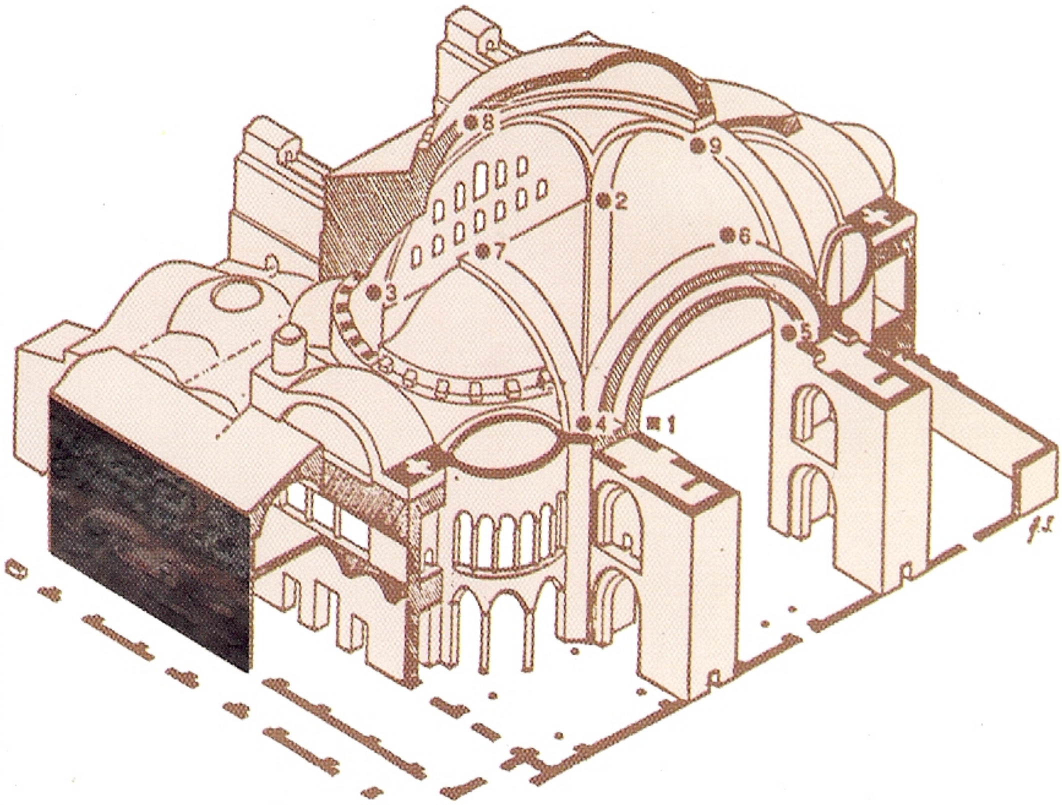
INCOMARECH - RAPHAEL 97/E/412

COMPATIBLE MATERIALS FOR THE PROTECTION OF EUROPEAN CULTURAL HERITAGE

PACT 55 1998

Revue du groupe européen d'études pour les techniques physiques, chimiques, biologiques et mathématiques appliquées à l'archeologie - Conseil de l'Europe



Scientific Editors : G. Biscontin, A. Moropoulou, M. Erdik, J. Delgado Rodrigues

In the memory of the late and regretted Professor T. Hackens

Organized by :
European Commission, Directorate General X
University Ca' Foscari of Venice
National Technical University of Athens
National Laboratory of Civil Engineering, Lisbon
Bogazici University of Istanbul
Technical Chamber of Greece

Under the auspices of :
PACT - Council of Europe
UNESCO - ROSTE - Cultural Heritage
ICOMOS
ICCROM
Ministry of Culture of Greece
Ministry of Cultural Heritage of Italy
Ministry of Culture of Turkey
Ministry for the Development of Greece - General Secretariat of Research and Technology
National Research Council of Italy
Municipality of Athens
Municipality of Istanbul
Municipality of Venice

Published by :
TECHNICAL CHAMBER OF GREECE

NON- DESTRUCTIVE EVALUATION OF THE PERFORMANCE OF MORTARS ON HISTORIC MASONRIES

A. Moropoulou *, M. Koui *, B. Christaras [O], Th. Tsiourva *

* *National Technical University of Athens, Department of Chemical Engineering, Section of Materials Science and Engineering, Iroon Polytechniou St., Zografou Campus, 15773 Athens, Greece.*

[O] *Aristotle University of Thessaloniki, School of Geology, Department of Geology and Physical Geography, 54006 Thessaloniki, Greece.*

Abstract

In order to evaluate historic and restoration mortars regarding their behaviour on the masonry level, non destructive tests are applied. *Fibre Optics Microscopy (FOM)* allows for the observation of the building materials on site and permits their identification and classification to the various already studied mortar types (lime, hydraulic lime, crushed brick-lime, lime-cement mortars, e.t.c.). *Ultra-Sonic (US) measurements* allows for the comparative study of the outer (weathered) to the inner (sound) material layer and the various strengh levels of the different building materials. *Infra-Red Thermography (IR-TH)* allows for recording the thermal maps of the surfaces under study and provides information on the differential behaviour of the various materials on the masonry scale regarding as well the impact of the microclimatic variations on the same building material, since the water evaporation cycles are controlling the weathering effects in porous media. Pilot investigation has been performed regarding ancient, Byzantine, Venetian and recent monuments in Crete allowing for the comparison among various types of historic mortars and restoration ones (lime-cement mortars). The combined use of the above non-destructive techniques leads to conclusions regarding :

- The weathering depth and the damage level of ancient mortars (US) measurements as classified per mortar type and microstructure (FOM) observations
- The compatibility of restoration mortars and plasters with the original building units on the historic masonry scale, related to :
  - * The elastic moduli of the various types of historic and restoration mortars (comparative study by US),

* The physico-chemical behaviour of the capillary systems of the various building materials, governing the percolation and evaporation of salt solutions within the historic masonry (evaluation by IR-Th).

Finally, it is indicated that the longevity of the historic masonries might be investigated as a function of these behavioral patterns on the scale of the masonry by non destructive techniques.

Introduction

The main function of the mortar is to bind the building units together to provide a durable masonry. The historical masonry is thus, a composite system whose durability is related both to the nature of the single consituents and to the particular interaction between mortar and stone or mortar and brick. The adhesion between building units and mortar in all these complex systems can be really different depending on the interaction between binder and load bearing units under various operating conditions, regarding the environment and the structure [1].

The adhesion and the durability of the masonry is influenced by workmanship and by the environmental conditions or the pollution. The environmental conditions (humidity, in particular) can play an important role : favoring the reactivity between the constituents inducing the disaggregation of the matrix, or modifying the kinetics of the hardening [2]. The study of the elastic behaviour of the mortars gives information on bonding between binder and bearing unit and to the aggregate / matrix interface governing compatibility of masonry materials on the masonry structure [3,4].

The longevity of the examined historic composites is more or less related to :

- The degradation of historic mortars, which is attributed mainly to the chemical dissolution of the mortar matrix, i.e the calcitic binder and is known as the washing out of mortar joints, concerning specifically lime mortars [4]. Damage processes as acid attack or salt crystallization vary, according to the physicochemical and the mineralogical characteristics of the mortars, their microstructure and the adhesion of the binder to the aggregates.
  The original mortars, which have been deteriorated by natural weathering, salt decay and by the corrosive action of polluted atmosphere, had to be replaced.
  At the same time, the uncontrolled and rather extensive use of cement and polymer-based mortars, erroneously believed to be more resistant than the traditional ones, gave very unsatisfactory results, due to the high content of soluble salts and the limited compatibility between these hard, impermeable materials and the original components of the masonry.
  Modern mortars and adhesives are less porous than building stones and bricks, with higher values of hardness, mechanical resistance and thermal

expansion coefficient attributing to them a performance rather incompatible to the original materials [5].

- The compatibility to the wall constituents, as far as the raw materials, the mortar production process and the physico-chemical and microstructural properties are concerned, which allows for continuous stresses and strains. Study of the historic mortars behaviour is a priority need in terms of restoration of the historical buildings in marine and urban centers.These systems, in fact, are deemed more compatible with the porous building stones than the modern cement. Acid attack of cement generally involves expansions due to the ettringite formation, successively followed by the gypsum one, in the cracks which directly damages the masonry. On the other hand, if cement is used in restoration, it infers sulphates to the masonry as an inner source of acid attack and efflorescences [6].

Hence, the compatibility of conservation interventions to historic masonries becomes a critical factor for the selection of appropriate conservation materials (repair mortars, grouts and consolidants). In order to assess and evaluate the compatibility of conservation materials to various types of historic masonries and original building materials, several techniques should be employed. Non-destructive in situ applied techniques have been proved, in previous works [7,8], to permit evaluations, like :

- the Fibre Optics Microscopy to identify the microstructure and to classify the investigated materials to several categories according to their mineralogy, texture, etc.,
- the Infra-Red Thermography to evaluate the respiration behavior and the compatibility of the capillary systems of the materials on the masonry scale.

These in situ techniques validated by laboratory investigations of the actual microstructure, composition, texture, etc. have been proved that they might develop a tool to interpret compatibility or incompatibility phenomena at material / material interfaces on the masonry scale regarding its behavior to the water percolation and evaporation phenomena. This tool might be integrated with other adjoint techniques like Ultra Sonic measurements relating ultrasonic velocity to the moduli of elasticity, in order to serve integrated on site non-destructive evaluation of conservation interventions and materials on historic masonries [9,10].

Measurement techniques and procedures
The following Non Destructive Tests have been performed on site:

Fiber Optics Microscopy
By using the Fiber Optics Microscopy (FOM), with the aid of a video recorder, pictures can be obtained in several magnitude range, examining on site the

morphological characteristics of the surface [11], like the texture, the structure – even the microstructure – the salt growth, efflorescences, etc. The method is used for the first time in combination with Infra Red Thermography and Ultra Sonic measurements.

In previous works [3, 11, 12] various mortar types were studied by FOM, and their classification to certain well distinct historic mortar technology was achieved (lime, hydraulic lime, crushed brick-lime, lime-cement mortars, e.t.c.). In the present work FOM is performed on site, in order to permit mortars classification on the basis of previous standardization.

