# APPROACH FOR COMPATIBLE MORTARS FOR RESTORATION PURPOSES: STONE REPAIRS OF THE ROMAN AMPHITHEATRE OF ARLES (FRANCE)

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## 1. Introduction

In France, repair mortars are currently used within the context of restoration work on monuments and other buildings, but a specific study on the compatibility of the repair material with the existing stone has been very scarcely undertaken. Although this compatibility is required to ensure that the repair do not initiate further decay in the historic substrate, only few cases can be reported where physical properties and durability of different repair mortars were evaluated in order to select the most appropriate one.
In 2001, the preliminary study for the restoration of the amphitheatre of Arles provided such an opportunity. Built during the first century on the base of an elliptic shape (136x108m), the large roman amphitheatre was in a relative bad condition of conservation (fig. 1) and its restoration project required a multidisciplinary work program.

Figure 1: The roman amphitheatre of Arles, before restoration.

Within the framework of this program, the architect responsible for this task (Alain-Charles Perrot, Architecte en Chef des Monuments Historiques), a restoration workshop (Atelier Jean-Loup Bouvier) and various laboratories (LERM, LRMH, CICRP) worked together to assess the main degradations and to set up the cleaning procedures, replacement, repair of the ashlars [1]. The study dealing with reparation of stones using mortars was undertaken to select not only the most appropriated repair material but also the most suitable reparations. Analyses in laboratory and tests on site were conducted. The mortar had to fit the stones in various ways: petrophysical properties (water storage and transfers, strength…), durability, visual appearance, workability and repairing feasibility, taking into account the wishes of the architect who was in charge of the definition of the restoration project [1]. The architect did not want the restored decayed stones to look like new ones. He wanted to keep their current appearance and to preserve them from further weathering. Mortars had to be used to fill holes and to smooth the faces on the exposed surface of the stones in order to reduce the rain-water infiltration and also to provide the historical substrate with a sacrificial mortar layer.
The preliminary study aimed to select the mortars which will be used for the first restoration work planned for 7 of the 60 bays of the monument.

## 2. Methodology

The preliminary study dealing with reparation of stones using mortars was undertaken in successive steps: characterization of stones from the monument but also from the quarry where new stones had to be extracted for several replacements, and characterization of various possible repair mortars. Mortars based on different binders were studied according the same methodology. The results allowed mutual comparison of their performances and also with the stones. Mortars were also tested in the field at selected areas of the masonry.

**Stone characterization**
The tests were performed on more than 3 probes of the original stone as well as the fresh replacement stone taken from the antique quarry of Fontvieille, near Arles.
The range of tests carried out was limited due to time and cost:
- petrographical examination
- density and total porosity (NF EN 1936)
- capillarity (NF EN 1928)
- compressive strength (NF EN 196-1)
- accelerated ageing test (salt resistance RILEM V.2) :
    - 2 hours under salinated water (10% $Na_2SO_4$),
    - 19 hours drying at 60°C
    - 3 hours at 20°C
    - measurement (weighing)

**Mortar characterisation**
After numerous preliminary tests made on more than twenty formulations and taking into account general recommendations on binders and repair mortars [2], four mortars were chosen and tested.

- 1 : A natural hydraulic lime mortar with specific additions designed by LERM,
- 2 : An original mortar designed by LERM by mixing sulfatic binder, lime and other additives,
- 3 : A ready to use repair mortar from Lafarge named Parex, containing lime and hydraulic phases
- 4 : A Jahn repair mortar M70, based on hydraulic and organic phases.

