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The binder of the «Roman Concrete» of the Ponte di Augusto at Narni (Italy)

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ABSTRACT. — The main aim of this work was to study the characteristics of the mortar binder used in the building of the bridge called «Ponte di Augusto», erected over the river Nera (Narni, Italy) in 27 B.C..

Mineralogical, chemical, physical, micropaleontological, granulometric and petrographical analyses were carried out on whole samples and on the binder itself, particular care being devoted to lumps.

In the past, the Romans were able to create high-quality mortars of relatively low porosity, with strong mechanical characteristics and high hydraulicity. The mortars used in the «Ponte di Augusto» also show the same characteristics and are excellently conserved.

Preliminary results ascribe these good characteristics to the use of a binder of high hydraulicity, obtained by calcinating local impure limestone and not by inserting any particular additives.

RIASSUNTO. — Scopo di questo lavoro è stato studiare il legante della malta usata nella costruzione del «Ponte di Augusto», eretto sopra il Fiume Nera (Narni-Italy), nel 27 a. C..

Sono state condotte analisi mineralogiche, chimiche, fisiche, micropaleontologiche, granulometriche e petrografiche, sui campioni del legante e sui grumi presenti in esso.

Nel passato i Romani furono in grado di realizzare malte di elevata qualità, con una porosità relativamente bassa, forti caratteristiche meccaniche e grande idraulicità. Le malte utilizzate nella realizzazione del «Ponte di Augusto» mostrano anch'esse queste caratteristiche e si presentano in ottimo stato di conservazione.

I risultati preliminari attribuiscono queste buone caratteristiche all'uso di un legante ad alta idraulicità, ottenuto dalla calcinazione di un calcare impuro e non dall'aggiunta di particolari additivi.

KEY WORDS: *mortar, binder, lumps, hydraulicity.*

INTRODUCTION

Narni is located in Umbria, not far from the border with Latium. It was founded by the Sabin people and then turned into a Roman colony (Narnia), of high military importance because of its strategic position on the «Via Flaminia». The road crosses the valley of the river Nera over an imposing bridge known as the «Ponte di Augusto», built in 27 B.C. during widening of the consular road ordered by the emperor Augustus himself.

This bridge is one of the longest ever erected by the Romans. It was 170 m long and in all probability originally had four spans. At present, only one arch is left standing, probably not the largest (fig. 1). Its chord is about 20 m long and its height at the intrados is about 27 m. The arches, piers and abutments are made of masonry of well-cut travertine ashlars, filled with mortar of such strong cohesion and good

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mechanical characteristics that is similar to modern concrete.

In December 2000, the territory of Narni was struck by an earthquake and the State Cultural Heritage Authority, warned about the endangered condition of the remaining arch of the bridge, constituted a commission to check its degree of safety and study its history and construction.

The main aim of the present work was to characterise the mixture used by the Romans in preparing concrete (a mortar made of a binder and a coarse aggregate), particular care being taken to determine the kind of limestone used to prepare the lime and to study possible mixing with additives capable of increasing the cohesion, hydraulicity and durability of the mortar.

ANALYTICAL PROBLEMS OF ANCIENT MORTARS

Study of ancient mortars often presents difficulties concerning determination of the so-called «recipe». Over the centuries, several kinds of mortars have been made according to age, place and function. The preparation of a mortar involves several technological variables:

- the kind of limestone used to prepare the lime;
- the kind of kiln and burning conditions (temperature, time of burning, size of limestone fragments);
- slaking conditions (amount of water, seasoning);
- use of additives;
- composition and granulometry of aggregate;
- method of setting.

Architectural treatises from the Roman age until nowadays give precious information on the selection of raw materials and the technology of preparing of mixtures, although poor-quality products often result when attempts are made to exploit such «recipes». There are several reasons for the present-day good characteristics of some ancient mortars, e.g.:

Fig. 1 – River Nera (province of Terni, Italy), with imposing bridge called Ponte di Augusto, built in 27 B.C.

– optimal carbonation, favoured by the long period of time since setting;

– further cementation due to precipitation of calcite from water solutions circulating inside the masonry;

– mortars were prepared without following «classic recipes». This sometimes depended on the difficulty of finding the required raw materials, so that materials from various nearby areas were used.

