OLD STONE BRIDGES IN EPIRUS, GREECE
HARDNESS TEST USING A THIN SECTION LAPPING MACHINE

by

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ABSTRACT

In the present investigation the stability of the old stone bridges and the weathering conditions of the raw materials were studied experimentally by means of hardness test, sonic velocity, dry density and water absorption determination; thin sections of these stones were studied also. Hardness was measured as abrasion loss of weight using a thin section lapping machine. Test results were sufficiently related to the weathering.

INTRODUCTION

Epirus is perhaps the more mountainous part of Greece. Pindos, the highest and most important mountain chain in the area creates deep valleys traversed by a large number of rivers with a considerable water flow, due to heavy rainfalls and snowfalls. Aoos, Voidomatis, Arachthos, Acheloos are some of the more important rivers in the region.

The inhabitants (Epirotes) in order to find their needs had to cover different distances ranging from short trips to much longer commercial journeys not only over Greece but also beyond it. It was therefore self evident that from early times it has been imperative that these aqueous obstructions be surmounted to allow the inhabitants to move freely from place to place.

The stone bridges, in Epirus were built in days when the lack of mechanical knowledge was being replaced by the experience. The rock materials exposed to atmospheric factors are captured to the action of various agents causing their destruction, in relation to the climatic changes; water / salt combination, activated by the fluid circulation, provoke their weathering and decomposition.

Although these bridges are not any more used in our days for transportation, it is necessary to be preserved by the State, as their construction technique was unique. Loose blocks (Fig. 5 c), zonal weathering of stones, starting from the surface and continuing inward (Fig. 6.8, 6.10, 6.19) and creating "stalactites" of secondary calcite (Fig. 5 e, 6.20) cause damage of these bridges, in relation to the tectonic conditions.

The purpose of this investigation was a first approach to estimate the damage of these old bridges so that the more proper conservation measurements to be taken. A thin section polishing machine used for abrasion loss of weight measurements, as hardness and weathering values gave quite good results.

WEATHERING OF NATURAL STONES

One of the greater dangers to the historical monuments is the weathering caused by the climatic changes and air pollution. Building stones are susceptible to various atmospheric factors causing their destruction. The type of weathering varies from one climatic regime to another. In humid regions, chemical weathering is more significant than that of mechanical disintegration. If the temperature is high, like in the Mediterranean basin, then weathering is extremely active; pore water activity, as a media of transporting salts, accelerates the decomposition and the desintegration of the material by shrinking – expansion and freezing – fusion phenomena. According to BELL & DEARMAN (1988), when the temperature of the water is raised from 0°C – 60°C, it expands some 1.5 % exerting a pressure of up to 52 MN/m^2 within the pores of a rock. Percolating water increases the weathering processes on calcite, feldspars, plagioclases, micas, as well as pyroxenes, olivine and other easily dissolved and altered minerals by passing through the fractures of the stones.

The presence of harmful soluble salts, such as sulfates and chlorides of Ca, Mg, and Na in pore water, as a result of reaction of atmospheric gases with rock minerals, is also a main factor of stone decomposition; the crystallization of these hydrous salts requires water and results in their expansion causing the loosening of the cement fabric of the stone.

Concerning the quantitative expression of weathering, several methods have beeen proposed involving the ultrasonic velocity (IRFAN & DEARMAN, 1978), the measure of abrasive pH of feldspars in granites (MALOMO, 1980) or the microscopic measurement of the altered and unaltered parts of the minerals (CHRISTARAS *et al.*, 1989). The method that we used concerns the determination of the abrasion loss of weight, using a thin section polishing machine, in relation to the ultrasonic velocity determination.

GEOGRAPHICAL AND GEOLOGICAL SETTING

The studied area is located in Zagori region of Pindos mountain range in Epirus (Fig. 1). Epirus consists the North-Western part of Greece. Geologically the area belongs to the eastern part of the Ionian zone, near the boundary with the Pindos zone. Therefore the used raw materials derive from the eocenic limestones and the flysch (sandstone) from the surrounding area. Only the bridge in Votonosi (no 15) is found in Pindos zone (ZOUROS & MOUNTRAKIS, 1990) and is constructed of sandstones derived from Pindos zone.

THE BRIDGES

Concerning the site investigation, to put a bridge, flat areas were avoided because of the great amount of mud collected there, causing considerable difficulties to the foundation activities. The most suitable site was at the point where the river narrowed, especially in case it happened to be rocky too.

In these cases bridges of a single arch, such as these of Konitsa and Plaka, were constructed. In cases that this was not possible, long bridges of many arches, such as the famous bridge of Arta, were constructed.

The architecture of these bridges present a large variety of styles, due mainly to the number and the shape of the arches. Regarding the shape of the arches the intersection is either semicircular or slightly pointed. On the body of most of the bridges, small arched openings were used to help at times of flooding. The paved way used by those crossing the bridge is quite narrow, some times not more than two metres wide. Data for the construction of the 15 studied bridges are given in Table 1 as well as in the map of Fig. 1 and the pictures of Fig. 2-5.