Apart from the petrographical examination, the tests performed on the stones were also carried out on the different selected mortars. Complementary characterizations were :
- setting time : start and end of the hardening (Vicat's needle)
- shrinkage (NF P 15-433) 20°C and 50%RH
- flexural strength (NF EN 196-1)
- adhesion measured by pull-off test on stones from the quarry of Fontvieille (NF P 18-852)
- soluble salt content (Italian Normale 13/83 : dosaggi dei Sali solubili)

**Field-test**
Several applications were done on selected areas by the restorers. These applications in the field had different objectives:
- to experiment with the use of the mortars following the recommendations of laboratories and manufacturers,
- to evaluate the workability and the general behaviour of the products in the field,
- to define a reference point concerning the degree of reparation that should be reached according the architect
- to assess the aesthetical compatibility (colour, texture…) of the repairs with different weathered stones

## 3. Results

### 3.1. Laboratory investigations
**Stone materials**
The stones on the monuments were sampled as well as some stone material in the quarry of Fontvieille in order to replace several very decayed ashlars of the amphitheatre. The main results are reported in table 1. The stones are capillary, moderately porous and rather soft than hard limestone, with fragments of shell, from the Miocene age [3].

**Replacement mortars**
The main results [3, 4] are reported in table 2.

| Stone materials | Stone from the quarry of Fontvieille (hard type) – 6 probes | Ashlar from the antique masonry 5 probes |
|---|---|---|
| Density kg/m$^3$ | 1970 (1940-1950-1940-2020-1950-2030) | 2020 (1960-2080-2030-1990-2020) |
| Total open porosity % | 26.8 (27.6-27.9-27.9-25-27.5-24.9) | 24.7 (27.1-22.3-23.7-25.8-24.6) |
| Absorption rate g/m$^2$/√s<br>- // bedding<br>- ⊥ bedding | (131-129.6-157.8-195-119.8-165.5)<br>(125.7-116.9-155.8-185.3-110.4-144.9) | (128.4-67.1-93.8-97.4-69.6) |
| Compressive strength MPa | 17 (17-21-17-14-16-16) | 19 (19-15-23-21-16) |

Table 1: Characterization of the building stone materials of the amphitheatre, mean value (individual values).

| Mortars | | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Setting time mn | Beginning<br>End | 193<br>707 | 105<br>136 | 43<br>106 | 180-230<br>355 |
| Shrinkage µm/m | 3 days<br>28 | -950<br>- 1680 | - 70<br>-160 | -350<br>-1415 | -250<br>-720 |
| Flexural strength MPa | 7 days<br>28 | 0.6<br>1.2 | 1.1<br>2.8 | 1.8<br>2.6 | 1.5<br>3.3 |
| Compressive strength MPa | 7 days<br>28 | 1.3<br>3.7 | 3.2<br>8.7 | 4.1<br>7.5 | 8.3<br>11.8 |
| Density kg/m$^3$ | 28 days | 1760 | 1490 | 1290 | 1430 |
| Total open porosity (%) | 28 days | 33.7 | 42.4 | 47.5 | 32.6 |
| Absorption rate g/m$^2$/√s | 28 days | 105.7 (96-117.4-103.8) | 61.4 (62.7-57.5-64.1) | 31.4 (26.7-32-35.7) | 132.6 |
| Soluble salt content (%) At 7 days | Sulphates<br>Chlorides<br>Nitrates | 0.09<br>0.06<br>0.02 | 7.19<br>0.07<br>0.03 | 0.63<br>0.08<br>0.02 | 0.44<br>0.04<br>0.02 |
| Adhesion MPa (rupture) | 28 days | 0.26 (adhesive and mixte) | 0.23 (adhesive) | 0.69 (cohesive and mixte) | 0.1 (at 7days) |

Table 2: Characterization of the 4 repair mortars

The 4 mortars show very different behaviours.

**Mortar 1** has a long setting time, which starts late and goes on for many hours as expected for a natural hydraulic lime based-mortar. The shrinkage is very significant. The mechanical strength is the lowest while its density is the highest. It has a high absorption rate and has a very low content in soluble salts. Its adhesion strength is low and the rupture mainly occurs in a mixte mode: a part of the rupture occurs at the interface between the mortar and the stone (adhesive way) while the other part takes place 1mm below the surface of the stone (cohesive way).