In addition, special additives could be mixed in, at the master mason's discretion. Such manufacturing technologies were often kept secret, so that no kind of documentation is left.

As regards analytical methods, great difficulties arise when studying binder composition – for two principal reasons:

– the difficulty of separating binder from aggregate. In some cases, partial separation may be obtained by soft mechanical grinding, followed by exposure to ultrasonic waves. The sample is then sieved and the < 63 μm fraction is considered to belong to the binder, although more or less significant quantities of finely grained aggregate may sometimes be found in this fraction (Bakolas *et al.*, 1995). The presence of large lumps, not mixed with the aggregate, can be particularly useful because they represent the remains of pure binder, before the addition of any additive and it is easier to separate it from the mixture;

– the nature of the binder itself, which may sometimes be composed of not negligible amounts of amorphous or poorly crystalline compounds, e.g., hydrated calcium aluminium silicates or organic compounds. In this case, mineralogical study only provides partial information about the nature of the binder, and different types of determinations are needed.

MATERIALS AND METHODS

The mortar samples studied here come from the ruins of collapsed bridge piers and were taken by coring.

The following analytical methods were applied on the total sample (binder + aggregate):

– *macroscopic description of mortar;*

– *optical microscopy:* thin sections of mortar samples were examined under a polarising Zeiss microscope, for mineralogical-petrographical characterisation;

– *granulometry by image analysis:* thin sections were examined under a polarising Zeiss microscope linked to a video analysis system, to determine the granulometry of the finer aggregate (< 1 mm). The granulometry of the coarser aggregate was determined from macrophotographs. Both analyses yielded the binder/aggregate ratio;

– *physical characteristics determined with the following analytical methods:*

total open porosity: a total of 20 test samples 1.5 × 1.5 × 3 cm were prepared. Samples were dried at 60°C and dry weights were determined. Real volume V_r (measured by a Quantachrome helium pycnometer) and bulk volume V_b (measured on a Chandler Engineering mercury pycnometer) were also determined. Total open porosity (P) was computed as:

$$P = 100\,(\,(V_b - V_r)/V_b);$$

water absorption through total immersion: each test lasted 21 days. Water absorption through total immersion yielded the water absorption coefficient, which may be expressed as weight (IC_w) or as volume (IC_v):

$$IC_w = 100\,(W_w - W_d)/W_d$$

where W_w = wet weight; W_d = dry weight

The IC_v gives the Saturation Index (SI):
$IC_v = IC_w\,\gamma_s$ where γ_s = bulk density
$SI = 100\,IC_v/P$

For correct information about the binder, both lumps and binder separated from aggregate were studied. Powder from lumps (which represent fragments of pure binder) was extracted with a scalpel. As regards the binder, soft mechanical grinding of mortar samples was followed by exposure to ultrasound. Samples were then sieved and the <63 μm fraction was considered to belong to the binder.

The following analytical methods were applied:

– *XRD analysis* (Philips PW 1729 diffractometer with Cu anticathode) to determine mineralogical composition;

– *calcimetry* (Dietrich Fruling instrument) to determine quantity of calcite, obtained by the CO_2 volume method;

– *XRF analysis* (Philips PW 1480 spectrometer) to determine chemical composition of major elements;

– *thermal analysis (TG)* (Thermoanalyzer NETZSCH STA 409). The weight loss of mass of 20-50 mg was monitored through a heating cycle from 20 to 800°C with a temperature gradient of 10°C/minute in a static air atmosphere. This process reveals thermal transformations such as dehydration, dehydroxidation, oxidation and decomposition, giving quantitative information on binder compounds. TG data were processed according to Moropoulou et al. (1995) in the range 200-600°C and weight loss due to water bound to hydraulic components was determined; for temperatures > 600°C, weight loss due to decomposition of carbonates was obtained;

– *microchemical analysis* of both binder and lumps was made by EPM (Jeol Superprobe JXA-8600 WDS);

– *micropaleontological analyses:* carried out in order to detect any fossils present (siliceous and/or calcareous); for siliceous fossil contents (radiolarians), analyses were performed with a stereoscopic microscope (Leica HZ8) on the <63 μm powder fraction (considered to belong to the binder); for nannofossil and diatom contents, smear slides (again on the <63 μm fraction) were observed under a light polarised microscope (Orthoplan).