Fiber Optics Microscopy was applied in the field (by PICO-SCOPEMAN-MORITEX) in several magnifications, X25, X50, X100, X200. The images were stored in a video system, and they were processed in the laboratory (Fig.1: $FOM_{1,2}$ - Fig. 2: $FOM_{3,4,5}$ - Fig. 3: FOM_6 - Fig. 4: FOM_7 – Fig. 7: $FOM_{8,9,10}$).

Infra Red Thermography

In large heterogeneous systems like masonries it is the capillary movement and evaporation rate of water - either ground water rising or sea salt spray attacking - that plays the most important role within the processes of leaching out, transport, concentration, and precipitation of soluble salts in the porous building stones. The humidity rises up as far as a steady state is reached between the water supply and the evaporation [13]. The capillary rise phenomenon proceeds with migration of water or aqueous solutions according to well-defined equilibrium laws [14,15,16]. The phenomenon is more complex, due to the presence of salts and the deriving physicochemical effects, related with the solubility of salts, in conjunction with the susceptibility of the porous stones as determined by their micro-structure [17]. From multicomponent solutions the different salt phases precipitate in sequence according to the different solubilities or ion activities. The system fractionates and the salts are being deposited from the moving solution at different places on the wall forming a spatial sequence.

Infra Red Thermography detects the radiation that different parts of the masonry emit and can render the image of the surface area in colors, in relation to a temperature scale [18]. Since the surface roughness determines the emissivity of the various parts under examination [19,20], porosity estimations by FOM are coordinated as well, in order to support the interpretation of the Infra Red Thermography.

Infra Red Thermography (IR) is a measurement technique providing thermal maps. A thermographical system consists of an Ir Detecor (TVS-2000 MK II LW) and a Processor (AVIO Thermal Video System). The IR Detector uses germanium optics with a peak coating at about 10 im, manufactured by mercury-cadmioum-telluride (HgCdTe) which gives a spectral responce between 8 and 14 μm wavelengths and requires a stirring cooler system (He gas 99,99 %). The IR Detector is connected with a processor which detects the electronic signal , stores it in memory, processses it according to a given software and presents it in an LCDS, by the form of a thermograph (Fig.1:

Thermal Images$_{1,2}$ – Fig.2: Thermal Images$_{3,4,5}$ - Fig.3: Thermal Images$_{6,7}$ - Fig.4: Thermal Images$_{8,9,10}$ - Fig.5: Thermal Images$_{11,12}$ - Fig.6: Thermal Images$_{13,14}$ - Fig.7: Thermal Images$_{15,16}$). The temperature range of an IR Detector spans from -40 C to + 300 C.

Ultra Sonic measurements

The ultrasonic velocity is related to the moduli of elasticity of rocks, such as Young's modulus and Poisson's ratio. Furthermore, it is a very good index for rock quality classification and weathering determination (ASTM 597, ASTM D 2845- 8, Clark, 1966).

Tests are made using the direct or the indirect method, depending on the case. The direct method is referred to the arrangement of the transducers of the apparatus on the opposite surfaces of the specimen tested. The indirect method, used especially on in-situ measurements, refers to arrangement of the transducers on the same surface of the stone.

The depth of weathering at a stone surface can be evaluated using the indirect ultrasonic velocity technique [9]. In this case the transmitter is placed on a suitable point of the surface and the receiver is placed on the same surface at successive positions along a specific line. The transit time is plotted in relation to the distance between the centres of the transducers. A change of slope in the plot could indicate that the pulse velocity near the surface is much lower than it is deeper down in the rock. This layer of inferior quality could arise as a result of weathering.

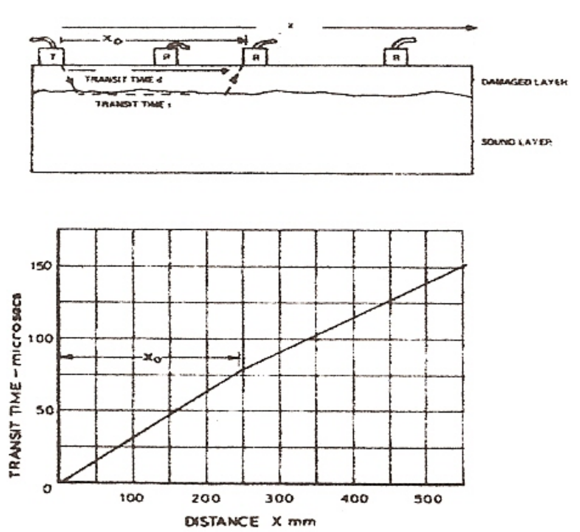


Diagram showing the depth of the damaged layer

The thickness of the weathered surface layer is estimated as follows :

$$D=\frac{Xo}{2}\sqrt{\frac{Vs-Vd}{Vs+Vd}}$$

Where, Vs: Pulse velocity in the sound rock (Km/s)
Vd: Pulse velocity in the damaged rock (Km/s)
Xo: Distance at which the change of slope occurs (mm)
D: depth of weathering (in mm)

On site investigation on monument masonries

On site investigation was performed on ancient, Byzantine, Venetian and recent monuments in Crete, allowing for the comparison among various types of historic mortars (lime, hydraulic lime, crushed brick-lime, lime-cement mortars, e.t.c.) and restoration ones (lime-cement mortars).

More specifically, the masonries investigated on monuments, were :

- On the Venetian fortifications of Heraklion. The surfaces under investigation were related to previous sampling and analyses performed on the building stones and mortars [22] at the Vituri (Fig. 1) and Bethlehem (Fig. 3) Bastions and at the fortification masonry facing the National Stadium (Fig. 2).
- On the recent industrial monument (19th c. AD) of the Tobacco Cutting Factory situated in the center of the historic Heraklion market nearby the seaboard. More specifically, the Northern (Fig. 4 north-western, Fig. 5 Northern Facade on the center) and the Western Facade (Fig. 6) were examined, as well as the garden wall surface (Fig. 7).
- Building stones vary :
  * from biomicritic calcarenites (sub-yellow to white-yellow, compact enough, comprised of small clastic grains of quartz dispersed in the main biomicritic calcareous mass),
  * to bioclastic lime-stones (porous calcarenites among grey-yellow and brown-grey comprised of fossiliferous clasts and porosity augmenting up to 35%, when calcareous sandstones are concerned),
  * or, marly fossiliferous limestones (white-yellow to grey-yellow compact stones, of low porosity, comprised mainly of a calcareous matrix enriched by argillaceous compounds, embedded by fossiliferous clasts and quartz) [21].

Results and Discussion

The ultrasonic method can be used for the determination of the weathering depth of a mortar or a stone unit investigated on surface level. In this case, the first part of the diagrams corresponding to the exterior layer presents lower velocity until the infiltration depth. Then the velocity becomes higher, corresponding to the sound part of the building unit. Actually, at the Heraklion fortification site 1 (Vituri Bastion/OANAK) the U.S comparative Diagram 1, shows that building stones are more durable that the mortar and less weathered i.e. in smaller depth.

The same observation accounts for the Heraklion fortification site 2 (National Stadium) as shown in the U.S comparative Diagram 2.

The lower velocity and the higher depth could be explained by the weathering mechanism of the mortar. Dissolution of the calcitic binder is taking place along with Ca^{2+} depletion at the outer sound zone due to the Ca^{2+} diffusion towards the outer surface. This phenomenon, as far as mortars are concerned, is happening in rather higher velocity than in the limestones, due to the more active and finer crystallized calcite cementing material of the mortar.

The lime - cement restoration mortars are more durable to acid attack, by the salts solution in the masonry as shown by the higher velocity at the sound part - U.S comparative diagram 3 - in relation to the old mortar - diagram 2. However, the restoration mortar presents lower velocity as compared to the limestones in the masonry – diagram 3.

Regarding Tobacco Cutting Factory, the U.S comparative Diagram 4, shows that all the old mortars at the Northern Facade present lower velocity than the new ones, at the relative layers. This is attributed to the different damage level, as well as to the most porous microstructure of the old mortars. The later, can explain the lower velocity, which is observed at the inner part, which may be characterized, as more durable. The U.S velocity regarding new mortars at the sound inner part is relatively lower than that of the fossiliferous bioclastic calcarenite, while at the weathered outer zone the velocities are more or less coinciding.

At the Western Facade the old sound mortars present velocities relative to these of the new mortars and the limestones at the inner depths. However, the weathered friable old mortars present dramatically different velocities, due to the more porous microstructures. As far as crushed-brick-lime mortars in the garden wall are concerned, they present the same velocities as lime-cement restoration mortars, as expected by their similar elastic behaviour, studied exhaustively in other works. [3]

Finally, it is clear that apart from the different elastic behavior at the inner part and the different weathering depths estimated, U.S measurement all alone can not discriminate incompatible materials on the masonry, or different mortar types.

Hence, a combined interpretation of these results along with these of IR Thermography and FOM is performed.

In figure 1 Fibre Optics Microscopy shows a masonry comprised by compact limestone (FOM 2) and of a relatively coherent but more porous old mortar (FOM 1). Actual interventions by cement-restoration mortars are observed even macroscopically.

IR Thermal images show a different respiration / evaporation behavior of the joint mortar i.e. cold building stones and hot joint mortars among which the old ones attain nearer temperatures to the stones (violet to blue), while the cement mortars achieve much higher temperatures (red to yellow), due to their impermeability to salt solutions (FOM 3)..

In Figure 2 Fibre Optics Microscopy (FOM 3) shows the same compact limestone but with colour variations due to iron oxidized phases.

These allocated building stones may be distinguished at the Thermal Images at the bottom of the masonry by hotter colours, due to their composition (higher emmissivity). Old dissaggregated crushed brick – lime mortars (FOM 5) are observed, along with the cement restoration mortars (FOM 4).

