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Weathering phenomena on the Hagia Sophia Basilica Konstantinople

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Abstract

Materials' deformation under mechanical loads and stresses can not be studied without considering insidious mechanisms like microstructural and physicochemical degradation due to weathering.In the present study weathering phenomena and construction materials are examined in situ by macroscopic observations, according to parallel experience gained on the field in Roman and Byzantine churches with similar materials degrading in mild Mediterranean climate, in an intense humid and marine environment with prominent problems of urban pollution, specifically due to traffic.

The presence of harmful soluble salts such as sulphates and chlorides of Ca, Mg and Na, in pore water and reactions with atmospheric pollutants, are among the main factors of stone decomposition.

In the present study the parallel analysis of materials, used to Hagia Sophia according to historic evidence, like the paleochristianic tiles of Rhodes, providing clues for authentic ceramic technologies and consequent behaviour in environmental loading, was employed.

Following X-ray Diffraction Analysis, Infra - Red Spectrometry, Energy Dispersive X-ray Analysis, Scanning Electron Microscopy, Optical Microscopy and microstructural examinations, a tile quality with excellent performance to meet the Hagia Sophia structural requirements, was recognised, susceptible though to water impregnation.

Hence, the study of materials provenance, characterisation and the changes of materials properties over time seem to be a focal point in safety and conservation interventions, even in the precautionary ones, recalling the contribution of studies concerned with parallel experiences and in situ studies in a framework of interdisciplinary cooperation.

Introduction

The Great Church, Hagia Sophia of Constantinople (532-537A.D.), is famous for its architectural and artistic magnificence and complexity as well as for its complex problematic in restoration through the centuries. The first restoration work began, as well known, very early, already a little after its erection with the collapse of the Great Dome in the year 558 A.D.. The today- restoration efforts have to face wider spectrum of problems and need a broad cooperation and all existing experiences concerning the great monument itself as well as other parallel investigations in its geographic area with similar problems. How necessary is such a cooperation is obvious, after the last investigations concerning the monument presented in : " Hagia Sophia, from the Age of Justinian to the present, ed. by R. Mark and A. Cakmak, Cambridge University Press, 1992" especially the contributions referring in relevant buildings of Thessaloniki (pp. 83-99 and 132-157).

The present study has a similar character. It concerns with the weathering phenomena on a common material, the bricks, used in monuments of the island of Rhodes as well as in Hagia Sophia of Constantinople at the same century, that after a useful base for comparison in both places. Our research started some years ago, aiming at the study of weathering phenomena and construction material of the bricks (titles) on the island of Rhodes. The connection to Hagia Sophia is based on the description of the byzantine source "Diegesis" (Narration), dated in the ninth century, which refers to the construction of the Dome and other parts of our monument before and after its collapse in 557 A.D. The relative information of the "Diegesis" has as follows :

"...Special light bricks are now ordered from the island of Rhodes weighing one-twelfth the weight of normal bricks, and they are used to build the four main arches and the dome. They are laid twelve courses at a time, and then a hole is made for the insertion of holy relics. The structure is thus completed..." (C.Mango, p.47). The same material seems to be used some years later, after the strong earthquake of 557 A.D., according to the same historical source :

"...on the advice of experts, a new consignment of light-weight bricks is ordered from Rhodes and the Dome is rebuild..." (o.p.c., p.48).

The above is confirmed by Hidaka, Aoki and Kato (Kato, S., Aoki, T., Hidaka, K., and Nakamura, H., 1992) who in their attempt to represent cross sections of the first and second domes clarify the structural superiority of the second dome. Since both static analysis and the recorded survival of the first dome in 558 AD, unharmed except for that part of it that had been deprived of support below, show that it was adequately stable in itself, the true structural superiority of its successor could lie only in its reduced thrusts on the supports.