RESULTS

Macroscopic observations

The mortar has high cohesion and shows a quite abundant binder, light brown in colour. The aggregate covers several granulometric classes (fig. 2). The coarsest is made up of large angular clasts (∅ 5-15 cm), disposed in beds and composed of micritic limestone and travertine; the finest classes are made up of various limestones (cherty limestone, red «scaglia», etc.). Widespread in the mixture are several lumps of variable consistency, sized between 0.1 and 1 cm.

Microscopic observations

Binder is quite abundant, with microsparitic structure and a heterogeneous aspect, generally characterised by high birefringence (fig. 3a). Many lumps with microsparitic structure and a homogeneous aspect are present, generally with a compact aspect but sometimes revealing large pores.

Aggregate: mainly made up of rounded fragments of micritic limestone and secondarily of chert and travertine fragments, quartz, feldspars, and rare pyroxene grains. The chert and limestone fragments show often well-developed reaction rims (fig. 3b). Macropores (>150 μm) are mainly composed of microfossil chambers and cavities inside travertine fragments and lumps; fractures due to shrinkage are not visible.

Granulometry by image analysis

Grain size distribution, expressed as volume per cent, indicates three main classes, with dimensions of 0.06-0.25 mm, 1.6-4 cm and 5-15 cm respectively. Calculating the granulometric cumulative curve expressed as weight per cent, comparisons with the Fuller curve ($P = 100 \sqrt{d/D}$, where P = undersize %, d = grain diameter, and D = diameter of coarser grains) are possible. This curve represents the granulometric distribution which determines the lowest presence of empty spaces among the

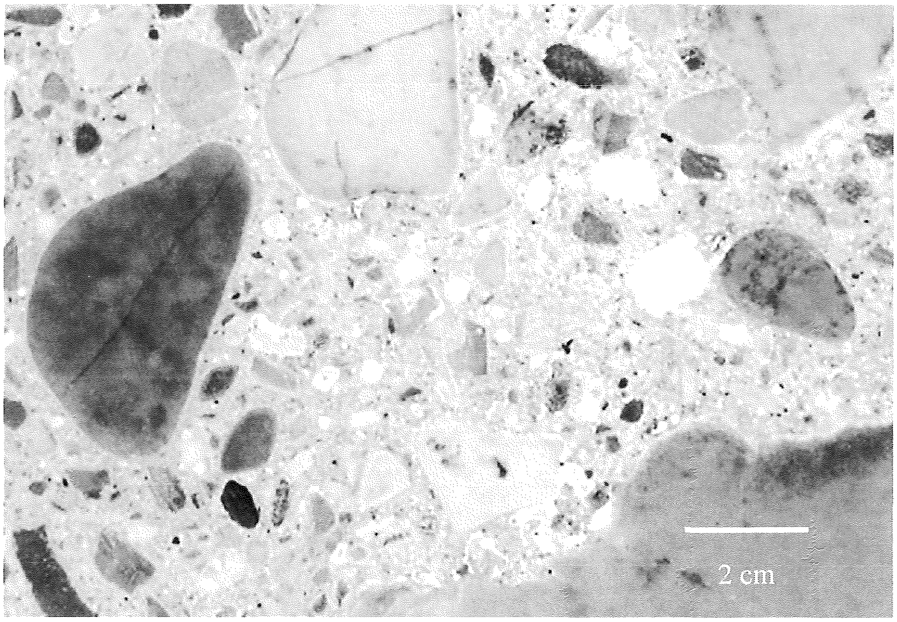

Fig. 2 – Macroscopic image of mortar, showing details of various granulometric classes of aggregate and several lumps (white grains) of variable consistency.

aggregate grains (fig. 4). A quite large difference between the two curves is evident. In particular, this is due to larger amounts of the middle grain classes with respect to the finer and coarser ones. Together with other factors (like original doses), this contributes towards producing a quite high binder/aggregate ratio (0.75 ± 0.10).

