MPa)	0.30	0.23	0.53	0.53
Compressive strength (MPa)	0.68	0.64	1.49	1.44
Total porosity (%)	30.3	26.5	26.7	28.6
Capillarity coefficient ($g/m^2s^{1/2}$)	152	186	266	206
Pozzolanicity	-	positive	positive	-

Mortar T3 containing lime/cement/fly ash and mortar T4 containing lime/cement present similar results for the elasticity modulus, bending and compressive strengths and these

results are higher when compared with T1, containing lime, and T2, containing lime and fly ash.
As expected, mortars T3 and T4 that contain cement as binding media show higher mechanical properties when compared to the lime-based mortars T1 and T2. Fly ash reduces porosity, showing that it interferes with the mortar microstructure. However, in spite of the positive reaction in the pozzolanicity test, it seems that fly ash has negligible (although positive) effects on the mechanical properties in the cement based mortars and seems to be slightly detrimental when added to the lime-based mortar. However, it is known from the literature that fly ash pozzolanic reaction increases with time and therefore it can reasonably be expected that properties of mortars containing fly ash will improve in time. The effect of fly ash in the capillarity coefficient shows a trend opposite to its effect on porosity. In fact, while it reduces porosity, the capillarity coefficient increases, which is a difficult to explain behaviour.

CALCULATING THE INCOMPATIBILITY DEGREE

The concept of Incompatibility Degree (ID) here used to assess the compatibility of the tested mortars integrates measurable parameters, namely, chemical and physical properties, as well as social and cultural components of more qualitative character, all of them considered as indicators relevant to the compatibility assessment. All parameters are rated under a coherent format that allows their integration under a unique computation formula [1,2,3]. For the present study, given its research character, the socio-cultural indicators were not applicable and the environment context was similar for all mortars and therefore it was not considered as well. For these reasons, only the physical and mechanical parameters were taken into account in this exercise on the application of this new approach to the compatibility assessment.
The Incompatibility Degree (ID) was computed as the quadratic mean of the relevant indicators, as follows:

$$ID_n = \sqrt{\frac{P_1^2 + P_2^2 + \dots + P_n^2}{n}}$$

Where ID_n = is the Incompatibility Degree, P_1 … P_n = are the ratings of the relevant indicators, n = is the number of indicators used in the computation of $ID_{n.}$

With a rating scale from 0 to 10 and the computation formula given above, ID_n has the following meaning: ID_n=0 characterises a perfect, compatible action and ID_n=10 characterises a fully incompatible one.

For the present case, the following parameters were included in the assessment:

- Capillarity coefficient
- Elasticity modulus
- Bending strength
- Compressive strength
- Total porosity

The ID of the mortars prepared in the laboratory were calculated considering the results presented on Table 3 of the chemical and physical properties using the weakest mortar composition (T1) as reference for computing the ID of the other three mortar formulations T2, T3 and T4. Being the weakest mortar, T1 was considered as a reasonable estimate for the substrate Roman mortar, since no data could be obtained for the in situ archaeological mortars. The tables for obtaining the ratings can be consulted elsewhere[2].
The computed IDs are presented in Table 4.

Table 4 - Incompatibility Indexes

Mortars Formulations	Incompatibility Index
T2 vs. T1	ID_5=2.9
T3 vs. T1	ID_5=6.7
T4 vs. T1	ID_5=6.9
T5* vs. T1	ID_5=9.2
* - data for T5 correspond to a typical cement mortar	

The computed IDs demonstrate that mortar T2 with lime and fly ash presents the lowest index (2.9) indicating that it may be very compatible with the substrate. Mortar T3 containing lime, cement and fly ash and T4 containing lime and cement have quite similar ID (6.7 and 6.9, respectively) and considerably higher than that of mortar T2. However, it should be mentioned that T1 is a very weak mortar, presumably much weaker than the Roman mortar still existing and in this situation the Incompatibility Degree results are certainly overestimated. Should we have used data from T2 as reference values for the substrate, the index for T3 and T4 would immediately undergo a substantial decrease. When a typical cement mortar (designed as T5 in Table 4) is compared to mortar T1, a high ID (9.2) is obtained, as could be expected, since the properties of a cement mortar[13] are extremely different from the properties of the substrate. Therefore it may be concluded that the Incompatibility Degree can indeed distinguish among different formulations. In this line, lower IDs should be sought for reaching better compatibility between the new mortar and the substrate.

In spite of the arbitrariness that may result in the selection of the substrate characteristics, the computation of the ID for different conditions can be taken as a parametric analysis and the results may be of great help in the comparison of different formulations.