Along the height of the masonry - Thermal Image 4 - presents the evaporation zone, where salt solution's evaporation and crystallization promote massive disaggregation at a certain height (~2/3 of the wall - Natural Photo 3). At this part, Thermal Image 4 distinguishes the various damage levels by different colours: the more deep parts with colder ones and the outer with hotter. Disaggregated old mortars behave in the same way, while at the outer part of the masonry (Thermal Image 5), new cement restoration mortars are discerned by hot yellow lines.

In Figure 3 the new mortars (FOM 6) are observed in the Thermal Images 6 and 7 - rendering the Natural Photos 4 and 5 - by hotter colours (violet to yellow), as compared to the colder ones of the stones, indicating an incompatible percolation by soluble salts.

In Figure 4, at the Northern Facade of the Tobacco Cutting Factory, the new cement mortars observed (FOM 7) are rendered by the Thermal Images 8 (bottom), 9 (middle), 10 (up) by hotter colours than the stones, presenting higher impermeability to salt solution as expected. Hence, incompatibility to water percolation is induced in the masonry by this restoration intervention, overloading building stones with humidity. As a result, the yellow saturated limestone (T1d) presents lower U. S. velocity than the fossiliferous limestone (T1c), which due to its composition and texture is less wet.

In figure 5, at the center of the Northern Facade of the Tobacco Cutting Factory, old and new, weathered and sound mortars (U. S. 14, 15) co-exist rendered by various colours in the Thermal Images 11, 12. The more weathered old mortars by colder colours (deep violet-blue), the sound old mortars by intermediate (light violet) colours, while the cement impermeable mortars by (red-yellow) hot colours. The same interpretation applies to site 4, where diminishing damage levels of old mortars (U.S. Diagrams 18, 19, 20) are presented by increasing temperature scale of colours, while cement restoration mortars, plastered on the masonry, present hot red - yellow spots.

On the Garden Wall, Figure 7, old white mortars are observed (FOM 9) as well as cement and dust - brick restoration mortars (FOM 8, 10). The old mortars present lower velocity and higher weathering depth as compared to the new restoration ones, interpreting thus the Thermal Images 15, 16, where old mortars are deemed as more compatible (violet to blue) to the blue building stones, while cement plastered on the masonry develop red to yellow spots.

Conclusions

The combined use of the above non-destructive techniques leads to conclusions regarding :

- The weathering depth and the damage level of ancient mortars (U.S) measurements, as classified per mortar type and microstructure (FOM) observations.
- The compatibility of restoration mortars and plasters with the original building materials on the historic masonry scale, related to :

* The elastic moduli of the various types of historic and restoration mortars (comparative study by US),
* The physico-chemical behaviour of the capillary systems of the various building materials, governing the percolation and evaporation of salt solutions within the historic masonry (evaluation by IR-Th).

Finally, it is indicated that the longevity of the historic masonries might be investigated as a function of these behavioral patterns on the scale of the masonry by non-destructive techniques.

References

1. Moropoulou, A., Bakolas, A., Bisbikou, K., *"Physico-chemical adhesion and cohesion bonds in joint mortars imparting durability to the historic structures"*, **J. Construction and Building Materials,** (1998), in press.
2. Papayianni, I., *"Durability lessons from the study of old mortars and concretes"*, **P.K. Mehta Symposium on Durability of Concrete,** Conference Proceedings, 23 May 1994, Nice, France (1994), 16 p.
3. Moropoulou, A., Cakmak, A.S., Biscontin, G., *"Crushed brick lime mortars of Justinian's Hagia Sophia"*, **Materials Issues in Art and Archaeology V**, edited by J.R. Druzik and P.B. Vandiver, Publ. Materials Research Society, (1996), pp.317-322.
4. Moropoulou, A., Biscontin, G., Theoulakis, P., Bisbikou, K., Theodoraki, A., Chondros, N., Zendri, E., Bakolas, A., *"Study of mortars in the Medieval City of Rhodes"*, **Conservation of Stone and Other Materials**, edited by M.J. Thiel, RILEM-UNESCO, Publ. E&FN SPON, Chapman & Hall, Paris, Vol. 1 (1993), pp. 394-401.
5. Moropoulou, A., *"Reverse engineering to reveal traditional technologies: A proper approach for compatible restoration mortar"*, **PACT, Journal of the European Study group on Physical, Chemical, Biological and Mathematical Techniques Applied to Archaeology,** Vol. 52 (1998).
6. Moropoulou, A., Biscontin, G., Bisbikou, K., Bakolas, A., Zendri, E., *"'Opus Caementicium' Mortars and Plasters in a Heavily Polluted Marine Atmosphere"*, **Il Cemento**, Vol. 92, (1995), pp. 261-278.
7. Moropoulou, A., Koui, M., Tsiourva, Th., Kourteli, Ch., Papasotiriou, D., *"Macro - and micro- non destructive tests for environmental impact assessment on architectural surfaces"*, **Materials Issues in Art and Archaeology V**, edited by J.R. Druzik and P.B. Vandiver, Publ. Materials Research Society, (1996), pp.342-352.

8. Moropoulou, A., Koui, M., Kourteli, Ch., Papasotiriou, D., Theoulakis, P., Tsiourva, Th., Achilleopoulos, N., Karakantas, Ch., Romanos, A., Tokatlidou, K., Koliadis, Th., Zarifis, N., Van Grieken, R., Delalieux, F., Silva, B., Molina, E., Vicente, M.A., Vicente, S., Macri, F., Zezza, F., *"Techniques and methodology for the preservation and environmental management of historic complexes - The case of the Medieval City of Rhodes"*, **4th International Symposium on the Conservation of Monuments in the Mediterranean Basin**, Conference Proceedings, edited by A. Moropoulou, F. Zezza, E. Kollias & I. Papachristodoulou, Publ. Technical Chamber of Greece, Rhodes, Vol. 4 (1997), pp. 603-634.

9. Christaras, B., *"Estimation of damage at the surface of stones using non destructive techniques"*, 5th Int. Congr. on **Structural Studies, Repairs and Maintenace of Historical Buildings, STREMAH V**, San Sebastian, in Advances in Architectural Series of Computational Mechnaics Publications, Southampton, (1997), pp. 121-128.

10. Clark, G.B, *"Deformation moduli of rocks"*, **Am. Soc. Test. Mater., Spec. Tech. Publ.,** (1996) 402, p. 133-174.

11. Bakolas, A., Biscontin, G., Contardi, V., Franceschi, E., Moropoulou, A., Palazzi, D., Zendri, E., *"Thermoanalytical research on traditional mortars in Venice"*, **Thermochimica Acta**, No 269/270 (1995), pp.817-828.

12. Moropoulou, A., Biscontin, G., Bakolas, A., Bisbikou, K., *"Technology and behavior of rubble masonry mortars"*, **J. Construction and Building Materials**, Vol. 11, No 2 (1997), pp. 119-129.

13. Bakolas, A., Biscontin, G., Moropoulou, A., Zendri, E., *"Salt impact on brickwork along the canals of Venice"*, **J. Materials and Structures**, Vol. 29 (1996), pp. 47-55.

14. Torraca, G., *"Physicochemical deterioration of porous rigid building materials. Notes for a general model"*, **Il mattone di Venezia**, Conf. Proc., Venice, (1979), p. 95-144.

15. Wikler, E.M., **Stone : Properties, Durability in Man's Environment,** 2nd edition, Spring-Verlag, Wien, (1975).

16. Stambolov, T., Van Asperen de Boer, J.R.J., **The deterioration and conservation of Porous Building Materials in Monuments,** 2nd edition, ICCROM, Rome, (1976).

17. Moropoulou, A., Theoulakis, P., *"Conditions causing destructive NaCl crystallization into the porous sandstone building material of the Medieval City of Rhodes"*, **2nd International Symposium on the Conservation of Monuments in the Mediterranean Basin**, Conference Proceedings, edited by D. Decrouez, J. Chamay & F. Zezza, Publ. Museum d' Histoire Naturelle & Musee d'Art et d'Histoire, Geneva, Vol. 3 (1991), pp. 493-499.

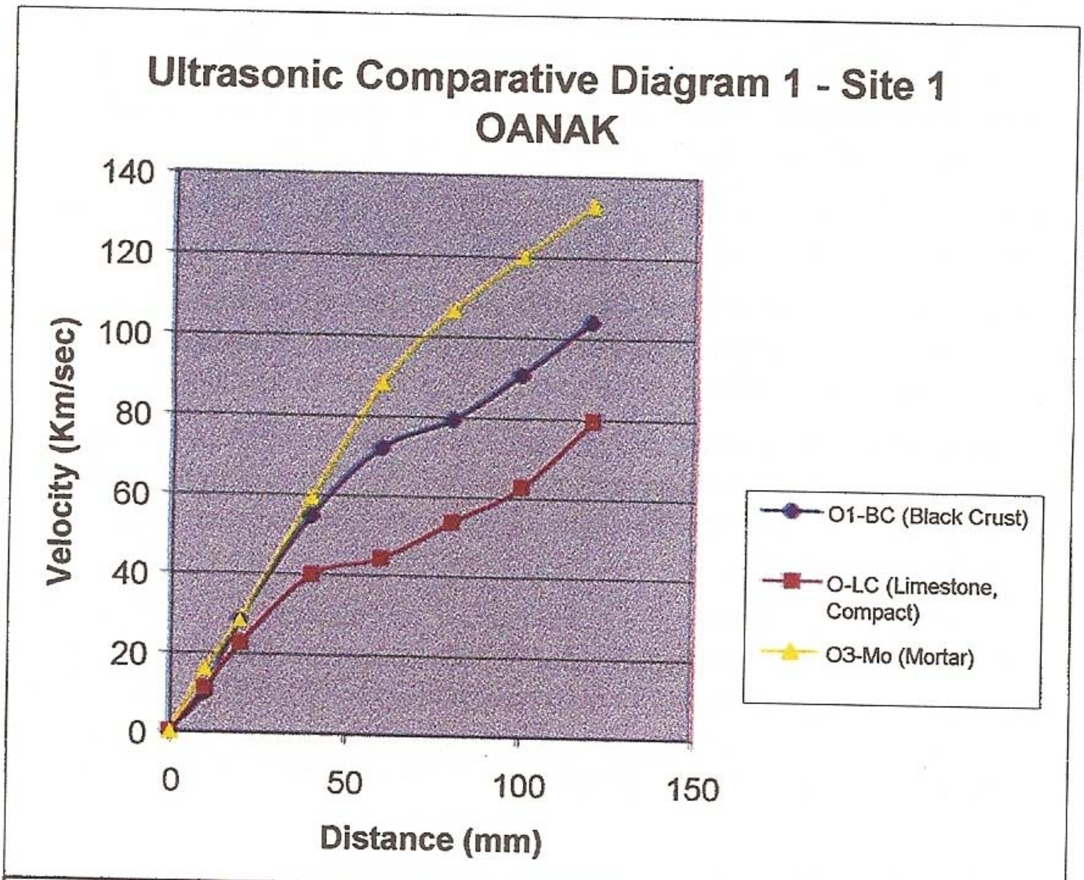
18. Ludwig,N.,Macario, F., Rosi, L., Rosina, E., Suardi, G., Tucci, G., *"L'integrazione del rilievo geometrico, termografico e stratigrafico per la conoscenza del patrimonio architettonico"*, **Scienza e Beni Culturali, XII,** Libreria Progetto Edittore Padova, (1996), pp. 279-288.

