**An Experiment Measuring Water Consumption in Roman Hydrophobic Mortar (opus signinum)**

**Javier Martínez Jiménez, Juan Jesús Padilla Fernández and Elena H. Sánchez López**

**SUPPLEMENTARY MATERIAL**

# **Supplementary Material 1**

This compiles all the information pertaining to each individual *opus signinum* recreation.

**Frame 1**

The first frame (main article, Figure 6.1) was designed to contain a mix with a 1 : 3 lime putty to fine chamotte volumetric ratio. Four scoops of lime putty were used with 12 scoops of chamotte. The pottery absorbed a lot of moisture, and 3.83 scoops of water (vw) were added to correct the rheology of the mix. This resulted in added water being 19.31% of the mix (rd).

In order to polish the surface, the builders suggested creating a thinner mortar to apply as a top, polished layer. This consisted of 0.5 scoop of putty, 1 scoop of chamotte powder, which required an extra 0.667 scoop of water. In this case, added water was 30.88% of the mix.

Enough mortar was to be applied to a single brick, so we could have a smaller, lighter, and easier to transport sample (0.13l in total). After this, 2.67 scoops of mortar mix were left unused.

In total, 5.5 scoops (3.85l) of water were necessary to create a two-layered all-pottery no-sand *opus signinum*. Considering the volume of the sample plus the leftovers (8.5l), 45.28% of it was water (rw) input to correct the rheology of the mix. The difference in volume between the separate components and the final mortar (rr) shows a volume reduction of 52.81%.

After applying this mix, the frame was 12.7kg heavier, meaning that the density of this mortar is 1.96kg/l when fresh. After three weeks of carbonization, Frame 1 had lost 4.4kg in water vapour, so the density of this mix when dry is 1.28kg/l.

Considering the water input to correct the rheology and number of scoops of putty used in this mix and how they relate to the final volume of fresh mortar (37.04%), this mortar was the wettest: 67.51% water.

**Frame 2**

The second frame (main article, Figure 6.2) was meant to contain a 1 : 3 lime putty to coarse chamotte mix, but the resulting mix was deemed unusable by the builders. We realised that during the process of separating the chamotte we had removed all the smaller components from the coarse chamotte, meaning that the granulometric curve of the dry aggregates lacked all the finer elements.

In the end, the mix designed for this frame contained a 1 : 1 : 1 lime putty to fine chamotte to siliceous fine sand. We added 6 scoops of each but in this case the sand was still rather damp, so it only required 1 extra scoop of water to correct the mix. This means that for this mix with damp sand, added water was only a 5.2% of the volume of the ingredients.

After the mixture was applied to the frame, there was enough leftover mortar to make another small brick sample (0.13l), and still 3 scoops of mix were unused. That overall volume of mix is 65.5% of the sum of the volumes of the separate components, and of it 8.03% was added water.

The frame, after the mortar was applied, was 12.6kg heavier, making its fresh density 1.94kg/l. After three weeks, the frame had lost 3.2kg in water vapour, making its dry density 1.45kg/l.

This mortar had the highest proportion of lime putty (48.21%), but the damp sand reduced the quantity of added water needed. Overall, this mix was 36.96% water.

**Frame 3**

The mortar used in Frame 3 (main article, Figure 6.3) was a 1 : 1 : 3, lime putty to coarse chamotte to siliceous river sand mix. The total used was 3 + 3 + 9 scoops, and this in total required 4 additional scoops of water. In this case, the added water was 21.05% of the volume of ingredients, a similar result to the one obtained from Frame 1.

No brick sample was made with this mortar because the coarse chamotte made it difficult to make it stick to such a small sample. Only 1.33 scoops of mix were left over. The coarser pottery fragments and the river sand absorbed a lot of water, and the overall volume reduction of the mix was 55.79%. In this case, the water input was 37.74% of the volume of the final mortar.

This mix added 14.1kg to the frame, and it lost 3.6kg as the mortar carbonized. The resulting densities for this type of *opus signinum* are 2.24kg/l when fresh and 1.681kg/l when dry.

Sample 3 is the first that required only 3 scoops of lime putty. This resulted in an average lime putty proportion of 28.3%. Considering the fraction of water in that and the water input, this mortar was 54.72% water.

**Frame 4**

Frame 4 (main article, Figure 6.4) was made following the same 1 : 1 : 3 ratio as in Frame 3, and, while it used coarse chamotte, we used calcareous quarry sand for this mix. Again, this required 3 + 3 + 9 scoops, but only 2 additional scoops of water had to be added, so only 11.76% of the starting ingredients were additional water.

No brick sample was made with this mix either, but 2 scoops of mix were left over. Since the sand did not absorb that much water in this case, the volume reduction was 66.27%, and the water added to correct the rheology resulted in a total of 17.75% of the fresh mortar.

This mix added 13kg to the frame and since less water was added than in Frame 3, it also lost less weight: 2.4kg. The density of this type of fresh mortar was 2.00kg/l, which went down to 1.63kg/l after it dried.