THE BUILDING MATERIALS

The main raw materials were limestones and sandstones while the bond was composed of a mixture of crumbled tiles, limes, pumice-stone, water and dried grass. Hair of animals and the white of eggs were also used for greater binding effect.

Thin sections of the used sandstone and limestone were studied under the microscope. The sandstone is composed of medium grained phenocrysts and fine grained groundmass. Geologically the material belongs to the Ionian flysch. Usually the phenocrysts cover the 30-60 % of the total mass of the material. The rock is composed of quartz, K-feldspar, calcite and plagioclase. Both K-feldspars and plagioclases are kaolinized and sericitized.

Fig. 1 : Location of the studied area.

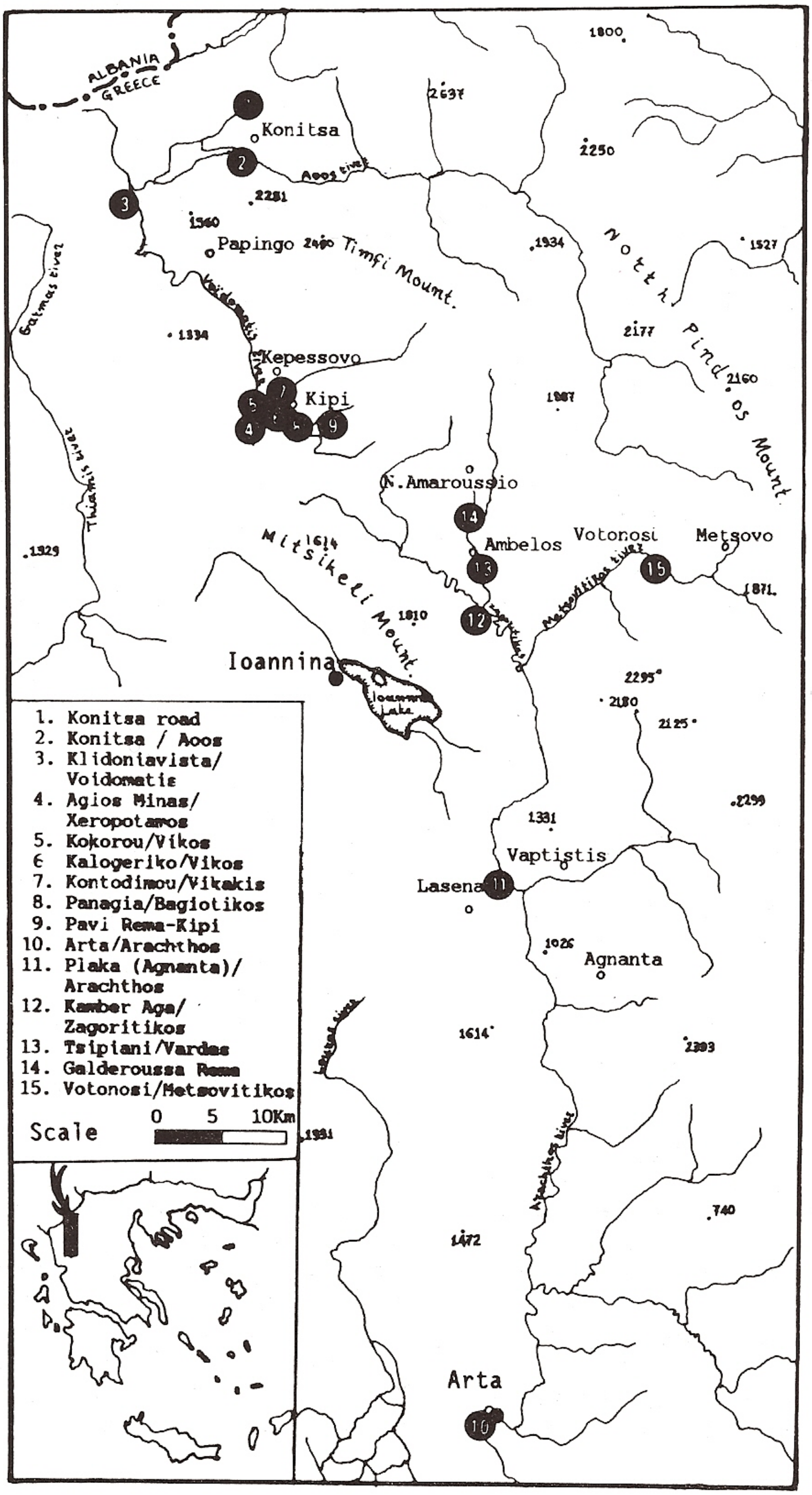
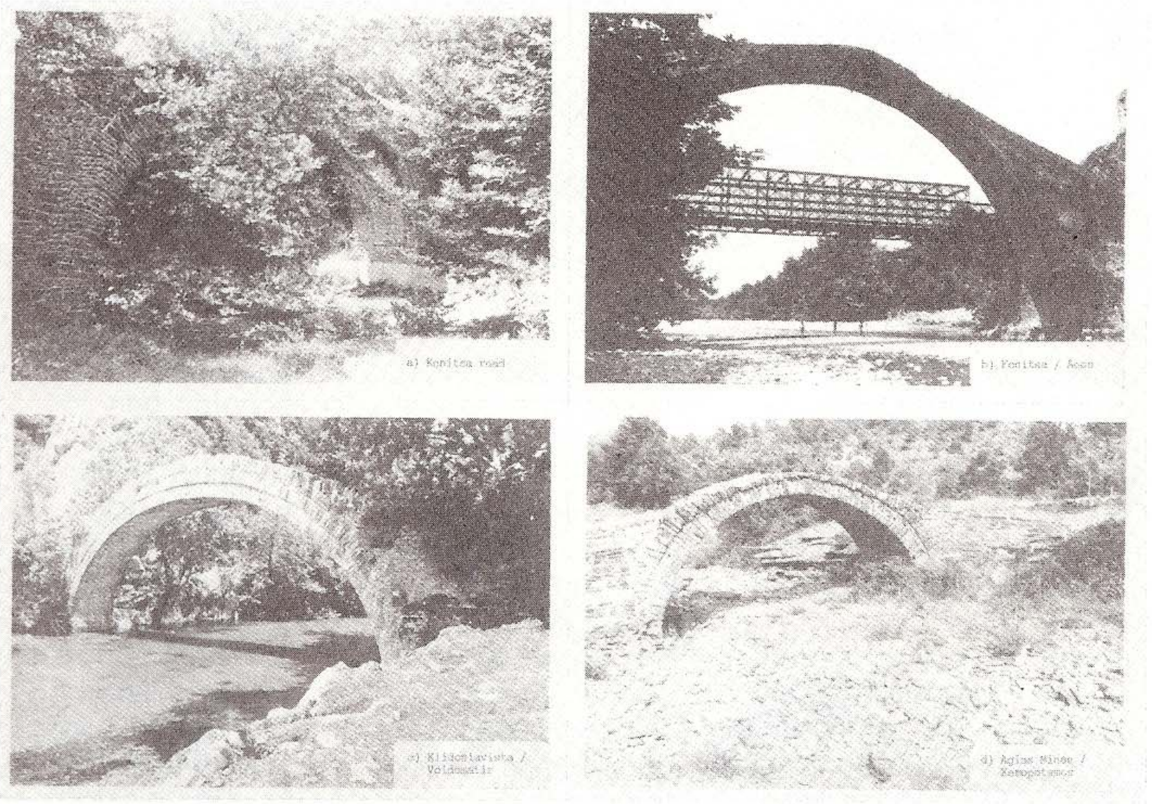