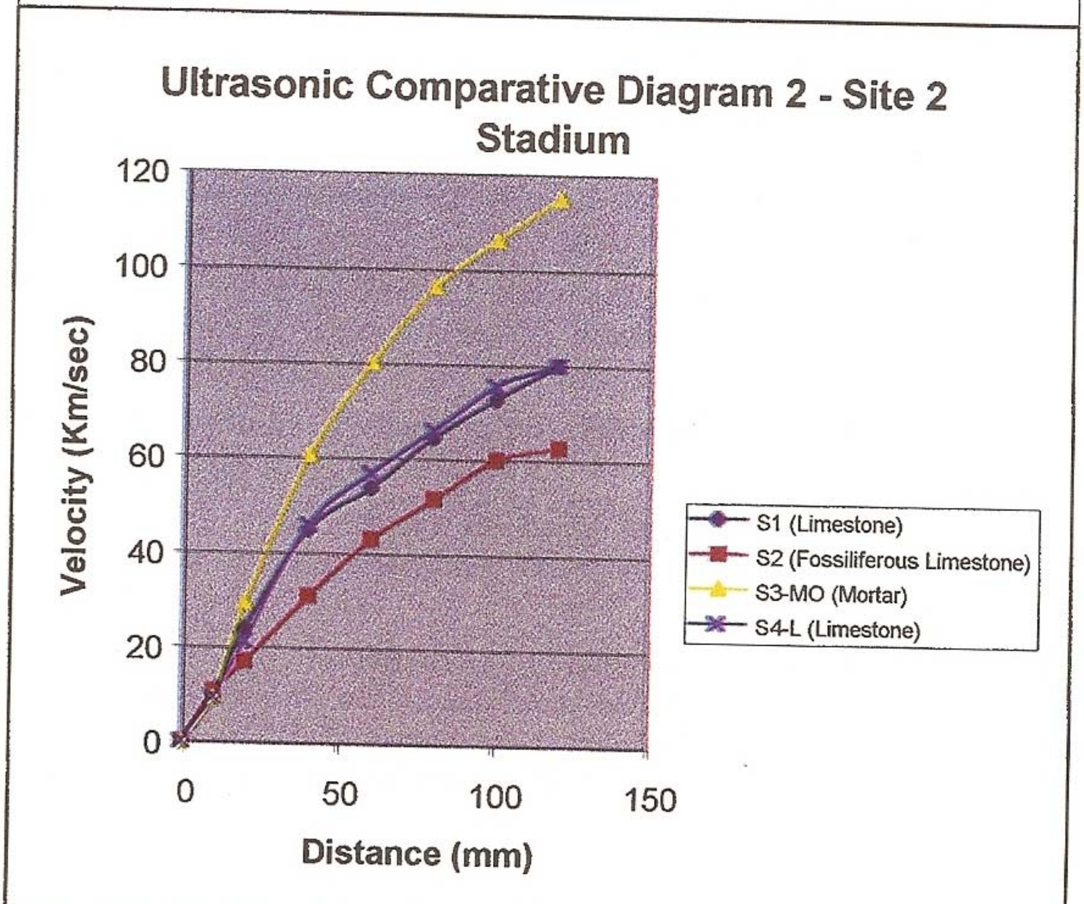
19. Gubareff, Jansen, Torborg, **Thermal Radiation Properties Survey**, Honeywell Research Center, Minneapolis, (1960).

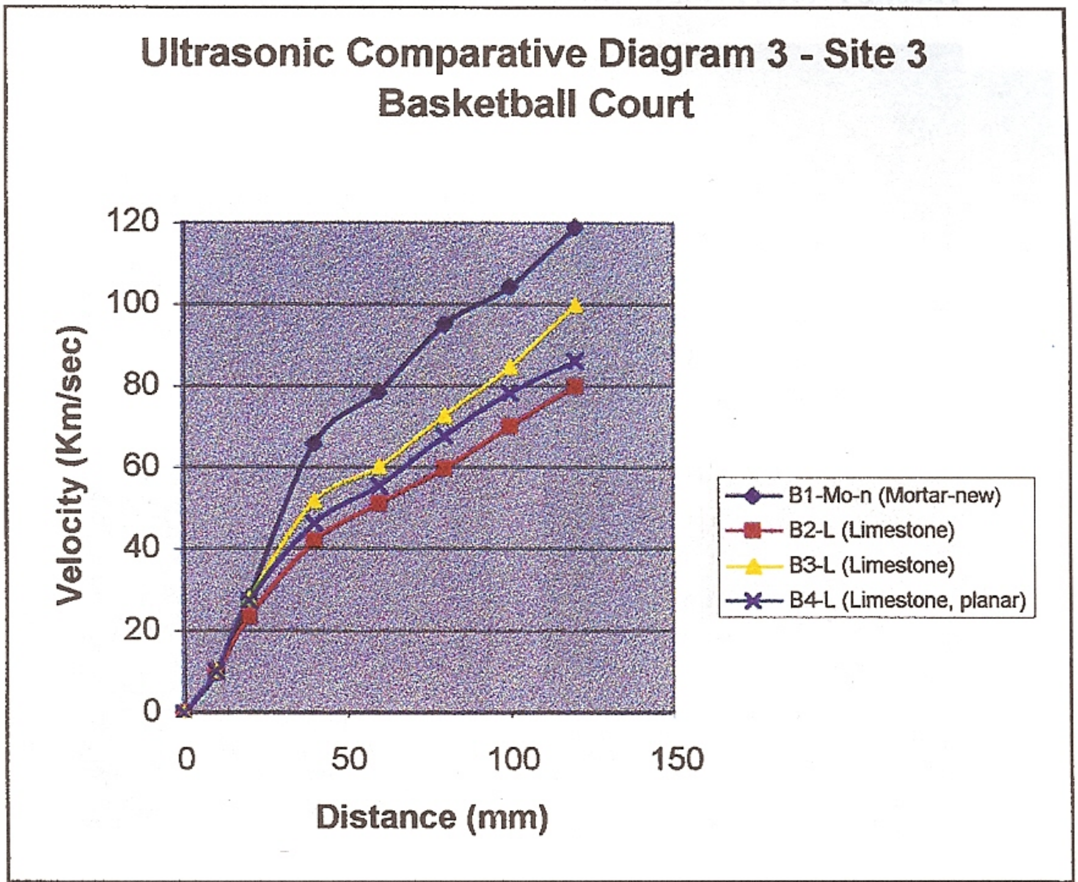
20. Goldsmith, Waterman and Hirschhorn, *"Thermophysical Properties of Solid Materials"*, **WADC**, TR58-476, Vols I-V, Wright-Patterson, Air Force Base, Ohio, (1960).

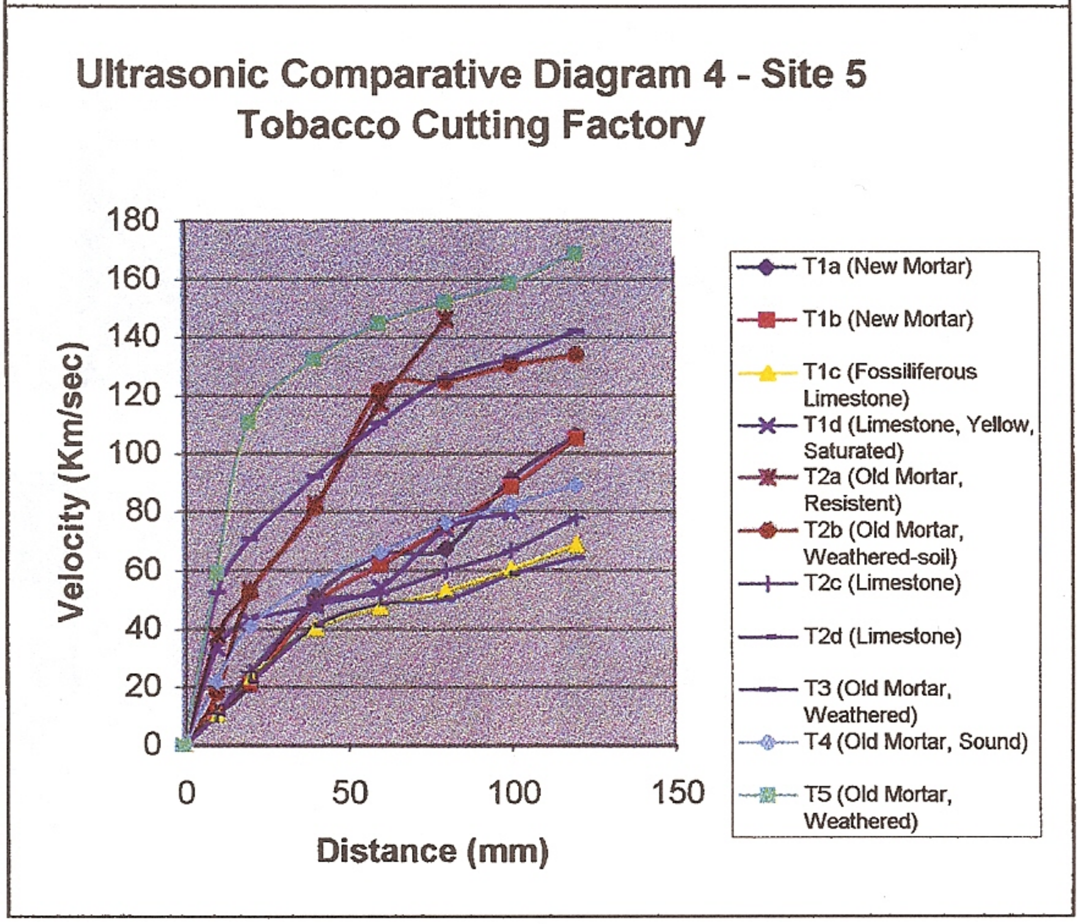
21. Markopoulos, Th., Maravelaki, P., et al., *"Corrosion of the stone facades of the Venetian Fortifications of Heraklion"*, Technical Report of the Polytechnic of Crete for the Municipality of Heraklion – Office for the Fortifications (1996).