Thus, we have to examine the same material, which was applied in Hagia Sophia as well as in the Great Basilica Church of Rhodes, both dated in sixth century. Our investigation is also extended in other monuments of the island, e.g. Saint Katherine's building (Knight's period, 14th century), which is repaired later by the Ottomans (17th century), where the early " coccio pesto" (mortar with brick dust) has been restored by the Turkish "Kourasani". In the following we present the main results of our investigations .

Historic evidence on the construction materials and their behaviour

Many questions have been raised about structural behaviour under environmental loading over almost fifteen centuries and about present safety in the face of future earthquakes.

Current modelling proposals (R.Mark, A.Cakmak, and M.Erdik, 1992) directed to the analysis of the structural behaviour acknowledge the impossibility of establishing directly the relevant material properties. Most contribution details and aspects of the present structural condition - materials used, bonds and lacks of bond, cracks and separations - are unrecorded and hidden from view behind surface renderings and revetments.

It is equally clear that the present structure contains work of many periods, which has undergone different past loading. Evidence of this is provided (R.Mainstone, 1988) by the presence of masonry of markedly different characters, by documentary records of past partial collapses and partial rebuildings, additions, and consolidations, and, less directly, by incompatible deformations.

Van Nice's observations (Van Nice, 1986), coupled with Mainstone's (R.Mainstone, 1988) probes in carefully selected positions, leave no doubt that none of the major supporting elements is a continuous homogeneous mass. There are numerous unbounded joints and changes of material as well as far more numerous internal surfaces of weakness in both brick work and ashlar masonry. And there is extensive cracking throughout, sometimes accompanied by relative rotations or slips of the adjacent masses. This cracking includes separations at joints (both full separations and the splayed ones typically seen in arches), separations due to primary tension failures (around the bases of the dome and semidomes), and splitting of the masonry blocks of the piers under the tensile stresses that inevitably occur at right angles to the primary compression (especially where there are local concentrations of this compression due to uneven bearing between blocks).

However, the study of materials provenance, characterisation and of the changes of materials properties over time seem to be a focal point in safety and conservation interventions, even in the precautionary ones.

Materials deformation under mechanical loads and stresses or even thermal strains cannot be studied without considering insidious mechanisms like microstructural and physicochemical degradation due to weathering. In the present study weathering phenomena and construction materials are examined in situ by macroscopic observations, according to the experience gained on the field in Roman and Byzantine churches with similar materials degrading in mild Mediterranean climate, in an intense humid and marine environment, with prominent problems of urban pollution, specifically due to traffic.

However, historic sources (Salzemborg 1854) provide evidence for materials from all Greece, Minor Asia and all over Mediterranean basin.

Concerning marble revetments, the green marble of Karystos, the rose-coloured from Frigia, the red Syinitis from Egypt, the green marble of Lakonia, the buff Iassikos from Karia, the white-yellowish marble from Lydia, the goldish marble from Libya, the melan Keltic, the honey-coloured Onyx, the green Attraceous from Thessalia, the white marble from Prokonisos and the grey-coloured marble from Vosporos are named.

This integrated materials resistance study is indispensable, not only for a proper restoration - conservation intervention but for a proper estimation as well as of the construction behaviour facing a future earthquake.

In the event that any structural intervention is decided upon, it should be kept in mind that the aim of the restoration is to preserve and reveal the aesthetic and historical value of the monument and is based on respect to original materials and authentic structures. This imposes on the specialists responsible for the restoration a duty to consider what limitations these considerations place on the choice of methods and materials of repair and strengthening, according to the principles of the UNESCO and ICOMOS international methodology and ethics.

The key to the choice of materials is the classification of the restoration techniques into two: reversible and irreversible. Materials used in reversible interventions usually impose very few restrictions. In contrast, materials used in irreversible interventions impose the following two additional restrictions: compatibility of the new materials with the original ones and very long term durability of the new materials. These restrictions necessitate a thorough knowledge of the properties for the original materials, so that they can be used as a guide to the choice of materials for repair and strengthening. It is generally accepted that the best way to satisfy the requirements for compatibility and durability is to choose "traditional materials" for restoration.