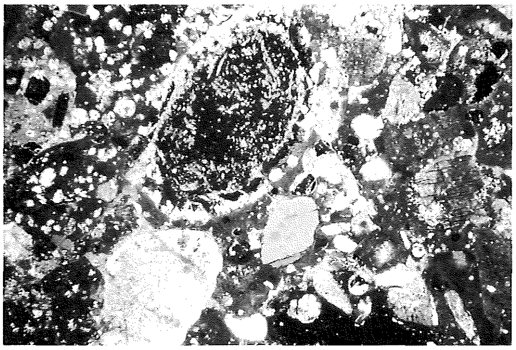

Fig. 3a – Micrographic image of thin section (6.2x crossed nicols): abundant binder characterised by high birefringence and aggregate, mainly composed of various kinds of limestone.

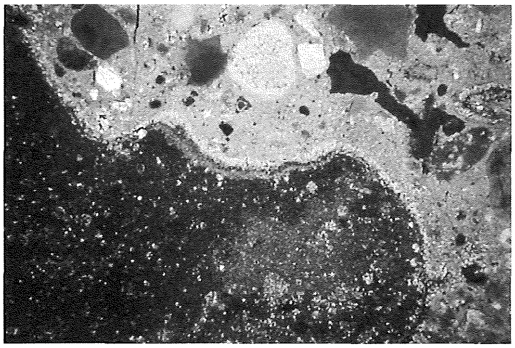

Fig. 3b – Micrographic image of thin section (6.2x crossed nicols). Centre: large chert fragment showing reaction rim with binder.

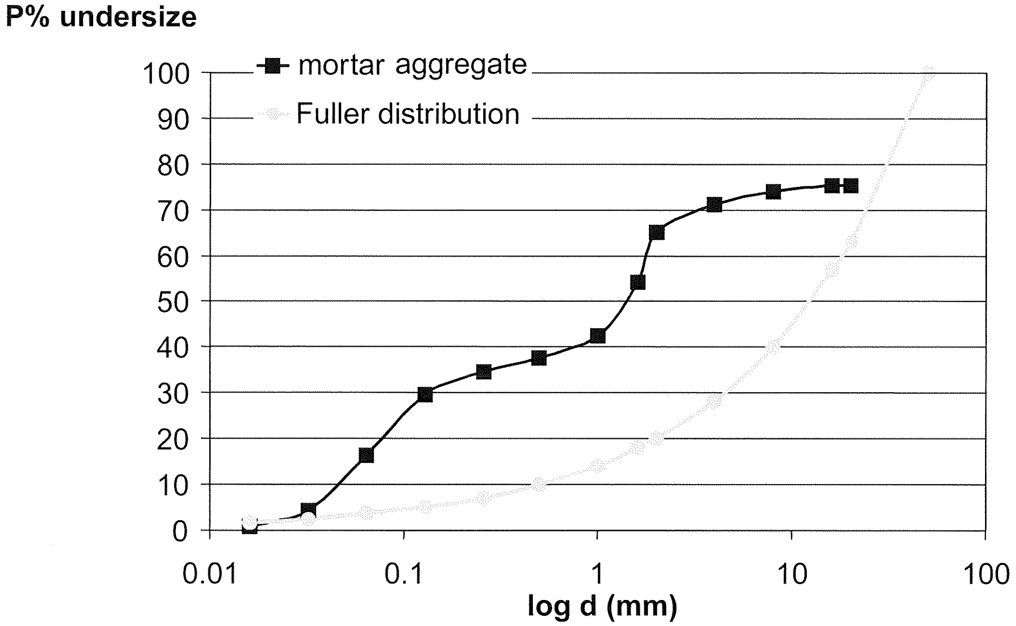

Fig. 4 – Fuller distribution and grain size cumulative curve of mortar: note quite large difference between curves.

Physical analyses

Table 1 lists the physical characteristics of the mortar. Porosity is quite low (31%) particularly when compared with that of pure lime mortars, which is in the range 35-45% (Franchi *et al.*, 1985; Fratini and Giovannini, 2000; Moropoulou *et al.*, 2000). Nevertheless, it is higher than that of mortars made with Portland cement (values around 15-20%: Fratini *et al.*, 1990, 1992; Moropoulou *et al.*, 2000) and shows values similar (or slightly higher) to magnesian lime mortars (Fratini *et al.*, 1996; Atzeni *et al.*, 1996).

As regards water absorption, the material is almost completely saturated (SI= 99%), showing behaviour similar to that of hydraulic mortars (Fratini *et al.*, 1992).