ON SITE TRIALS

The mortars studied in the laboratory were afterwards prepared onsite and applied on a few areas in the walls of the *cetariae* in the harbour and inland areas. The conservation mortar T1 was applied on the interior wall of the cetariae at the inland fish processing structure (Figure 2).The conservation mortar T2 was applied in the wall of a *cetariae* in the harbour area (Figure 3). The conservation mortars T3 and T4 were applied in the floor and in the vertical walls of the *cetariae* in the harbour area (Figure 4). Also a set of two brick panels were covered with mortar T1 and T4 and placed at the interior fish plant and at the harbour to monitor their behaviour.

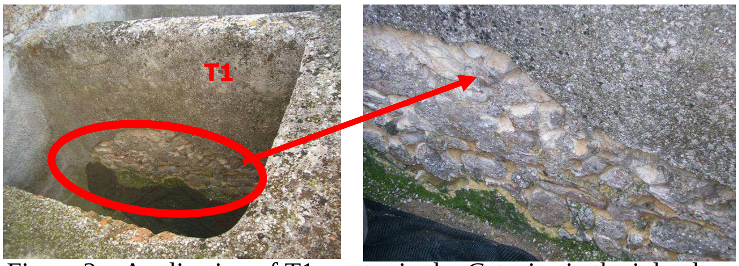

Figure 2 – Application of T1 mortar in the *Cetariae* in the inland area

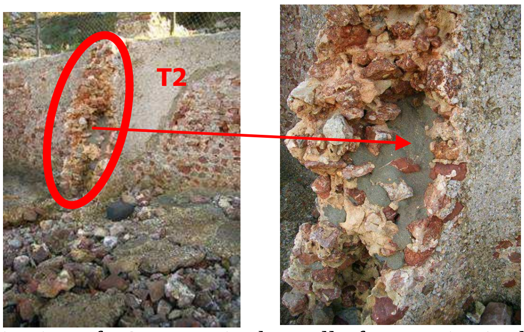

Figure 3 – Application of T2 mortar in the wall of a *cetariae* in the harbour area

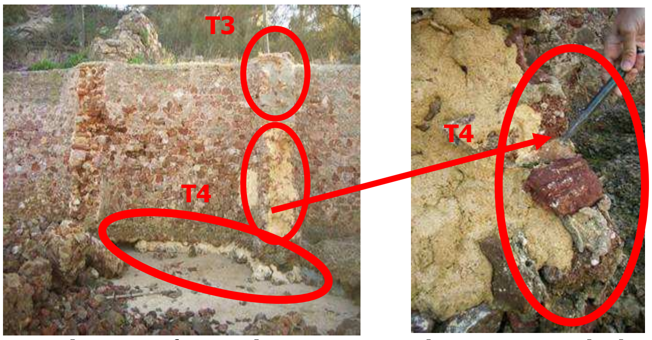

Figure 4 – Application of T3 and T4 mortars in the c*etariae* in the harbour area

About five months after the mortars application, an inspection to the site was carried out to assess the performance of the new mortars and to collect samples for laboratory analysis. The visual inspection of the new mortars applied in situ showed that all the four types presented good adhesion to the substrate and that they can be removed from the substrate without damaging it significantly. T3 and T2 were the hardest when pressed with nail, indicating that they have high strengths and suggesting that fly ash might have incremented the mortar strengths, a fact known from the bibliography but that we could not prove in the lab tests, possibly due to insufficient curing time. In the seashore, even the strongest T4 mortar underwent a significant erosion loss and T1 applied on the brick panel was completely destroyed, showing that it will not be easy to find a compatible mortar able to resist to the severe sea actions prevailing onsite.

CONCLUSIONS

Mortar T1 showed to be too weak to be used in the structures in the harbour area and therefore it was applied inland only, where it behaved satisfactorily. T3 and T2 presented the hardest condition suggesting that fly ash might have a strengthening effect. However it should be mentioned that the test trials were carried out only a few months before the end of the project and this period is too short to assess how the different mortars perform. In any case, we may conclude that some of the formulations were ineffective for solving the serious erosion problems caused by sea waves. This means that, in spite of being compatible, a more resistant mortar might be necessary to support the high erosion loads. The strength of mortars might need to be increased, but it should be understood that the potential for incompatibility increases concomitantly.

The exercise of the application of the Incompatibility Degree showed that it is easy to apply and that the results are logical. Besides the meaning that each one might give to the ID values, the very application is beneficial in itself, since it forces the operator to revisit all the parameters available and to give a use to them, and this immediately turns apparent how strong or weak are the arguments to support the use or the rejection of any mortar in question.

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[13] The incompatibility index for the hypothetical cement mortar T5 with binder aggregate ratio of 1:3 was calculated with the following indicators: elasticity modulus of 28.000 MPa; compressive strength of 55.4 MPa; bending strength of 6.6 MPa and capillary coefficient of 10 $g/m^2s^{1/2}$.