From the above point of view, original materials provenance and characterisation is of importance. Even recent studies provide clues for their superiority, concerning structural and design problems concerned. The sixth century form of Hagia Sophia is considered (Mainstone 1992) as the paradigm of ameliorated design and structure, after the main 562 AD rebuilt.

In order to face the complexity of Hagia Sophia, structural and architectural analogous of simpler structures from late Roman domed Rotundas to the typical later domed Byzantine church, are serving, with all the relevant imperfections, as parallel guide studies to quasi static analysis.(Penelis 1982, 1985, 1992, Theoharidou 1992)

In the present study, the parallel analysis of materials, like the early Christian tiles of Rhodes, providing clues for authentic ceramic technologies and consequent behaviour in environmental loading, was employed.

Albeit for restoration - conservation purposes, the study of the sixth century Hagia Sophia is necessary in order to disclose the authentic structures and materials, the additions, transformations and their impact to stability and resistance of constructions and materials, up to date, have to be taken into consideration.

In situ investigation
Construction Materials and Weathering Phenomena: Preliminary results

In the present investigation the Church of Hagia Sophia in Konstantinople was studied regarding the influence of weathering on the building materials consisting of rocks,mortars and ceramics.

In situ, investigation permits to recognise the construction materials and to distinguish their weathering form and state.

Concerning **masonry building materials the following are observed**:
as main building stone, biogenic porous limestone is consisted of large and fine fossils in a coherent calcitic matrix. It deteriorates through granular disintegration in the form of alveolar disease like pitting and cavities, as well as following the "striped pattern" in parallel to the layers of the rock, according to microclimatic differentiations.

These forms of stone decay are due to ground water rising by capillary effect, and to soluble salts actions (crystallisation decay). High permanent humidity in the masonry is witnessed macroscopically, as well, whereas biological attack, favoured by the water, is discernible (fig 1: a-f).

Partially, the masonry consists of characteristic Byzantine red bricks, whereas the jointing mortars of brick powder in calcitic cementing materials present a weathering out of clay galls and aggregates. The mortars have already been examined (Livingston, Stutzmann, Erdik 1992).

They contain hydraulic materials due to the brick dust and their reaction with the calcitic matrix, presenting an actual concrete behaviour. However the masonry technique with wider than the bricks mortar joints, indicates a rather concrete technology, where the bricks may act as reinforcements.
Analogous results are obtained in ST. Katherine's building in the Medieval City of Rhodes on early knight's period (14th century), repaired later by the Ottomans (17th century), where the early "coccio pesto" (mortar with brick dust) has been restored by the Turkish "Kourasani" (Moropoulou, Biscontin et als, Rilem '93, Bresannone '93).

Porosity and granulometry of these analogous mortars, as measured in the case of Rhodes, show sufficient physicochemical resistance, i.e., a lesser degree of decay in comparison with other mortars of the same period.

Black crust formation seems to characterise as a general weathering form, masonry surfaces constructed of all the building and joint materials (a,d,f), where microclimatic conditions are in favour of traffic pollutants (SO_2) and suspended particles deposition.

Hence the presence of harmful soluble salts such as sulphates and chlorides of Ca, Mg and Na, in pore water and reactions with atmospheric pollutants, are among the main factors of stone decomposition that have to be searched after sampling, laboratory analysis and in situ measurements.

Concerning **columns** in and around the church, they consist of red and grey biotite granite (figure 2: a,b,c,d), typical of the serbomacedonian mass (Kockel et al, 1977) . Although that, granite is characterised from the antiquity as the symbol of strength, given the multiphase character of the material, composed of minerals with different weathering resistance, the weathering process is accelerated. In figure 2b the plagioclase alteration is obvious in the white spots, whereas fissures are observed all over the weathered surface. Columns substituted for ophiolitic breccia (serpentinite) (figure 2: e,f), most probably in a later period, present localised alteration to talc.
The marble revetments of the four great piers supporting the Dome are identified to the ophiolitic breccia (serpentinite) to Onyx and to grey-white marble (like the Cipolino of Euvia or the Semi-white of Magnesia) (figure 3).