This sample used 3 scoops of putty, which made up 26.63% of the volume of mortar, but it required very little added water, so in total, this mix was 33.73% water.

**Frame 5**

Sample 5 (main article, Figure 6.5) was the same as that of Frame 4, but with fine chamotte, so 1 : 1 : 3, putty, fine chamotte and calcareous quarry sand, with a total of 3 + 3 + 9 scoops. In this case 3 scoops of water had to be added, so that the extra water accounted for 16.67% of the volume of starting ingredients.

A small portion of this mix (0.08l) was applied to a tile, rather than to one of the larger bricks and there was a total of 1.5 scoops of mortar mix left. Three scoops of added water make up 27.57% of the final volume of fresh mortar, which had shrunk to a 60.44% of the total sum of volumes of the different ingredients.

In total, the sample applied to the frame weighed 13.8kg, which for the known volume gives a density of 2.13kg/l. Once it dried, it lost 3.5kg, so the calculated density for this mix once dried is 1.59kg/l.

Like the two previous samples, this mix used 3 scoops of putty, which amounted to a total of 27.52% of the overall volume of mortar. This means that this sample was 44.12% water.

**Frame 6**

Frame 6 is to Frame 3 what Frame 5 was to Frame 4 (main article, Figure 6.6), so the mix is still a 1 : 1 : 3 lime to chamotte to siliceous river sand, but this time using fine chamotte. Again, the total volume was 3 + 3 + 9 scoops, but it required 3.67 scoops of water, meaning that the water added to this mix adds up to 19.64% of the initial volumes.

This mix was also applied to a small tile, and 3 scoops remained unused after that. The water added to correct the rheology of the mix adds up to 29.62% of the resulting volume of fresh mortar. The calculated reduction in volume was 66.32%.

As for weights and densities, the fresh mortar that was applied to the frame weighed 12.6kg, giving a density of 1.94kg/l. Once dried, the sample had lost 2.6kg, lowering the density to 1.54kg/l. In this case, the 2 scoops of putty formed 24.23% of the mix, but this is perhaps because it needed much more water than previous samples. This also explains why once this water is added to the water content of the putty, it gives an overall total of 44.16% water in the mortar.

**Frame 7**

Frame 7 (main article, Figure 6.7) was designed to hold a two-layer lining.

The first layer was a 1 : 1 : 2 putty to coarse chamotte to calcareous quarry sand mix (quantities: 2 + 2 + 6), which needed 2.67 scoops of water. This means that the water adds up to 21.05% of the initial volumes. There was one scoop of the final mortar left over. The mix had shrunk to a 66.23% of its initial volume, and the water input accounted for 26.02% of the fresh mortar mix.

The second layer was deliberately made finer, a 1 : 1 : 1 lime to fine chamotte to calcareous quarry sand mix which required only one scoop of each plus 0.5 scoop of water. This additional water for the final polish represents 14.28% of the initial volumes. Since there was no leftover mix and it was applied as a single thin layer, it is impossible to calculate what the volume of water in this second layer was or how much the mix reduced its volume.

Overall, however, and taking both mixes as one sample, the rheological water represents 16.13% of the initial ingredients, but 24.35% of the final mortar, which had shrunk to a 66.23% of the sum of the initial volumes. This mortar weighed 13.3kg when it was fresh, and it lost 3.1kg as it dried. The density of the fresh mix was 2.05kg/l and 1.57kg/l when dry.

The first of the double-layered samples still used 3 scoops of putty. Lime added up to 29.22% of the mortar mix, which means that the total water content in this mortar was 41.88%.

**Frame 8**

The last frame (main article, Figure 6.8) was equivalent to Frame 7, but using siliceous river sand rather than calcareous quarry sand. The proportions were 1 : 1 : 2 with coarse chamotte, but the total quantities required were 2 + 2 + 6, which needed 1.5 scoops of water. In this case, the added water constituted 13.04% of the initial volumes. Since there was one scoop left over, the ratio of reduction was 62.49%. The water necessary for this mix adds up to 14.61%.

The second layer was, once again, thinner, with a 1 : 1 : 1 mix and just one scoop of each, which required an additional 0.667 scoop of water, and only 0.5 scoop was left unused. The dry mix ratio was 18.18%, but the reduction cannot be properly calculated.

Taking the sample as one single mortar, however: the dry ratio is 16.09%, the wet ratio 26.31%, and the volumetric reduction is 63.04%. In total, this sample weighed 12.9kg and it lost 2.6kg over three weeks. The density of the wet mix was 1.989kg/l which became 1.59kg/l when dried.

The last mix needed 3 scoops of lime as well. This made slaked lime putty in the mortar 27.87% of the total volume of mortar. Overall, this mortar was one of the ‘driest’, with only 36.85% of it being water.