22. Moropoulou, A., Maravelaki-Kalaitzaki, P., Borboudakis, E., Bakolas, A., Michailidis, P., Chronopoulos, M., *"Historic mortar technologies in Crete and guidelines for compatible restoration mortars"*, **PACT, Journal of the European Study group on Physical, Chemical, Biological and Mathematical Techniques Applied to Archaeology,** Vol. 53 (1998).


Ultrasonic Comparative Diagram 1 - Site 1 OANAK
Velocity (Km/sec)
Distance (mm)
140
120
100
80
60
40
20
0
0
50
100
150
O1-BC (Black Crust)
O-LC (Limestone, Compact)
O3-Mo (Mortar)


Ultrasonic Comparative Diagram 2 - Site 2 Stadium
Velocity (Km/sec)
Distance (mm)
120
100
80
60
40
20
0
0
50
100
150
S1 (Limestone)
S2 (Fossiliferous Limestone)
S3-MO (Mortar)
S4-L (Limestone)

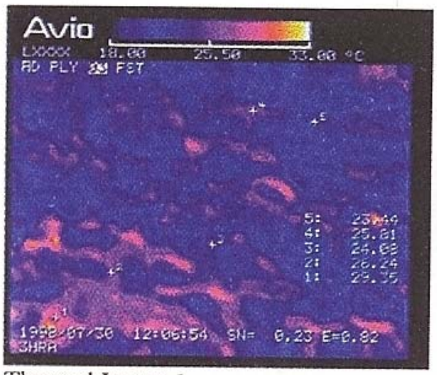

Ultrasonic Comparative Diagram 3 - Site 3
Basketball Court
Velocity (Km/sec)
120
100
80
60
40
20
0
0
50
100
150
Distance (mm)
B1-Mo-n (Mortar-new)
B2-L (Limestone)
B3-L (Limestone)
B4-L (Limestone, planar)


Ultrasonic Comparative Diagram 4 - Site 5
Tobacco Cutting Factory
Velocity (Km/sec)
180
160
140
120
100
80
60
40
20
0
0
50
100
150
Distance (mm)
T1a (New Mortar)
T1b (New Mortar)
T1c (Fossiliferous Limestone)
T1d (Limestone, Yellow, Saturated)
T2a (Old Mortar, Resistent)
T2b (Old Mortar, Weathered-soil)
T2c (Limestone)
T2d (Limestone)
T3 (Old Mortar, Weathered)
T4 (Old Mortar, Sound)
T5 (Old Mortar, Weathered)

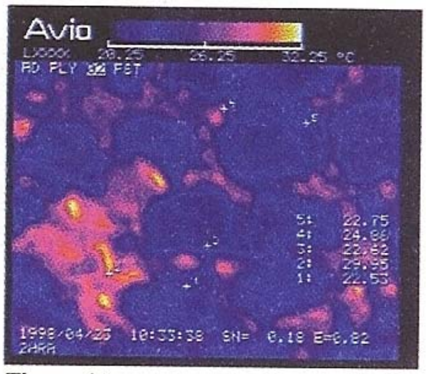
<u>**FIGURE 1 - SITE 1 - OANAK (IRAKLIO, CRETE)**</u>

Photo 1

Photo 2



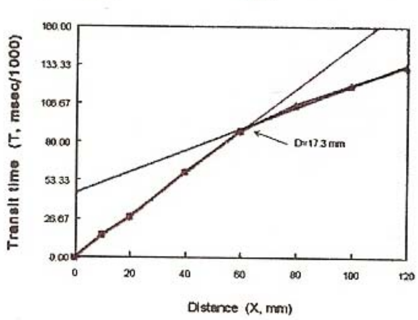
Thermal Image 1



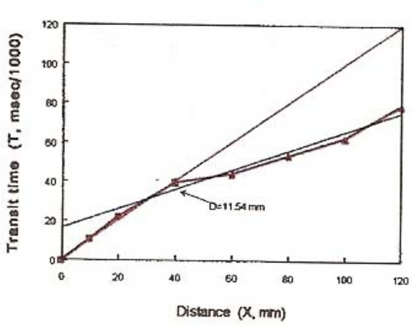
Thermal Image 2

FOM 1 Mortar (x25)

FOM 2 Limestone - compact (x25)



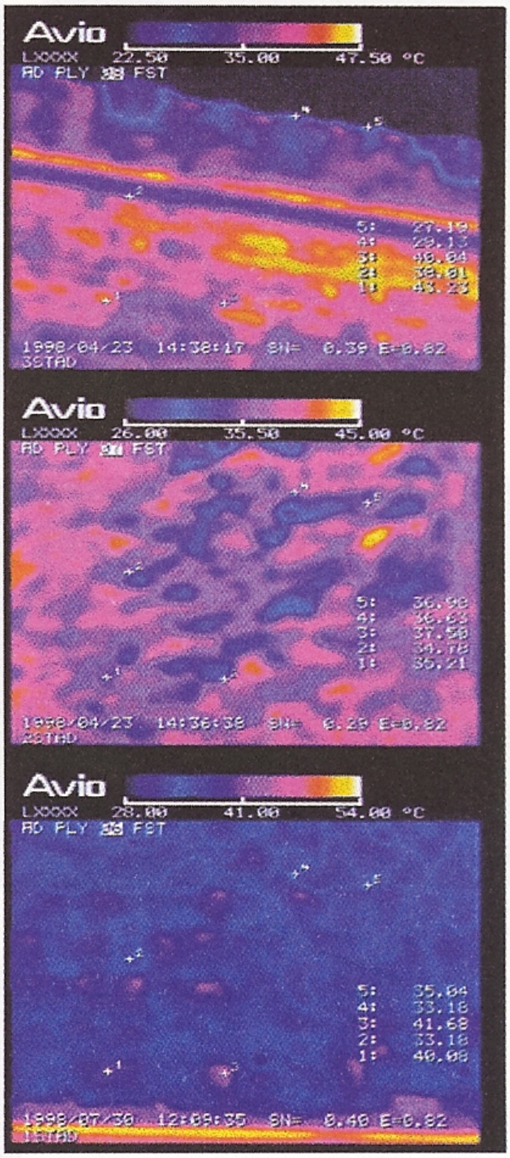
Ultrasonic Diagram 1

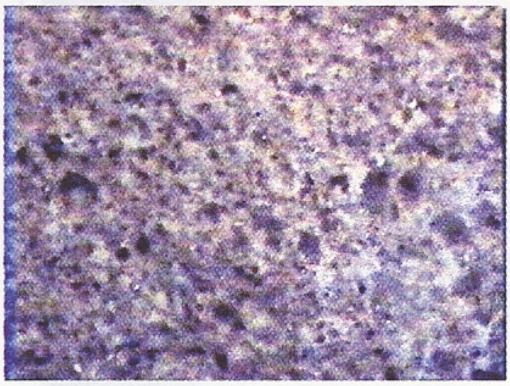


Ultrasonic Diagram 2

FIGURE 2 - SITE 2 - STADIUM (IRAKLIO, CRETE)

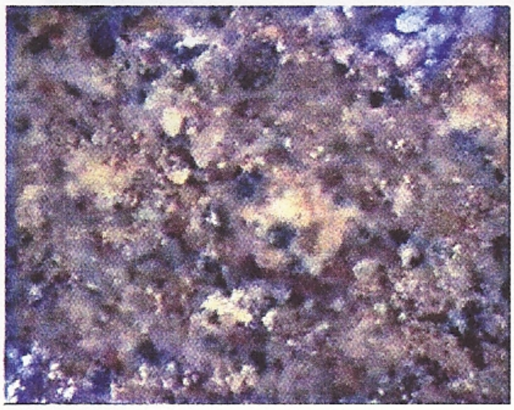
Photo 3



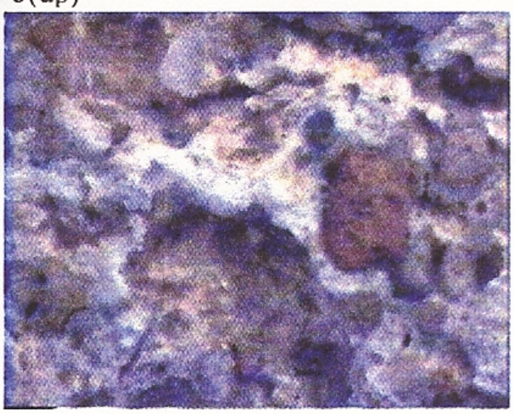


FOM 3 Limestone - compact (x25)

Thermal Images 3(bottom), 4(middle), 5(up)