Mineralogical and chemical analyses

Mineralogical analysis on samples obtained by mechanical separation of binder and lumps from the aggregate reveals the absence of quartz and feldspars. Nevertheless, slight contamination due to the carbonatic component of the aggregate cannot be excluded, as indicated by the higher calcite content in the binder than in the lumps (Table 2). In addition to calcite, two hydrated calcium silicates (tobermorite 11A, tobermorite 14A) were found. These minerals are distinctive of hydraulic mortars and represent the reaction between calcium oxide and microcrystalline silica. The lumps contain the same minerals.

Chemical analysis by XRF of both binder and lumps revealed a slightly greater amount of CaO in the binder, which depends on the scarce contamination due to the carbonatic component of the aggregate (see above) (Table 3, fig. 5).

On the whole, these data indicate the hydraulic nature of the binder, further confirmed by calculation of the hydraulicity index:

$$I = SiO_2 + Al_2O_3 + Fe_2O_3/CaO + MgO = \\ = 1.2 \pm 0.1$$

TABLE 1

Physical characteristics determined on samples mortar.

Mortar	γ (g/cm^3)	γs (g/cm^3)	P%	ICv%	SI%
mean*	2.53	1.74	31	31	99
standard deviation	± 0.05	± 0.16	± 5	± 5	± 4

*determined on 15 samples. g = density, gs = bulk density; P% = porosity; ICv = imbibition coefficient in volume; SI = saturation index

TABLE 2

Mineralogical analyses (XRD) of the binder and the lumps of the roman mortar.

samples	Tobermorite 11A** (ASTM 19-1364)	Tobermorite 14A** (ASTM 29-331)	Calcite (%)***
Lumps *	xxx	xxx	32
Binder *	xxx	xxx	38

* determined on 10 samples
**XRD
***calcimetry

TABLE 3

Chemical analyses (XRF) determined on the samples of binder and lumps of the mortar.

samples*	L.O.I.	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	Fe_{tot}
Binder	26.0	0.06	0.83	2.37	36.47	0.03	0.49	32.60	0.06	0.04	1.05
standard deviation	2.00	0.02	0.18	0.65	3.50	0.01	0.07	2.92	0.02	0.01	0.11
Lumps	29.60	0.02	0.94	1.95	36.55	0.01	0.41	30.35	bdl	0.02	0.15
standard deviation	1.00	0.01	0.37	0.53	2.45	0.01	0.05	3.05	-	0.01	0.06

mean values determined on 5 samples for each typology
% values
bdl =below detection limit