# **Supplementary Material 2**

The fossa of the amphitheatre of Mérida is a rectangular structure sunk into the arena of the amphitheatre, which was lined with *opus signinum* at some point in the Late Roman period to allow for the flooding of the structure. The main rectangle measures 25 × 19m, with corridors projecting from three of its sides.

A GIS calculation based on current plans and visible remains gives the fossa a total perimeter of 152m and a floor area of 725m2. For a depth of 1.2m and an *opus signinum* layer 30mm thick, the total volume of *opus signinum* for the walls is 152 × 1.2 × 0.03 = 5.47m3. For the floor, the volume would be 725 × 0.03 = 21.75m3. The total volume of *opus signinum* is thus 27.22m3.

For the average ratios of rheologic water input based on the final mix (17–37%), the results are a low estimate of 4.63m3 and a high of 10.01m3.

# ***Table S1*** *Bulk densities of the materials used in the experiment.*

|  |  |
| --- | --- |
| **Material** | **Calculated bulk density (kg/m3)** |
| Quicklime (calcium oxide, CaO) | 1138 |
| Siliceous quarry sand | 1121 |
| Siliceous river sand | 1236 |
| Calcareous quarry sand | 1600 |
| Slaked lime putty (Ca(OH)2 (aq)) | 1200 |
| Cartuja Roman brick/tile | 1592 |
| Cartuja ceramic chamotte | 1075 |

***Table S2*** *Summary of calculations related to the* opus signinum *experiments.*

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|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | *Frame* | | | | | | | | Average |
| *Calculation* | *Unit* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* |
| Rheologic water input (relative to pre-mix dry volumes) | **%(vol)** | 23.913 | 5.263 | 21.052 | 11.765 | 16.666 | 19.644 | 16.129 | 14.287 | **16.09** |
| Rheologic water input (% of the mixed volume) | **%(vol)** | 45.281 | 8.034 | 37.739 | 17.752 | 27.573 | 29.620 | 24.353 | 20.128 | **26.31** |
| Apparent shrinkage | **%(vol)** | 52.81 | 65.507 | 55.784 | 66.269 | 60.444 | 66.320 | 66.230 | 70.981 | **63.043** |
| Fresh density | **kg/l** | 1.958 | 1.942 | 2.235 | 2.004 | 2.127 | 1.942 | 2.05 | 1.989 | **2.031** |
| Dry density | **kg/l** | 1.279 | 1.449 | 1.680 | 1.634 | 1.588 | 1.542 | 1.572 | 1.588 | **1.542** |
| Excess/left over mix | **%(vol)** | 22.228 | 24.103 | 12.579 | 17.752 | 13.786 | 24.232 | 9.741 | 13.933 | **17.295** |
|  |  |  |  |  |  |  |  |  |  |  |
| Weight of added mortar | **kg** | 12.7 | 12.6 | 14.5 | 13 | 13.8 | 12.6 | 13.3 | 12.9 | **13.175** |
| Weight loss whilst drying | **kg** | 4.4 | 3.2 | 3.6 | 2.4 | 3.5 | 2.6 | 3.1 | 2.6 | **3.175** |
| Final weight (frame, total) | **kg** | 23.3 | 23.9 | 25 | 25.7 | 25 | 24.5 | 24.5 | 24.6 | **24.562** |
| Final weight (mortar) | **kg** | 8.3 | 9.4 | 10.9 | 10.6 | 10 | 10 | 10.2 | 10.3 | **9.962** |
| Weight loss whilst drying | **%** | 34.645 | 25.396 | 24.827 | 18.461 | 25.362 | 20.635 | 23.308 | 20.155 | **24.099** |
| Putty used | **scoops** | 4.5 | 6 | 3 | 3 | 3 | 3 | 3 | 3 | **3.562** |
| **l** | 3.15 | 4.2 | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 | **2.493** |
| Putty content in mix | **%(vol)** | 37.048 | 48.206 | 28.304 | 26.629 | 27.573 | 24.232 | 29.223 | 27.866 | **31.135** |
| Water content from putty | **%(vol)** | 22.229 | 28.923 | 16.982 | 15.977 | 16.544 | 14.539 | 17.534 | 16.719 | **18.681** |
|  |  |  |  |  |  |  |  |  |  |  |
| Overall water in fresh mortar | **%(vol)** | 67.509 | 36.958 | 54.722 | 33.731 | 44.117 | 44.159 | 41.887 | 36.848 | **44.991** |
| Water loss whilst drying | **l** | 4.4 | 3.2 | 3.6 | 2.4 | 3.5 | 2.6 | 3.1 | 2.6 | **3.18** |
| Water content in fresh mortar | **l** | 4.379 | 2.397 | 3.549 | 2.188 | 2.861 | 2.864 | 2.7168 | 2.389 | **2.949** |
| Difference between calculated water loss and measured water loss | **l** | 0.021 | 0.802 | 0.051 | 0.212 | 0.638 | -0.264 | 0.383 | 0.21 | **0.23** |