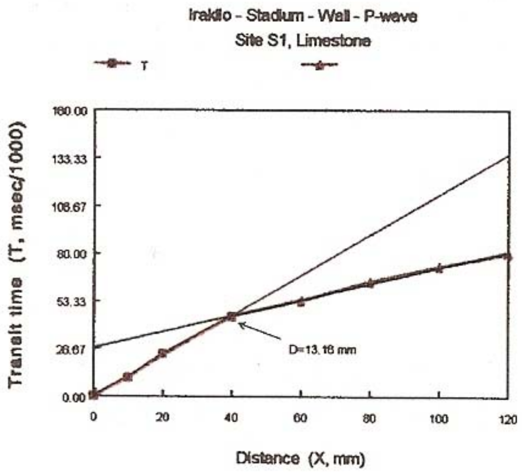


FOM 4 New Mortar (x25)

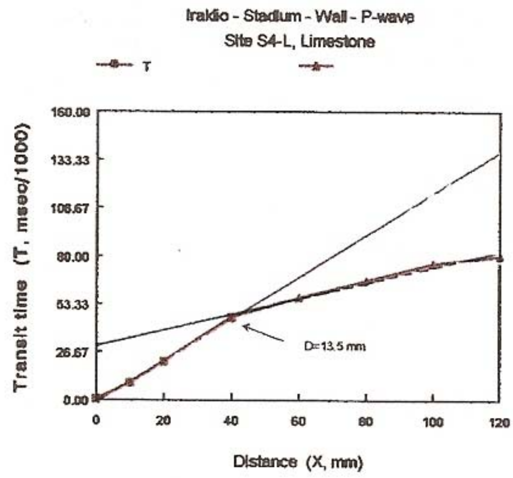


FOM 5 Old Mortar (x50)

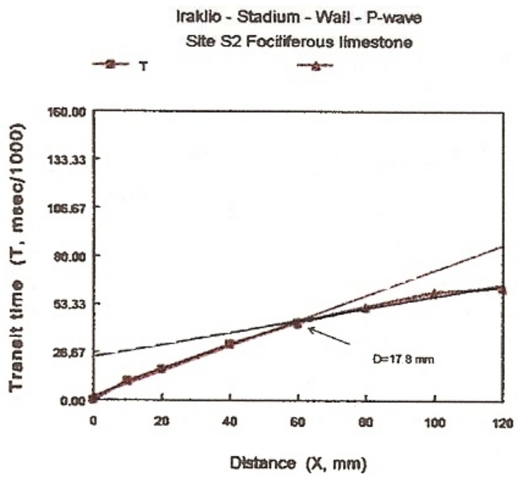
FIGURE 2 – SITE 2 – STADIUM (IRAKLIO, CRETE)



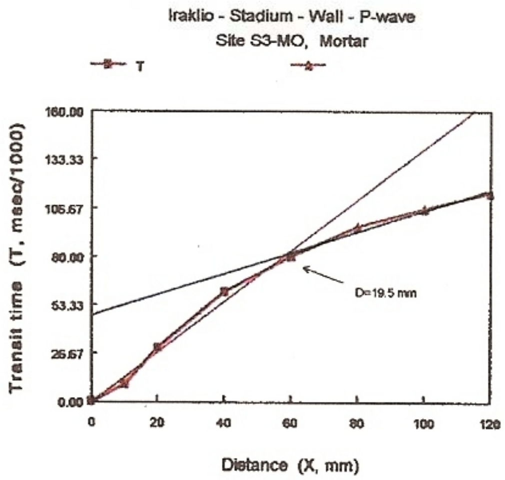
Ultrasonic Diagram 3



Ultrasonic Diagram 4



Ultrasonic Diagram 5

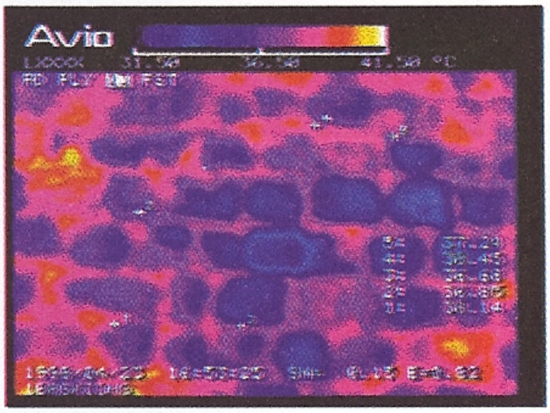


Ultrasonic Diagram 6

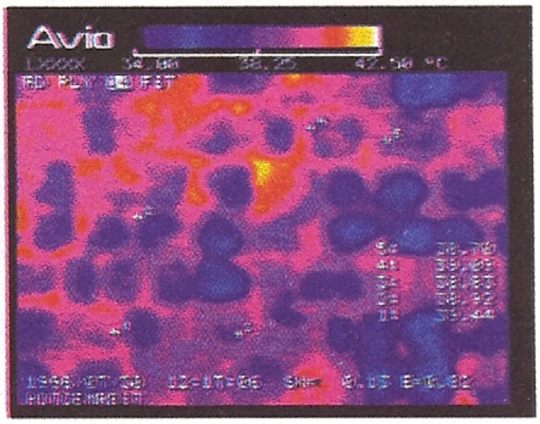
FIGURE 3 - SITE 3 - BASKETBALL COURT (IRAKLIO, CRETE)

Photo 4

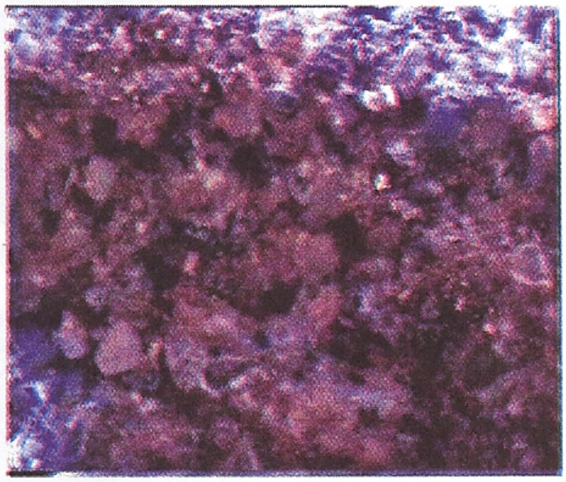
Photo 5



Thermal Image 6

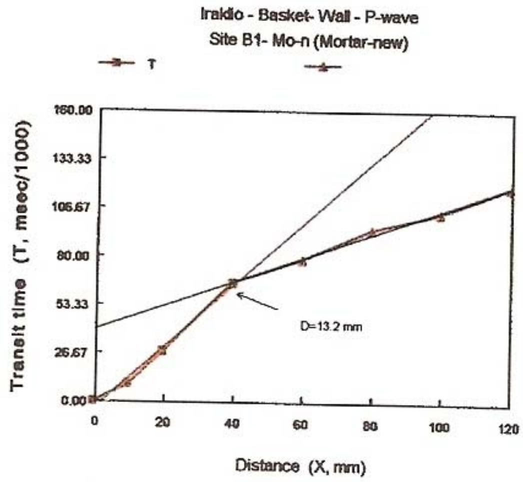


Thermal Image 7

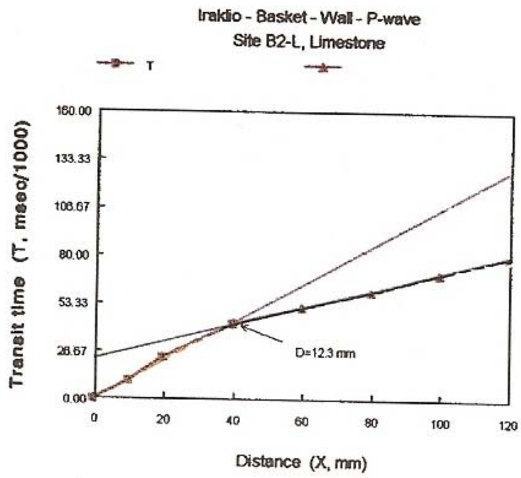


FOM 6 New Mortar (x25)

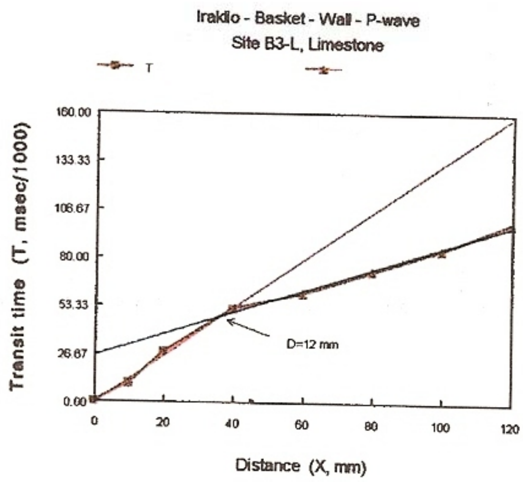
FIGURE 3 - SITE 3 - BASKETBALL COURT (IRAKLIO, CRETE)