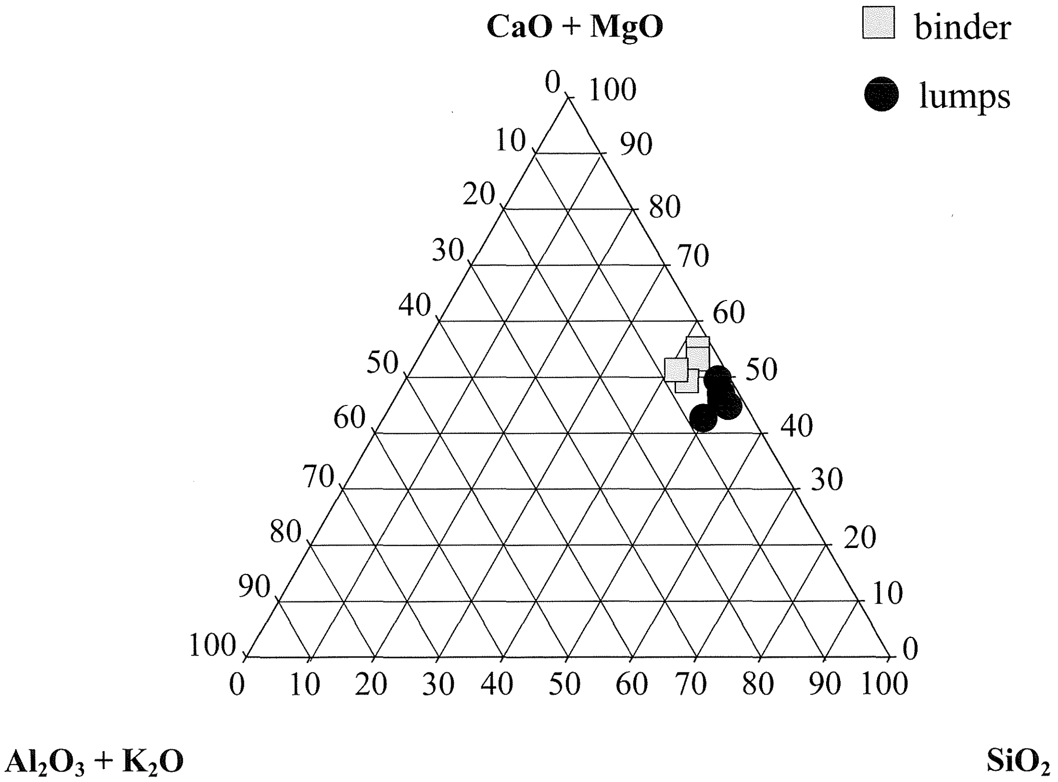

Fig. 5 – Chemical composition (CaO+MgO - Al_2O_3+K_2O - SiO_2 triangle) of binder and lumps, expressed as molar %, determined by XRF analysis. Note slightly higher amount of CaO in binder.

which shows a very high value - particularly when compared, for instance, with Portland 325 cement (I = 0.50-0.65).

As regards TG data, Moropoulou *et al.* (1995) set the CO_2 versus CO_2/H_2O diagram (where CO_2 is weight loss due to decomposition of carbonates and H_2O is weight loss due to water bound to hydraulic components) which classifies the mortars into different groups, as follows (fig. 6):

– typical lime mortars have less than 3% of structurally bound water (due to hydraulic components) (weight loss between 200 and 600°C) and CO_2 values (weight loss >600°C) of 30-40%;

– hydraulic lime mortars have CO_2 contents between 16 and 34% and chemically bound water higher than 3%;

– crushed lime brick mortars have CO_2 contents from 22 to 32% and chemically bound water from 3.5 to 6%;

– pozzolanic mortars have more than 5% of hydraulic water and less than 20% of CO_2.

Our binder falls in the field of pozzolanic mortars (although it is not truly pozzolanic, as indicated by the absence of *pozzolana*), and the lumps show even higher hydraulic characteristics according to the chemical data previously reported.

Chemical analysis of lumps and binder carried out on thin sections by EPM (fig. 7) confirms the XRF data. According to EPM

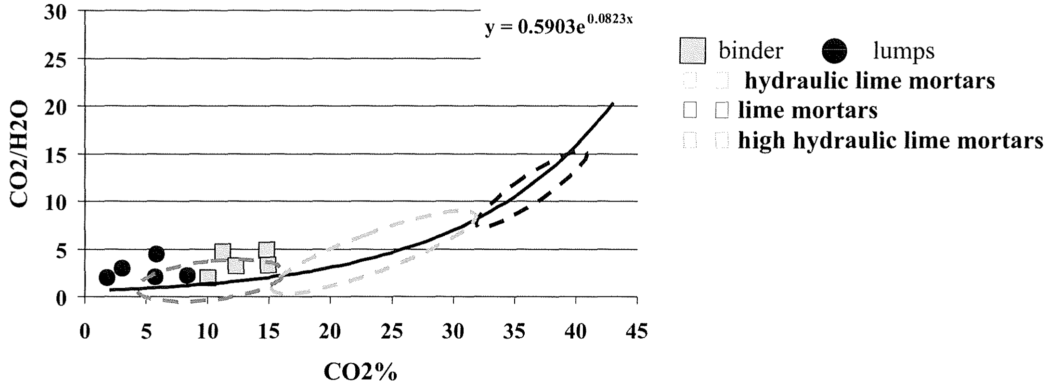

Fig. 6 – Correlation between TG data: CO_2 is weight loss due to decomposition of carbonates and H_2O is weight loss due to water bound to hydraulic components.