Fig. 2 : Stone bridges from Epirus.
Fig. 3 : Stone bridges from Epirus.


a) Konitsa road
b) Konitsa / Aoos
c) Klidoniavista / Voidomatis
d) Agios Minas / Xeropotamos

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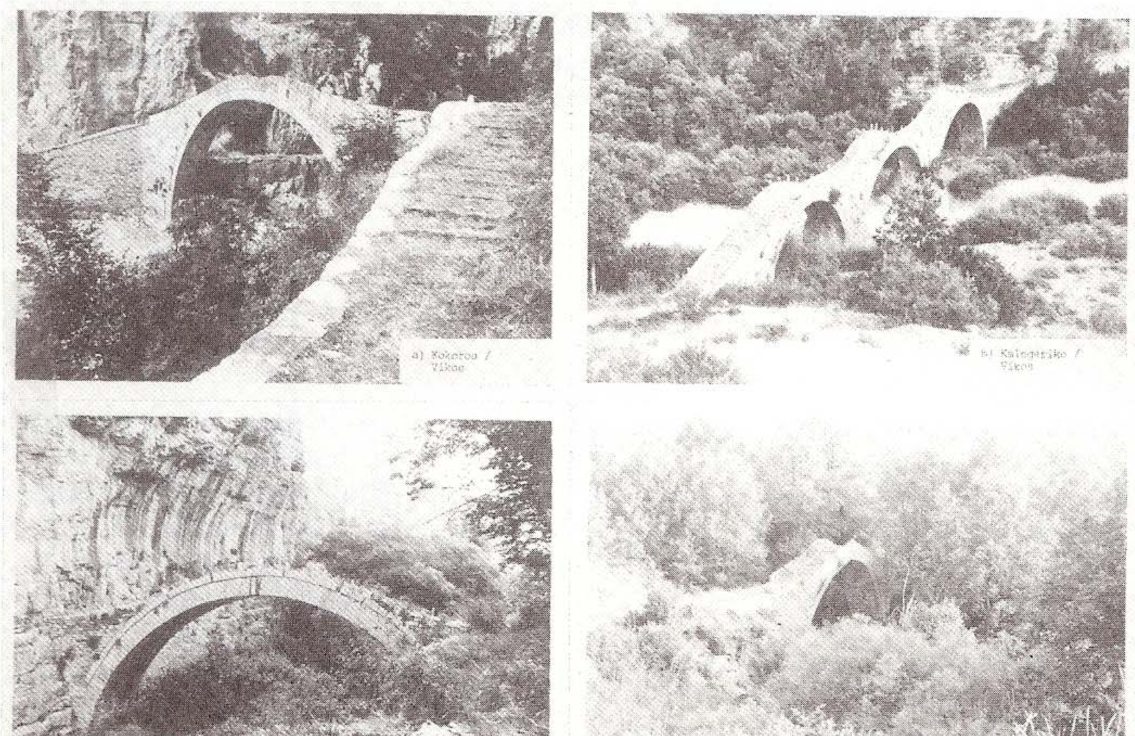
a) Kokorou / Vikos
b) Kalogeriko / Vikos
c) Kontodimou / Vikakis
d) Pangia / Bagiotikos