Ultrasonic Diagram 7



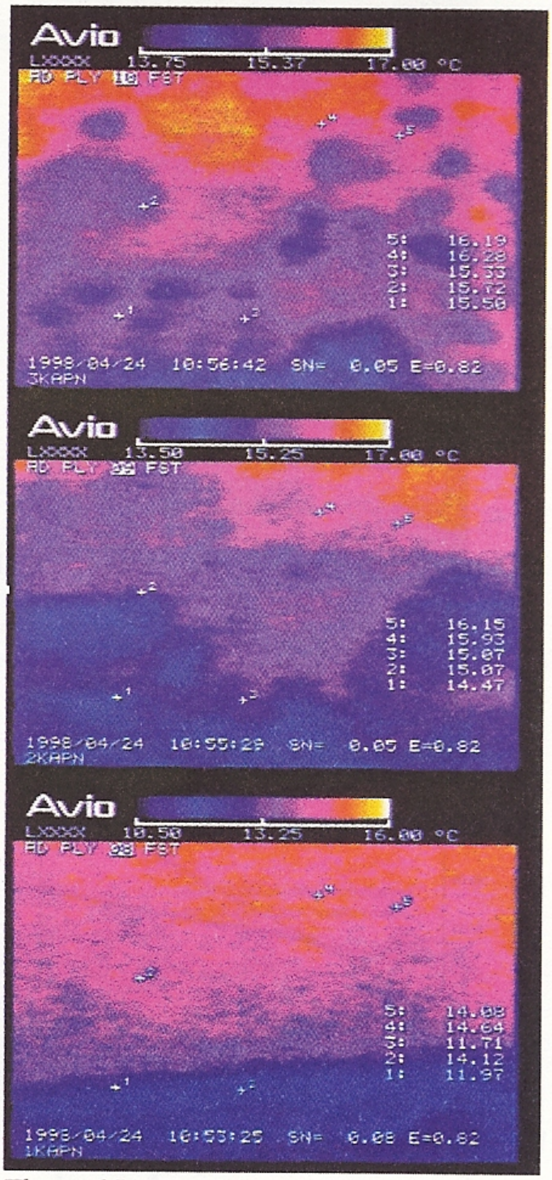
Ultrasonic Diagram 8



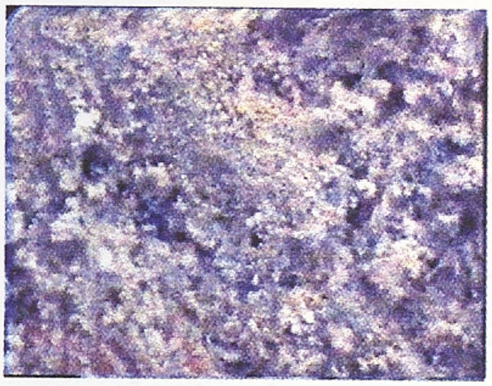
Ultrasonic Diagram 9

FIGURE 4 - SITE 5 - TOBACCO CUTTING FACTORY (NORTH) (IRAKLIO, CRETE)

Photo 6 (bottom), 7 (up)

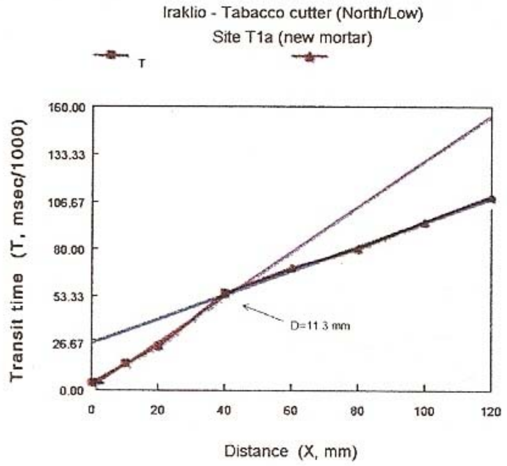


Thermal Images 8(bottom), 9(middle), 10(up)

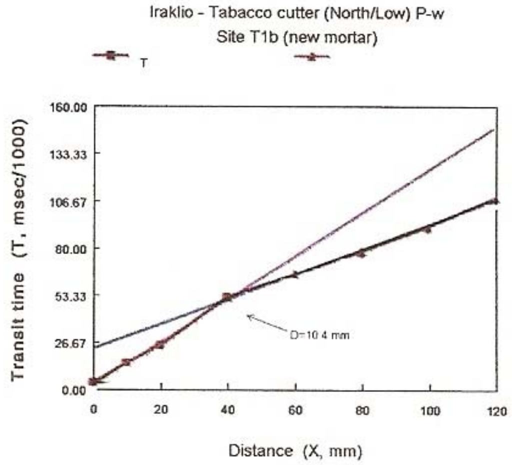


FOM 7 New Mortar (x50)

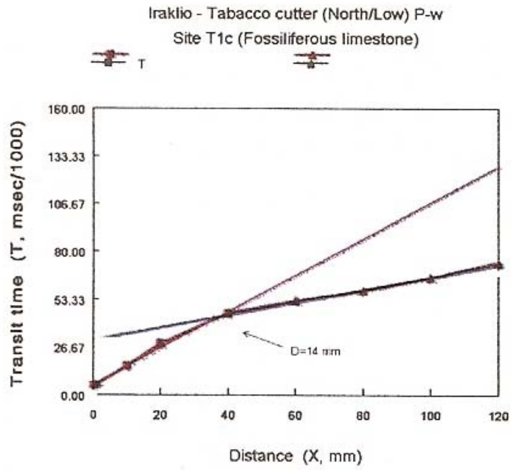
FIGURE 4 - SITE 5 - TOBACCO CUTTING FACTORY (NORTH) (IRAKLIO, CRETE)



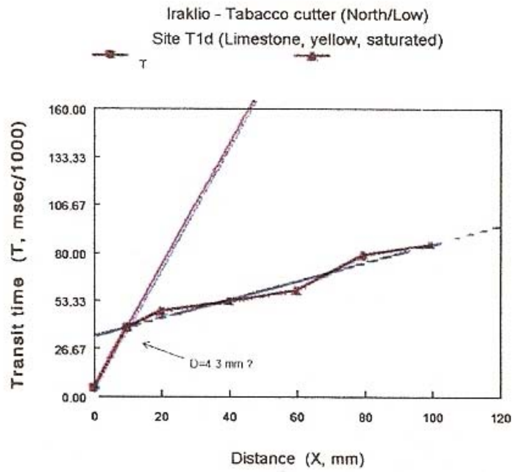
Ultrasonic Diagram 10



Ultrasonic Diagram 11



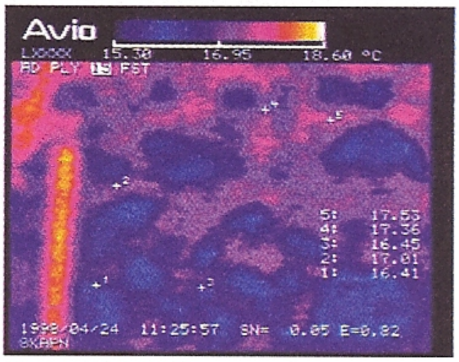
Ultrasonic Diagram 12



Ultrasonic Diagram 13

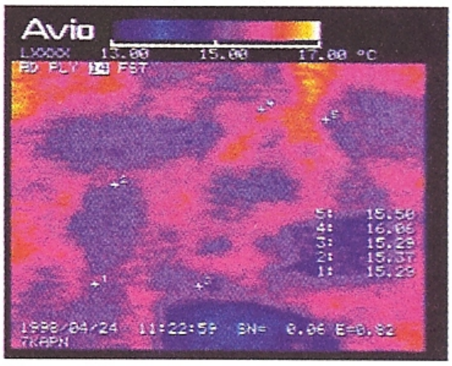
FIGURE 5 – SITE 5 – TOBACCO CUTTING FACTORY (NORTH/CENTRE) (IRAKLIO, CRETE).

Photo 8

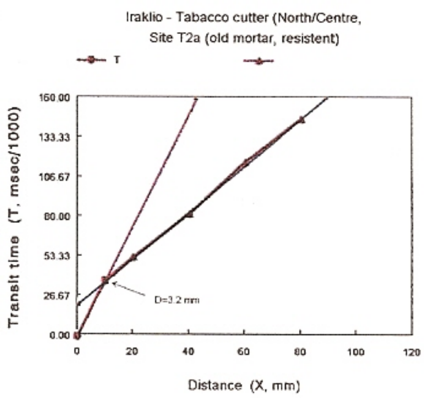


Thermal Image 11

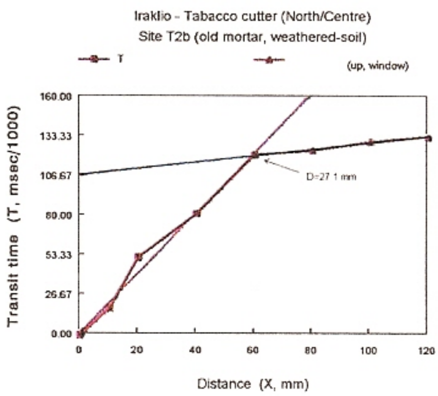
Photo 9



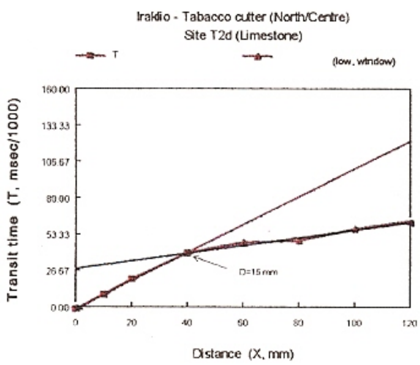
Thermal Image 12



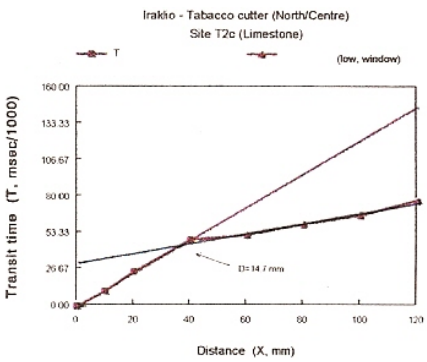
Ultrasonic Diagram 14



Ultrasonic Diagram 15



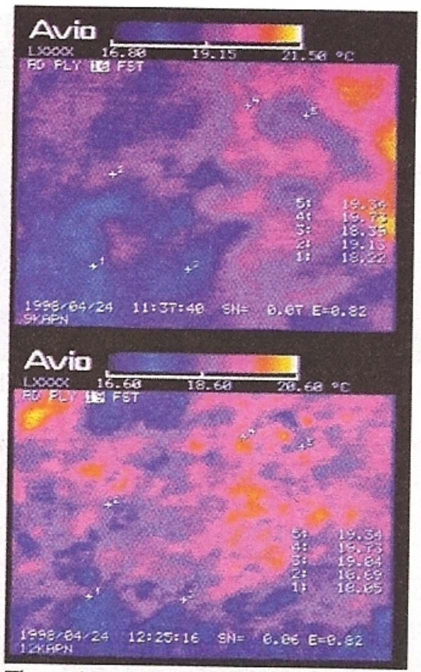
Ultrasonic Diagram 16



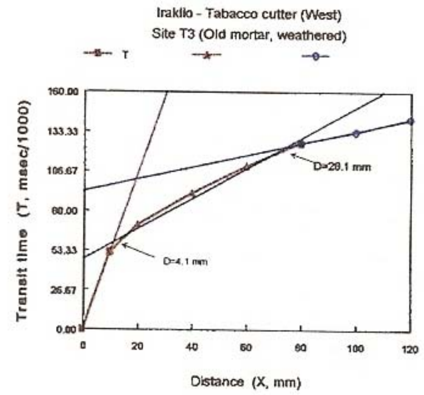
Ultrasonic Diagram 17

FIGURE 6 – SITE 5 – TOBACCO CUTTING FACTORY (WEST) (IRAKLIO, CRETE).