Fissures, cracks, deformation and detachment zones are observed, mainly on the grey-white marble surfaces (figure 3a), whereas decoloration to white and intense alterations to serpentine and to talc characterise the ophiolitic breccia. This serious decay is most probably due to the synergy of the heavy Dome loads and stresses and the high internal permanent humidity, as well as the prominent action of soluble salts.Mechanical stresses most probably do accelerate materials' degradation, which consequently tends to reduce mechanical strength.

Around the Dome the half Domes, the vaults and the soffits,_**serious problems of water penetration** are witnessed (figure 4a-f), either decolourating iconocraphies (figure 4 a,c,d), or damaging the mortar substrate (figure 4b) and weathering even up to deterioration, the famous mosaics (figure 4 e,f), mostly missing today.

Main problem, arising from the degradation of all the internal materials and objects of art is that of either the rainwater through the Dome, or of permanent wall humidity due to both, rain and capillary rising solutions.

Dome tiles characterisation and behaviour: a parallel study

However, for the protection of the Church' internals, the Dome is playing a critical role. The **Dome tiles** revealed, due to fissures and damages to the lead sheet coating, are a crucial material to study.

Dome tiles present a specific interest as construction materials. The requirements they had to meet were to be durable, but light as well. Historic sources (Kodinos,G., 1843) give evidence to miraculous yellow, porous, extremely light and coherent large tiles with which the Dome was rebuilt at its final design after 558 AD, determinated their provenance from Rhodes.

This piece of historic documentation confirms on the level of materials, what at the level of Architecture has already been a well established concept. That Hagia Sophia of Konstantinople is a monument, recalling parallel experiences to serve its conservation strategy and techniques. The characterisation and behaviour of Rhodes tiles from early byzantine monuments of the sixth century may serve as a paradigm, let alone the practical implications of a parallel study of an identical material in similar environmental conditions (mild Mediterranean climate in an intense marine environment), even though Dome reconstructions and particular material deviations are expected. The main argument of such a parallel study, confronting the serious problems of sampling is that, ceramic technology usually results to objects of apparent density around 1.6-2.0 gr/cm3 and that, values almost near the level of water apparent density (historic sources) could not but identify a rather certain composition, firing temperature and pore size distribution (Maniatis 1981, Moropoulou & Theoulakis 1993).

Sampling along the ruins of a sixth century church, the Great Early christianic Basilica of Rhodes, has taken place and the samples were examined by optical and scanning electron microscopy X-ray diffraction, infra-red spectroscopy and electron probe microanalysis (energy dispersive analysis), whereas microstructural characteristics are measured by mercury porosimetry.

As shown by optical microscopy, (figure.6) a buff sample (4-A) presenting an homogeneous, finely crystallised matrix, with oriented muscovite prevailing (a,b) can be distinguished in comparison with other buff brick samples, like 5 and 3 (c,d//), where larger inclusions of quartz, mica, but also calcite are met. Red

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bricks samples 2-B, 1-B and 4-B (e,f,g,h//) present large inclusions of calcite (e,f) in an intensively Fe bearing compounds oxidised matrix with large pores (g,h). In that specific quality among buff bricks, no free calcite in the crystalline phase is identified (table 1) by X-ray diffractometry. I-R diagrams (figure 7, table 3) show on the contrary a main peak of characteristically large surface of Al-Si compounds (table 3). This buff ceramic at scanning electron microscopy examination (figure 5) presents a rather non vitrified matrix, at the level of initial vitrification with high porosity (a,b,c) as compared to other buff (e,f) or red (d) samples, presenting higher vitrification and lower porosity, implying a low firing temperature technology no more than 750oC.

Microstructural characteristics (table 4) confirm the above results. The buff tile sample 4-A presents an extremely high ,~55% total porosity, and an unusually low, apparent density of 1.34 gr/cm3.