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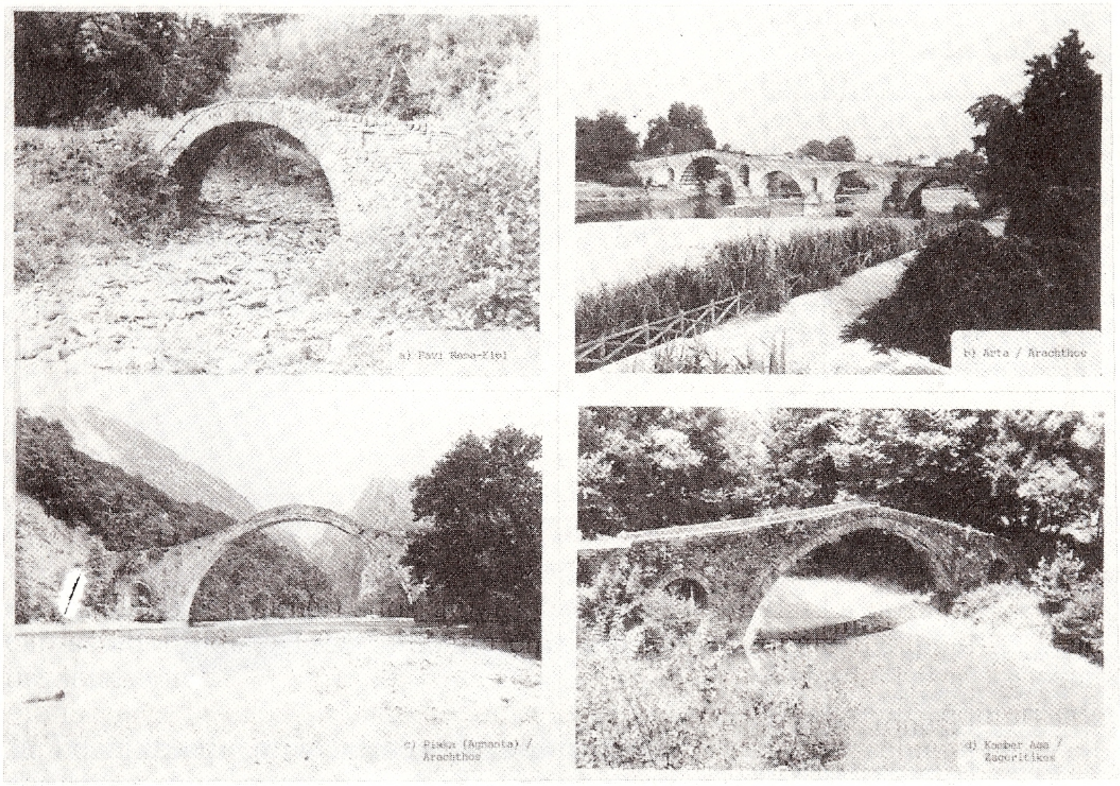
Fig. 4 : Stone bridges from Epirus.
Fig. 5 : Stone bridges from Epirus.