**Mortar 2** has a short setting time. The duration is limited to 30 minutes but the setting begins relatively late, more than 1h30 after the application. The shrinkage is the lowest. The mechanical strength is high but the density is rather low. The mortar shows a moderate absorption rate. The content in soluble sulphate is very high, due to the initial mixture (high quantity of sulfatic binder). Adhesion is low and the rupture is adhesive (at the interface), exactly as required.

**Mortar 3**, the ready-to-use Parex mortar begins to set very quickly but the setting and hardening process last twice the setting time of the mortar 2. The shrinkage is considerable. The mortar has moderate mechanical strength, but the lowest density linked to a very high porosity. The absorption rate is the lowest, indicating that the porosity mainly consists of bubbles, not so well connected. This closed porosity may be obtained due to the addition of an air-entraining agent. The soluble salt content is low except for sulphate, due to the cement part (gypsum is an additive to cement to regulate the setting process). The adhesion strength is very high, actually the highest of the 4 products. The rupture occurs mainly within the stone, at a depth from 0.5 to 10mm but in few cases, a part of the rupture takes place at the interface (adhesive mode).

**Mortar 4** is another ready-to-use mortar. The setting begins late (more than 3 hours after the water addition) and lasts more than 2 hours. The shrinkage is moderate. The flexural and compressive strengths are both high, 3 times higher than those of the hydraulic lime based mortar 1. The mortar is porous and shows a very high absorption rate. The soluble salt content is low, some sulphates being solubilized might come from a cement part included in the composition of this mortar. Due to a lack of time, because this last mortar was actually tested with delay, at the end of the preliminary study, the adhesion tests were carried out at 7 days instead of 28 days. The data are not comparable with those of the other mortars and one may assume that the adhesion would have been much stronger at 28 days (adhesion up to 0.6MPa according the technical documentation given by the manufacturer) with probably cohesive rupture within the stone.

The different behaviour of the 4 mortars can be explained by the type of binder (natural hydraulic lime, sulfatic hydrates, cement and lime). The addition of an air-entraining agent or other unknown additives may modify and improve the performance of ready to use mortars 3 and 4.

**Comparison stone vs mortar**

The stones are less porous and show a higher compressive strength than all the tested mortars. The absorption rate of the stones is close to those of mortars 1, 2 and 4, but at least twice the absorption rate of mortar 3. The adhesion of this mortar 3 is too high. Mortar 2 has a too high soluble sulphate content to be used on the external walls of any building. Such product is capable to supply the stone with harmful soluble salts [5], and despite its other advantages, it could not be selected for the restoration of the amphitheatre.

**Durability test**

The durability evaluated by the salt resistance (fig. 2) is not the same for the mortars and the stone.