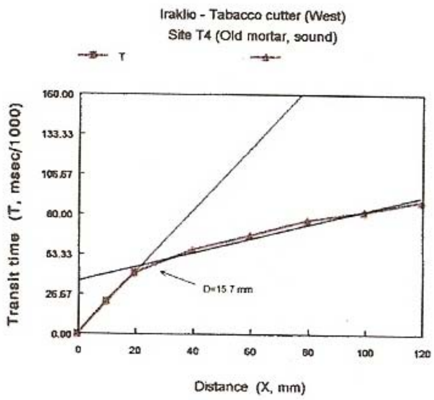
Photo 10



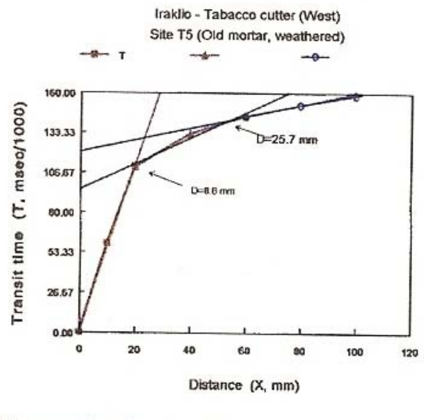
Thermal Images 13 (up), 14(bottom)



Ultrasonic Diagram 18



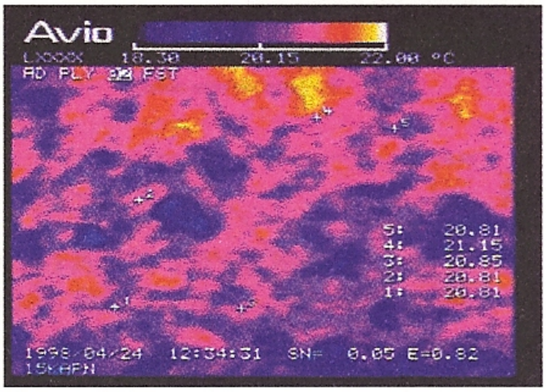
Ultrasonic Diagram 19



Ultrasonic Diagram 20

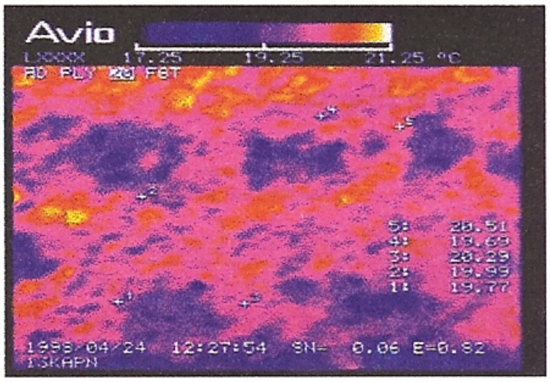
FIGURE 7 – SITE 5 – TOBACCO CUTTING FACTORY (GARDEN WALL) (IRAKLIO, CRETE).

Photo 11

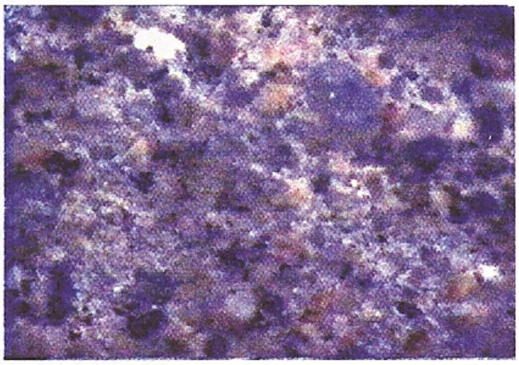


Thermal Image 15

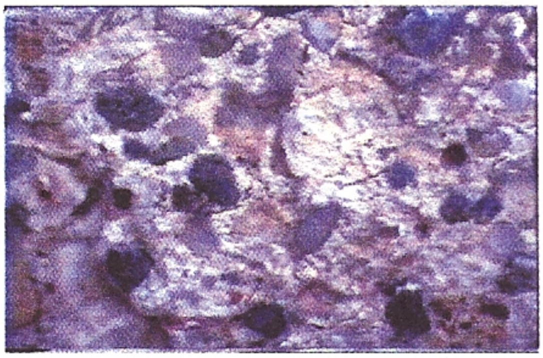
Photo 12



Thermal Image 16



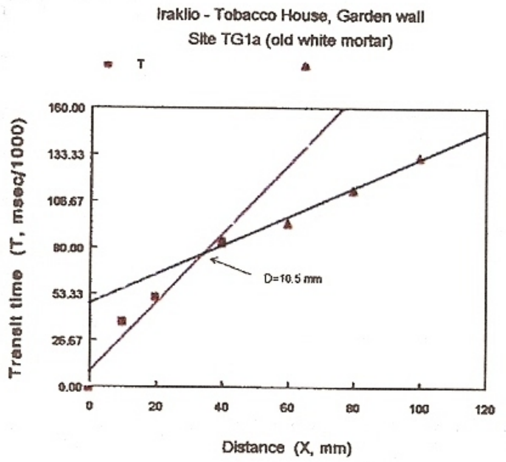
FOM 8 Mortar - Cement (x50)



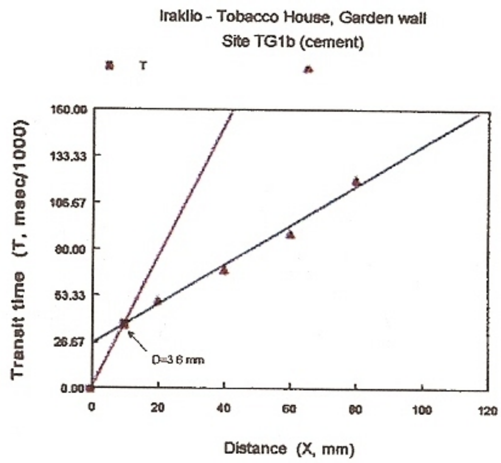
FOM 9 Mortar - White (x50)

FOM 10 Mortar - Red (x50)

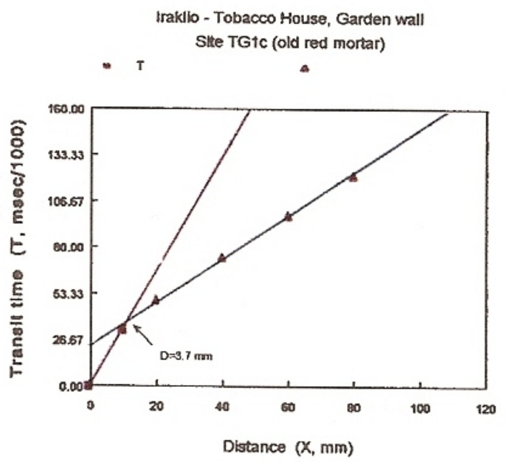
FIGURE 7 – SITE 5 – TOBACCO CUTTING FACTORY (GARDEN WALL) (IRAKLIO, CRETE).



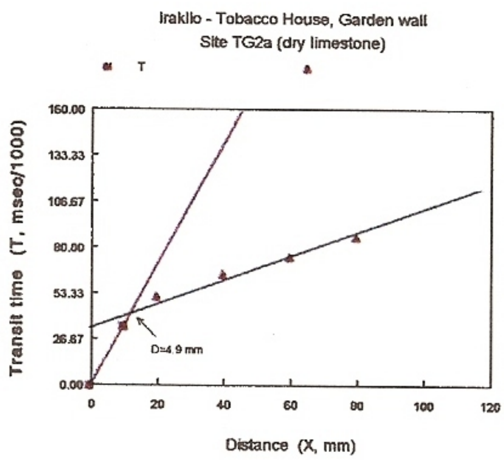
Ultrasonic Diagram 21



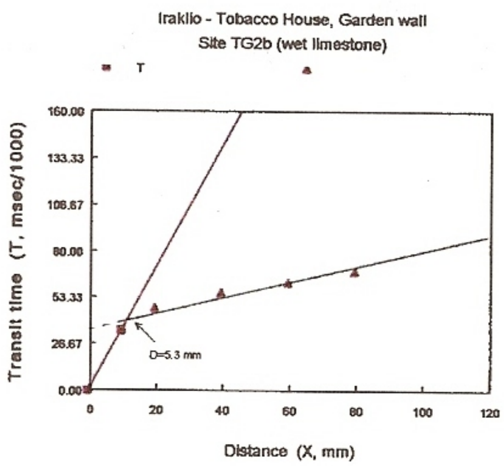
Ultrasonic Diagram 22



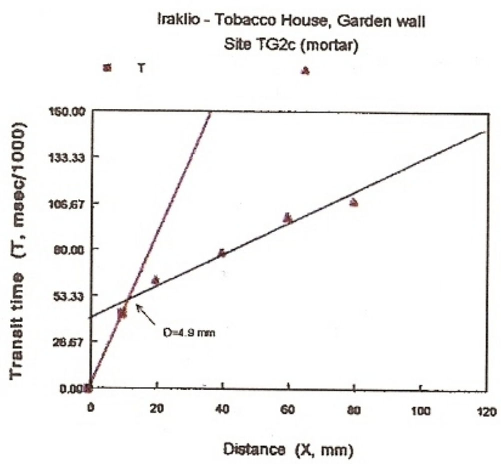
Ultrasonic Diagram 23



Ultrasonic Diagram 24



Ultrasonic Diagram 25



Ultrasonic Diagram 26