a) Pavi Rema-Kiel

b) Arta / Arachthos

c) Plaka (Agnanta) / Arachthos

d) Kober Aga / Zagoritikos

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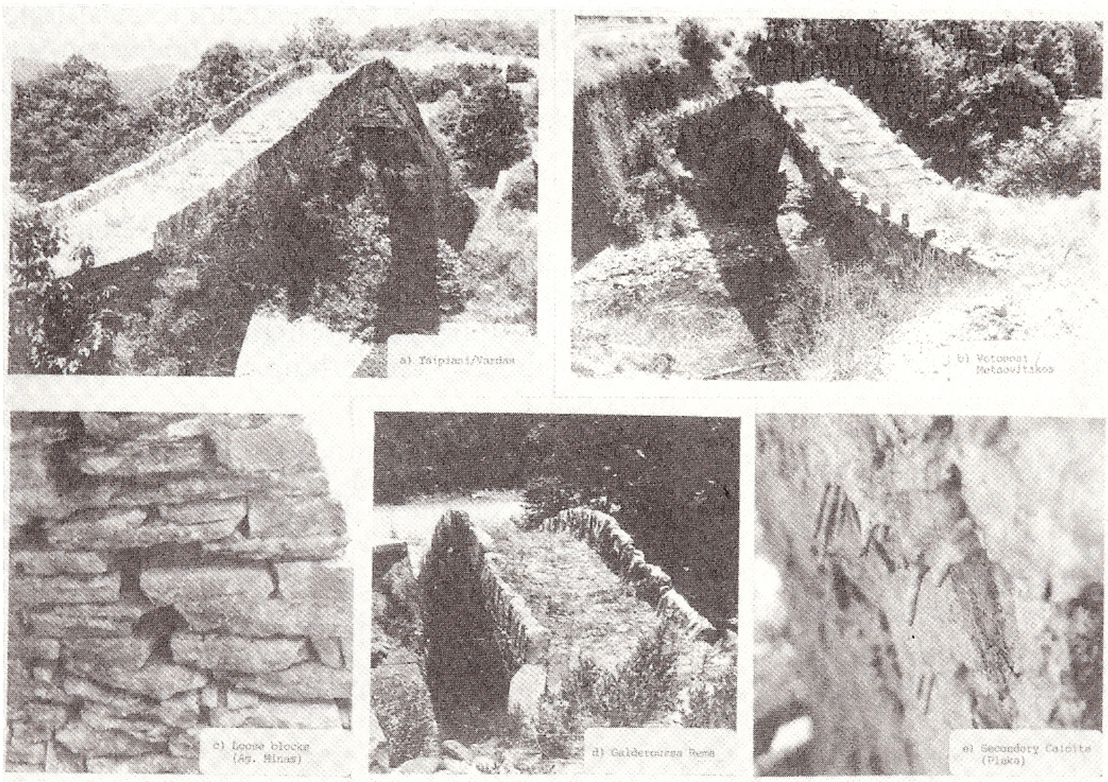

a) Tsipiani/Vardas

b) Votonosi / Metsovitikos

c) Loose blocks (Ag. Minas)

d) Galderoussa Rema

e) Secondary Calcite (Plaka)

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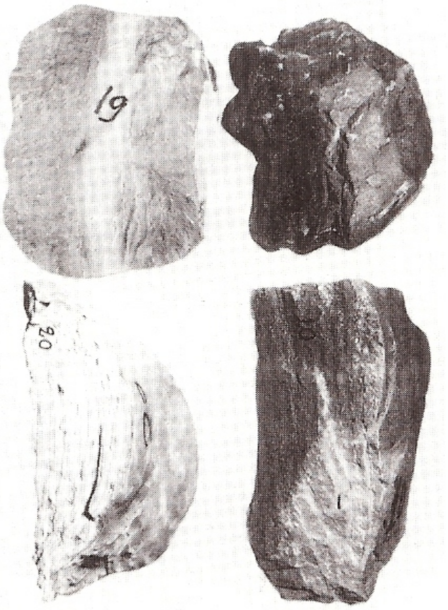
Table 1 - Construction data of the 15 studied stone bridges.
Names and dates by MANDAS, 1988.

No	Bridge	Arch	Date	Material	River	Fig
1	Konitsa road	1	-	Sandstone	-	2a
2	Konitsa	1	1870	Sandstone Limestone	Aoos	2b
3	Klidoniavista	1	1853	Sandstone Limestone	Voidomatis	2c
4	Agios Minas	1	-	Sandstone	Xeropotamos	2d
5	Kokorou	1	1750	Sandstone Limestone	Vikos	3a
6	Kalogeriko	3	1814	Limestone	Vikos	3b
7	Kontodimou	1	1753	Sandstone Limestone	Vikakis	3c
8	Panagia	1	1830	Sandstone	Bagiotikos	3d
9	Pavi-Rema / Kipi	1	-	Sandstone	Pavi stream / Bagiotikos	4a
10	Arta	4	3^{o}c.BC /1606	Limestone	Arachthos	4b
11	Plaka/Agnanta	1	1866	Sandstone	Arachthos	4c
12	Kamber Aga	1	-	Sandstone	Zagoritikos	4d
13	Tsipiani	1	1875	Sandstone	Vardas	5a
14	Galderoussa Rema	1	-	Sandstone	Galderoussa stream/Vardas	5d
15	Votonosi	1	-	Sandstone	Metsovitikos	5b

The groundmass is composed of quartz, calcite and clay. The used eocenic Ionian limestone is thin platy, fine grained and abundant in foraminifers. Its colour is white to light brownish white. Pieces of agglomeratic limestone were also used in some cases.

The building stones of the bridges are moderately weathered presenting usually a 20-30 % of weathering. The weathering starting from the surface continues inward, displaying a zonation (Fig. 6.8, 6.10, 6.19).

Fig. 6 : Building stone samples showing a zonal weathering.
8, 10 : Sandstones; 19 : Limestones; 20 : secondary calcite which cover building stones.