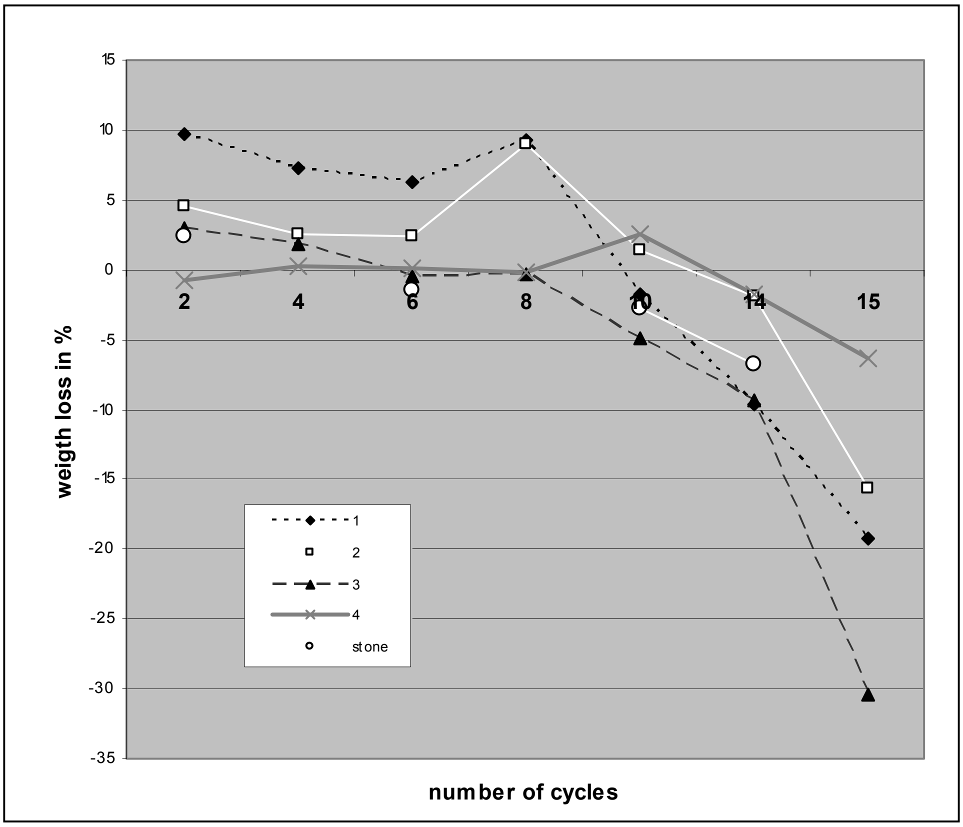


Figure 2: Result of the test of durability (salt resistance) of mortars 1, 2, 3, 4 and stone (quarry of Fontvieille).

During this test, mortar 3 is the material the most affected by salt crystallisations (30% of lost material). Mortars 1, 2 show a very similar behaviour and a higher resistance, but mortar 1 is more resistant during the 8 first cycles while the mortar 2, more porous and stronger, became more resistant after. Mortar 4 is the most resistant and decays at the same rate than the stone of the quarry of Fontvieille.

**3.2. Tests on site**

While the laboratory was analysing the products, the restoration workshop had selected with the architect 18 decayed stone surfaces as test-areas and located in one of the 60 external bays of the monument. First, the aim of these applications was to obtain the opinion of the restorers about the colour, the texture and the workability of the mortars. They were also useful to come to an agreement between the restorers and the architect not only about their aspect but on the level of reparation which should be reached.

The architect had a clear idea of what the restoration should be. He did not want the decayed stones to be repaired in order to look like new ones. He did not want a visible restoration but the preservation of the state of the roman monument, which would go on look like antique ruins. Therefore the restorers had to use mortar to fill holes, to smooth the decayed surfaces (fig. 3) with very thick to very thin mortar applications.