The mean pore radii are big enough to permit impregnation by rainwater and solutions and to trigger the argillic compounds swelling accordingly.

A high ceramic technology is acknowledged by the pore size distribution predicting durability and resistance to salt decay, as evidenced macroscopically as well (figure 8).

Hence, a tile quality with excellent performance to meet the Hagia Sophia structural requirements, according to historic evidence, is recognised. As a consequence of that composition and microstructure, serious problems can be caused like swelling and impregnation, due to the interaction with the environment and specifically rain water.

Conclusions

In situ investigations led to preliminary results concerning construction materials and weathering phenomena on Hagia Sophia in Konstantinople, as follows:

- masonry main building stone, a biogenic porous limestone ,suffers from alveolar and "stripped pattern" disease by granular disintegration and from biological attack
- partially, the masonry consists of characteristic Byzantine red bricks, whereas the joining mortars of brick powder in calcitic cementing materials present a weathering out of clay galls and aggregates
- black crust formation seems to characterise as a general weathering form, masonry surfaces.

Hence the presence of harmful soluble salts such as sulphates and chlorides of Ca, Mg and Na, in pore water and reactions with atmospheric pollutants, are among the main factors of stone decomposition that have to be searched after sampling, laboratory analysis and in situ measurements.

- Granite piers suffer from plagioclase alteration, whereas the weathered surface surface is fissured. Localised alteration to talc present columns substituted for ophiolitic breccia
- Marble revetments of the great piers supporting the Dome, consisted mainly of ophiolitic breccia and grey -white marble present fissures, cracks,

deformation and detachment zones in combination with decoloration to white and intense alterations to serpentinite and to talc.The synergy of the heavy Dome loads and stresses, the high internal permanent humidity and the prominent action of soluble salts has to be searched out.

- Iconographies decoloration, mortar substrate damage and deterioration of famous mosaics due to rain penetration through the Dome and capillary rising solutions demonstrate the critical role of Dome's material protection.

From a thorough analytical study of ceramic samples from the Great Basilica of Rhodes, from where according to historic evidence, the Hagia Sophia Dome tiles where brought in, conclusions on a rather parallel, but not identified material, were gathered.

Buff tiles of low vitrification, extremely high total porosity, a usually low apparent density with mean pore radii permitting impregnation by rainwater and solutions and triggering the argilic compounds swelling accordingly, were identified.

A high technology of ceramics to meet Hagia Sophia structural requirements was recognised, causing though serious weathering due to the environmental actions and specifically rainwater.

In the event that any structural intervention is decided upon, it should be kept in mind that the aim of the restoration is to preserve and reveal the aesthetic and historical value of the monument and is based on respect for original materials and authentic structures.

Hence the study of materials' provenance, characterisation and the changes of materials' properties over time seem to be a focal point in safety and conservation interventions, even in the precautionary ones. Materials deformation under mechanical loads and stresses or even thermal strains cannot be studied without considering insidious mechanisms like microstructural and physicochemical degradation due to weathering.

This integrated materials' resistance study is indispensable, not only for a proper restoration-conservation intervention but also for a proper estimation as well as of the construction behaviour facing a future earthquake.

In that direction, similar experiences and parallel studies of early christian and byzantine churches with identical materials degrading in mild Mediterranean climate, in an intense humid and marine environment, with prominent problems of urban pollution, could be recalled to contribute accordingly, especially when sampling is not accessible.

However, Hagia Sophia, as a unique monument of the World's Cultural Heritage, strongly demonstrates the need for integrated conservation actions, interdisciplinary cooperation and for an open international Forum of consultation likewise in the case of Parthenon.