The determination of weathering was made calculating the change of ultrasonic velocity, the water absorption and the dry density. The weathering of limestone, expressed by dilution of the $CaCO_3$ must be more intense than of sandstone. Nevertheless sandstone presents also high weathering because of the calcitic composition (together with quartz) of its groundmass. Both limestone and sandstone building materials are entirely covered of secondary calcite, looking sometimes like stalactites (Fig. 5 e, 6.20). Tectonic and slope stability conditions provoke big cracks on the body of the bridges causing the loosening of the blocks (Fig. 5 c).

PHYSICAL PROPERTIES

Tests were applied on mini cores of 24 mm diameter and 48 mm high. Specimens for hardness test are 10 mm high. The specimens were studied concerning the following properties:

1) Their dry density (d, ASTM C 97-47), which was obtained dividing the dry weight (after drying for 24 h at 110° C) of the specimens by the total volume (solids and voids). The calculated mean value is 2.384 gr/cc (σ_{n-1}= 0.2139) for the sandstones and 2.708 gr/cc (σ_{n-1}= 0.0713) for the limestones.

2) Their water absorption (Ab, ASTM C 97-47), by dividing the absorbed water weight (after a bath of 24 h, in vacuum) by the dry weight of specimens. The calculated mean value is 1.793 % (σ_{n-1}= 0.7915) for the sandstones and 0.304 % (σ_{n-1}= 0.0403) for the limestones. The observed difference between the two materials can be explained by the coarser character of the sandstones.

3) The ultrasonic velocity (v, ASTM 597, ASTM D 2845-83) through the material, as a good index characteristic of the physico-mechanical behaviour of the rocks. For this purpose a PUNDIT portable ultrasonic non destructive digital tester was used. The calculated mean value is 2178.8 m/s (σ_{n-1}= 726.13) for the sandstones and 4263.3 m/s (σ_{n-1}= 485.14) for the limestones. Ultrasonic velocity is too much higher in limestones than in sandstones depended on the porosity expressed by the higher water absorption of the sandstones.

4) Their hardness (Abrasion loss of weight, AR) as a measure of their mechanical behaviour and their ability to resist weathering. The used method consists to the calculation of the loss of weight of a pre-weighted sample after abrasion for a constant time under constant conditions. A LOGITECH-LP 30 thin section lapping machine with constant rotation of 40 rpm was used.

The polishing material was emery of 400 mesh and the specimens were loaded with 2 kg. The abrasion time was 1/2 h. The calculated mean value is 2,347 % (σ_{n-1}= 0.3135) for the sandstones and 4.094 % (σ_{n-1}= 0.44) for the limestones. The abrasion loss of weight is too much higher in the limestones than in the sandstones. This result comes in contrast to the results of the other physical properties, considering that hardness is high as density is high and absorption is low. Ultrasonic velocity in dense materials is high too. The different texture and mineralogy of the two rock types could explain this difference. Quartz, being the chief component of sandstone, is too much harder than calcite (limestone). On the other hand the relative grain size in sandstone is not uniform; the medium grained phenocrysts are surrounded of a fine grained groundmass, causing lower density and higher absorption conditions. According to the data of Table 2, it is obvious that in the same material high values of abrasion loss of weight correspond to low values of dry density and ultrasonic velocity in relation to high values of water absorption.

Tests were applied on samples collected representatively from the studied bridges. Test results were interpreted separately for each

Table 2 - Physical properties of sandstones used for the construction of the studied bridges.

Sandstones				Limestones			
d gr/cc	Ab %	AR %	vp m/s	d gr/cc	Ab %	AR %	vp m/s
2.57	0.91	2.12	2878	2.62	0.35	4.79	3680
2.37	1.69	2.35	1864	2.68	0.31	4.05	4106
2.62	0.95	2.10	2990	2.78	0.26	3.69	4823
2.60	1.02	2.10	3223	2.71	0.31	3.95	4465
2.41	1.71	2.22	2045	2.74	0.29	3.76	4350
2.38	2.08	2.35	1930	2.66	0.33	4.40	3985
2.32	2.17	2.42	1537	2.63	0.36	4.69	3732
2.48	1.34	2.20	2867	2.79	0.25	3.65	4860
2.44	1.35	2.24	2280	2.82	0.25	3.60	4895
2.36	1.75	2.33	1710	2.65	0.33	4.36	3737
1.79	3.78	3.38	545				
1.97	3.57	2.84	1245				
2.43	1.49	2.29	2081				
2.22	2.40	2.46	1545				
2.54	1.58	2.14	3078				
2.58	1.07	2.14	2763				
2.17	2.46	2.72	1884				
2.42	1.62	2.28	1964				
2.61	1.05	2.08	3259				
2.40	1.88	2.29	1889				

rock type but together for all the studied bridges, since the stones used belong to the same geological formation.

Test results of the above properties are given separately for the studied sandstones and limestones, in Tables 2 and 3.

INTERPRETATION OF TEST RESULTS

Test results were interpreted statistically to determine relationships between the studied physical properties. These relationships were expressed mathematically (Table 3) and by regression diagrams (Fig. 7 and 8).

Correlation coefficients as well as the other statistical parameters, such as standard deviation, standard error and confidence of Y were also measured given in Table 3.