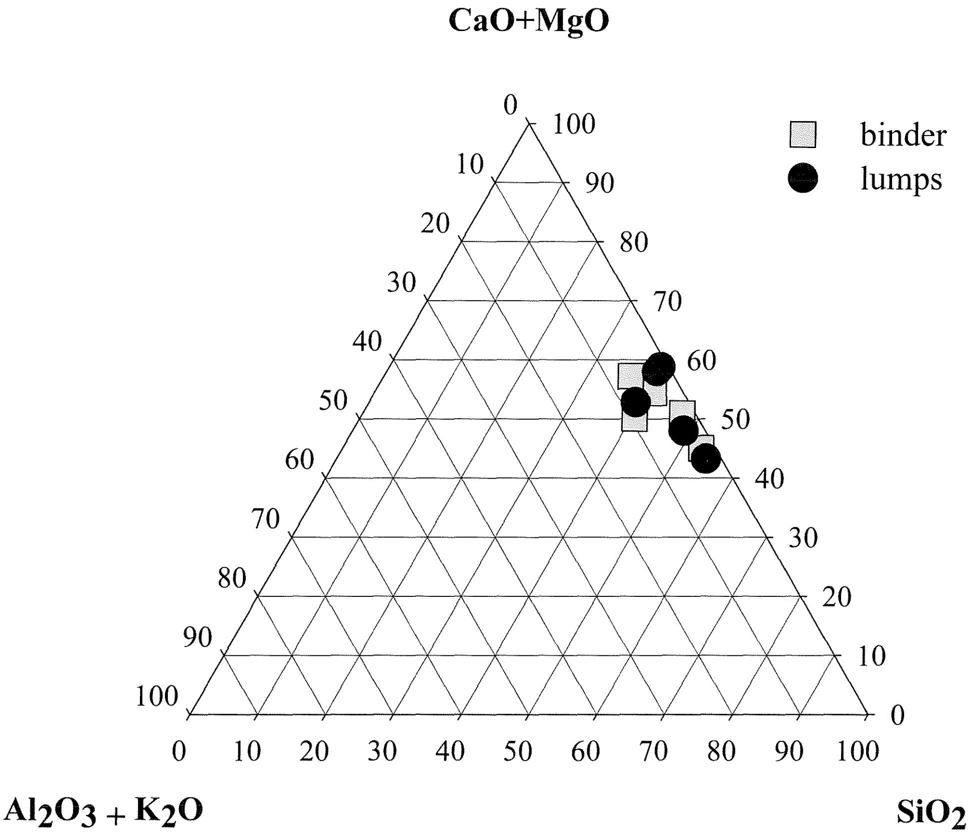

Fig. 7 – Chemical composition of binder and lumps, expressed as molar %, determined by WDS analysis.

analysis, the binder has the same composition as the lumps, demonstrating that, during mechanical separation between binder and aggregate, no significant contamination occurred.

The question of the nature of the strong hydraulicity of this kind of binder arises.

The low amounts of Al and K and the higher amount of Si exclude the use of marly limestone to produce the lime. One possible explanation for such a high degree of hydraulicity of the binder is the addition of a diatomaceous earth, as indicated by Franzini *et al.* (2000) for the Medieval mortars of the Leaning Tower of Pisa. At present, preliminary micropaleontological analyses of the binder do not reveal any traces of siliceous additives such as radiolarians or diatoms, but only calcareous nannofossils of Upper Oligocene age.

Another source of Si may be cherty limestone. As reported above, chert fragments are widespread in the mortar mixture. Hence this research will continue with experimental production of lime from the cherty limestone occurring at various levels of the Umbrian sequence outcropping around Narni, in an attempt to find the stone used by the Romans in lime production.

CONCLUSIONS

The analytical data presented here explain the good conditions of conservation of the mortar used to construct the bridge built by the Romans over the river Nera near Narni. It is important to note that data on the binder were gathered from the lumps representing the pure binder before the addition of any additive and without the influence of the aggregate fraction. In particular, the durability of the mortar is mostly due to the kind of binder used, with very good hydraulic characteristics (hydraulicity index = 1.2). This hydraulicity appears to be natural, and is not the result of additives (like *pozzolana*, diatomaceous earth, kaolin, etc.) because no differences were found between the mineralogical and chemical compositions of the binder itself and those of the lumps. The chemical data give further useful information: the high Si content and the Al_2O_3/SiO_2 and K_2O/Al_2O_3 ratios are not compatible with the use of marly limestone to produce the lime. Stone chemically compatible with the observed data is cherty limestone, which outcrops extensively around Narni and fragments of which are frequently found in the mortar mixture.

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