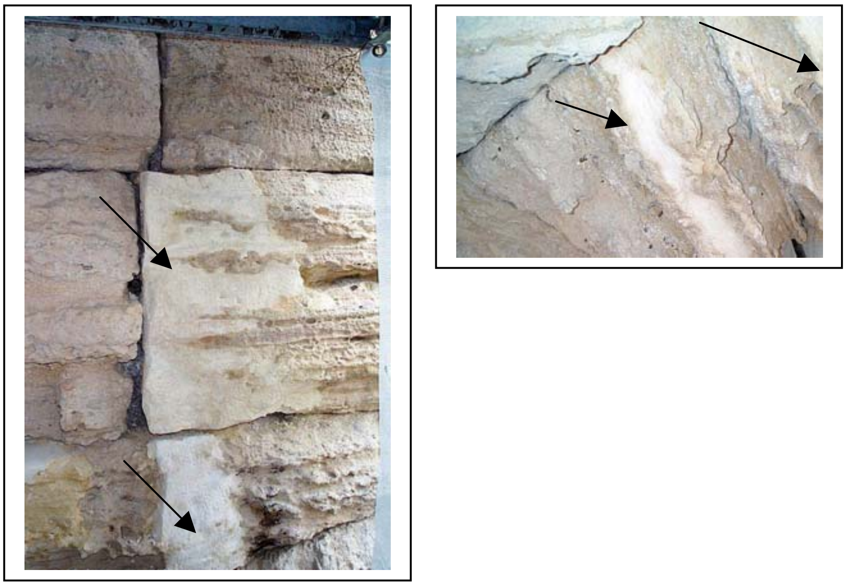

Figure 3: Experimental stone reparations on restricted areas of the vertical wall of a bay and on the intrados of an arch (on the left).

The restorers applied the 4 mortars (fig. 3) and an air lime based mortar as their own reference and gave their opinion in a report [6]. Visually, the best reparations were made with mortars 1, 2 and 3: they looked like the stones. But if mortar 1 was right in thin layer, it did not fit at all over 2 to 3cm, even in 2 layers : the reparations cracked and fell apart from the stone substrate because of their important shrinkage, their too long setting time and their difficult workability. Mortar 3 was more easy to use but was too dark and grey to be coloured yellowish like stone and then required a patina. Mortars 2 and 4 were much more convenient to use in different thicknesses and the various colours which were encountered. They were creamy, unctuous. They didn't crack whatever the thickness and the extension of the repairs.

## 4. Discussion and conclusions

With the data available at the end of the preliminary study, it was possible to conclude about the 4 repair mortars:

- Mortars 1, 2, and 4 matched the stone aesthetically (colour, texture…),
- Mortars 2 and 4 had the best workability, moreover, they didn't crack, due to a low shrinkage and an appropriated setting time,
- The rate of absorption of mortar 3 was twice lower than the stone, adhesion of mortars 3 was too high: the rupture took place within the stone. Mortar 1 (and probably 4 if values at 28 days had been available) was also adhesive but to a lesser extent,
- The durability of mortar 4 was higher than the 3 others,
- The soluble salt content of mortar 2 was too harmful for the stone conservation.

Finally, within the 4 very different mortars tested to repair the ashlars of the roman amphitheatre of Arles, 2 different mortars could have been selected for the restoration work : mortar 1 for the thin reparations and mortars 4 for thicker reparations (more than 2 to 3cm). But the "ready-to-use" mortar 4 which offered a regular industrial supplying and a commercial guarantee was definitively preferred.

A first experimental restoration work then was undertaken in 2003 on 7 bays (fig 4) over the total 60 bays of the amphitheatre. This initial work allows to assess the behaviour of the selected mortar (mortar 4) in the field before the beginning of the first phase of the restoration which will deal with 20 other bays of the monument [7].

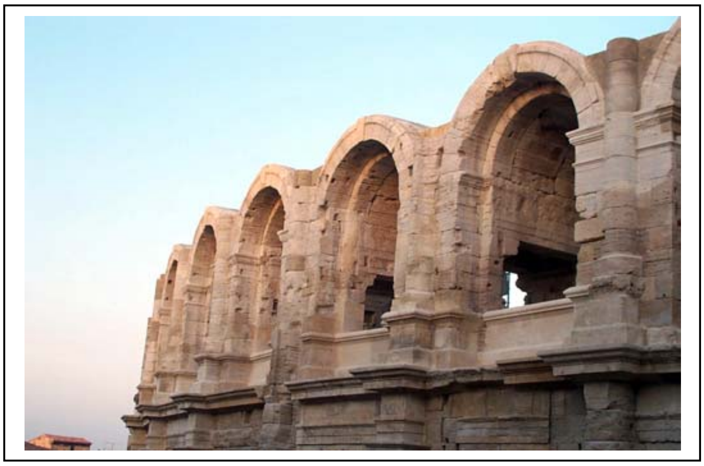

Figure 4: The first seven restored bays of the amphitheatre of Arles.

## 5. References

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