The correlations proved to be very significant (level 0.1), verified concerning their significance by calculation of the following equation, using the Student Tables.

$$t = \frac{I\sqrt{n-2}}{\sqrt{1-r^2}}$$

Ultrasonic velocity, hardness and water absorption changes were used to express the weathering condition of each material.

Table 3 - Mathematical relationships between the studied properties, for each type of rock (S : Sandstone, L : Limestone)

S/L	Regression X - Y Size [S:20, L:10]	Correl. Coef.	Standard Dev. Y	Standard Error Y	Confid. 95%, Y	Confid. 99%, Y
S	Ab=10.41-3,62d	-0.9772	0.7915	0.1770	0.3469	0.4566
L	Ab=1.81-0.55d	-0.9821	0.0403	0.0128	0.0250	0.0329
S	$AR=6.75d^{-1.23}$	-0.9883	0.3127	0.0699	0.1370	0.1804
L	$AR=195.5d^{-3.99}$	-0.9623	0.4400	0.1391	0.2727	0.3590
S	vp=-5169+3082d	0.9079	726.13	162.37	318.24	418.91
L	vp=-13749+6648d	0.9771	485.14	153.42	300.69	395.81
S	$vp=32016AR^{-3.25}$	-0.9354	726.13	162.37	318.24	418.91
L	$vp=17765AR^{-1}$	-0.9514	485.14	153.42	300.69	395.81

The ultrasonic velocity through a sound limestone could be equal or higher than 5000 m/s. In the same time an ultrasonic velocity of 3500 m/s in sandstones is not a low one, depending on the grain size of the material. It is obvious that ultrasonic velocity values could be used only for relative weathering determination, considering empirically that ultrasonic velocities of about 3500 m/s for sandstones and 5000 m/s for limestones could correspond to sound rocks. According to our test results, ultrasonic velocity is related positively to dry density while it presents a negative correlation with the abrasion loss of weight, expressed by a power regression.

The above relationships show that a slight increase of weathering, expressed by dry density and ultrasonic velocity decreasing, causes a significant increase of abrasion loss of weight.

Water absorption increasing strengthens the weathering velocity and the abrasion ability of the stones. A linear negative relationship between water absorption and dry density confirm the previous consideration, in relation to the existed relationships between dry density and abrasion loss of weight and ultrasonic velocity.

Dry density is related positively with ultrasonic velocity while it presents a negative relationship with abrasion loss of weight and water absorption.

The abrasion loss of weight, given as hardness expression, is related negatively to density and ultrasonic velocity, by a powered regression. It is obvious that the increase of the abrasion loss of weight is related directly to the material resistance and the fabric loosening of the construction.

CONCLUSIONS

Building stones from 15 old stone bridges from Epirus were studied regarding their mineralogical and physical data, in relation to their weathering condition. The purpose was to estimate the degree of weathering and resistance of these stones, in relation to the

Fig. 7 : Correlation diagrams of the tested properties in sandstones.

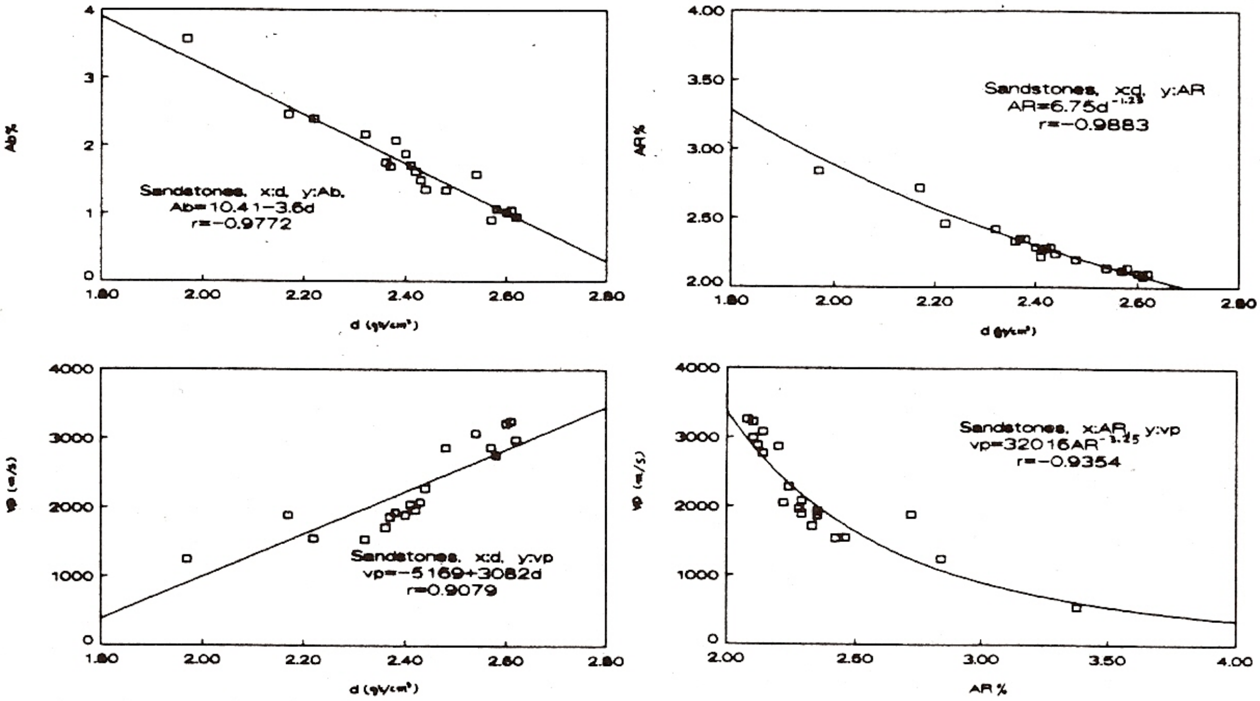
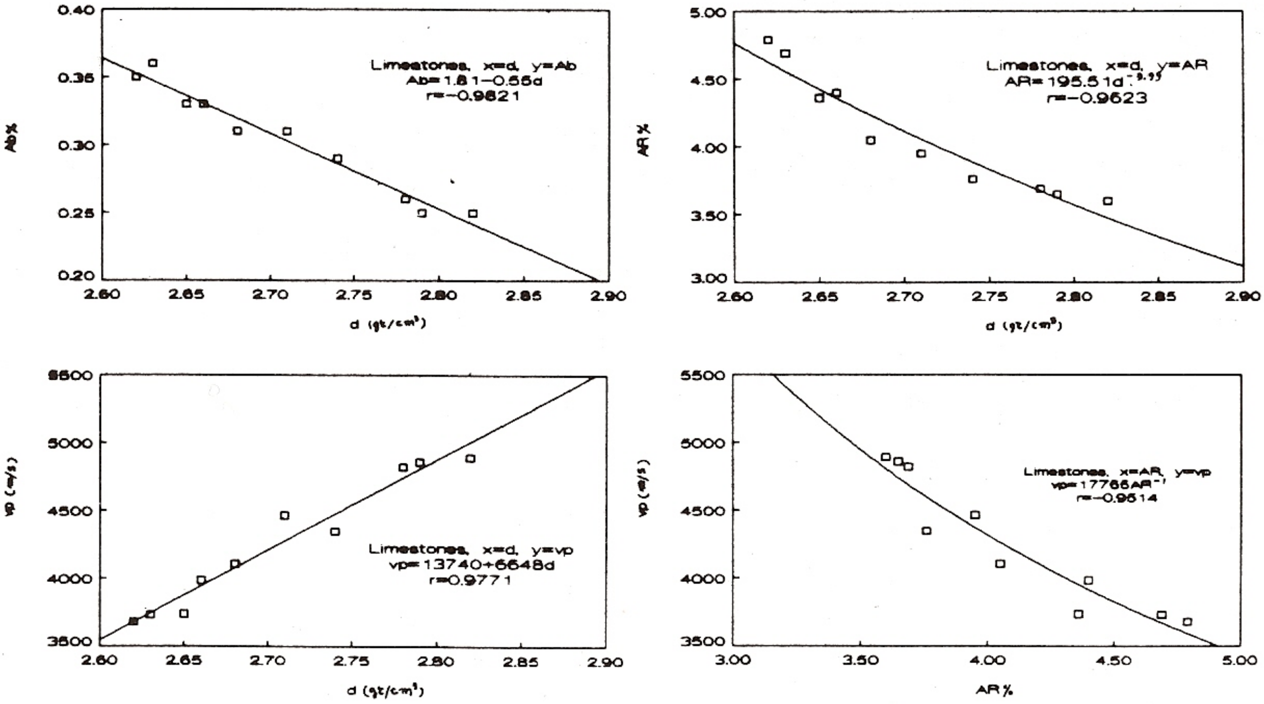


Fig. 8 : Correlation diagrams of the tested properties in limestones.



general stability and resistance of these bridges through the years. The above study showed the follows :

1) The building stones of the above bridges are mainly sandstones and limestones, derived from the Ionian zone. Only in the small bridge in Votonosi sandstones from Pindos flysch were used.

2) The different texture and mineralogy of the two rock types caused their different physical behaviour. Nevertheless in the same material dry density, water absorption, ultrasonic velocity and abrasion loss of weight gave results that represent sufficiently the weathering changes and the remained resistance of the stones. The calculated relationships between the studied are given in Table 3 and Fig. 7 and 8.

3) The abrasion loss of weight express not only the hardness of the material as a measure of its resistance but also its friction ability and velocity, in relation to the increase of weathering.

4) According to the calculated relationships a slight increase of weathering provoke a significant increase of the abrasion loss of weight and stone fabric loosening. The increase of weathering was determined by the decrease of the dry density and ultrasonic velocity in relation to the simultaneous increase water absorption.

5) Although these bridges are still in good enough condition, they have to be preserved by the State, because weathering condition is limited.

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