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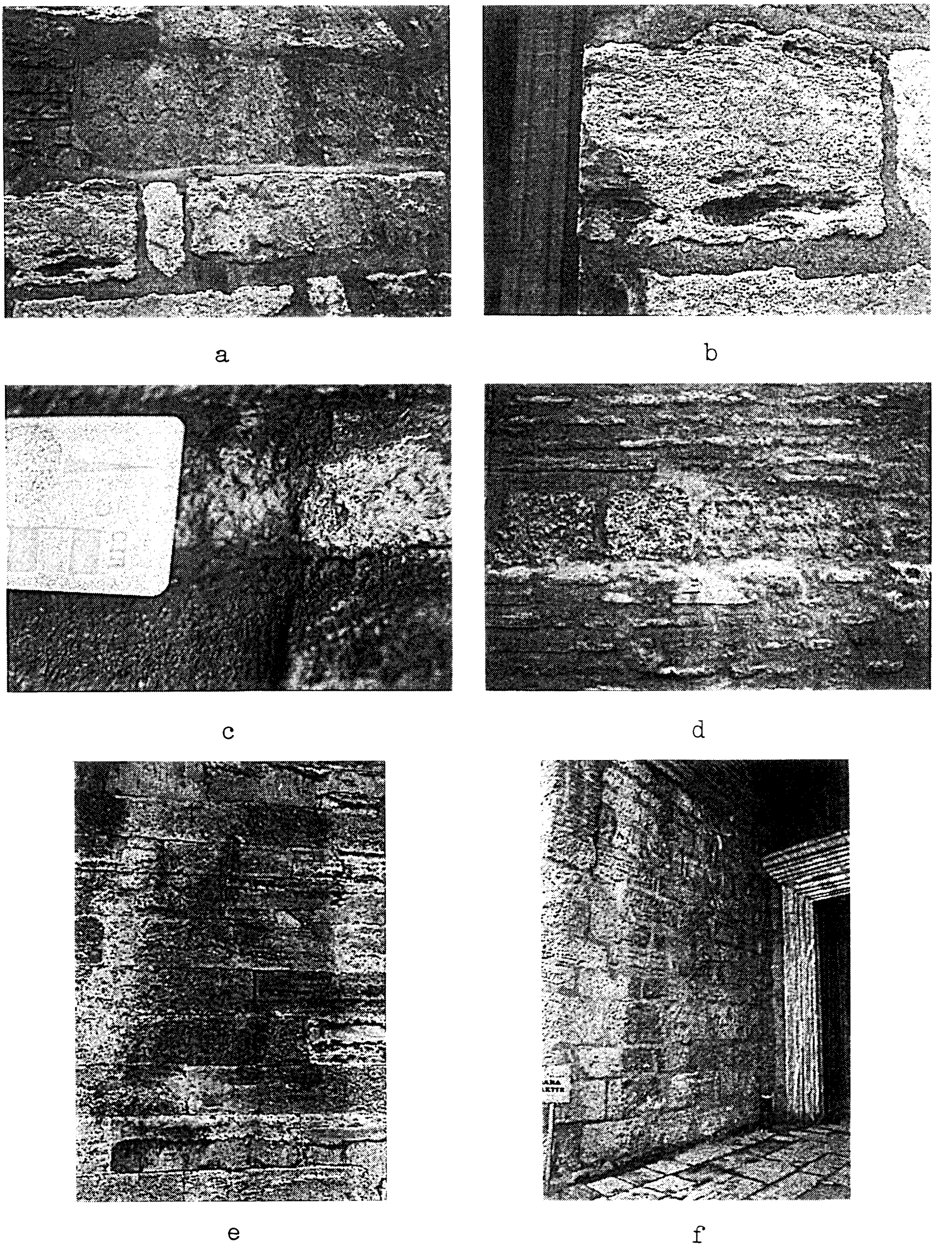


a b c d e f

Figure 1: Masonry building materials. Fossiliferous biogenic limestone's (a,b,c,e,f) weathered according to the alveolar (a,b) and stripped (f) pattern, by granular disintegration (c). Ophiocalcites are sporadically discernible (d to the right) suffering by granular disintegration and alteration to talc. Cementitious mortars (a,b,d,f) of brick dust are weathered out. Masonry build in a "concrete technology" way, where bricks are acting as reinforcements (d).

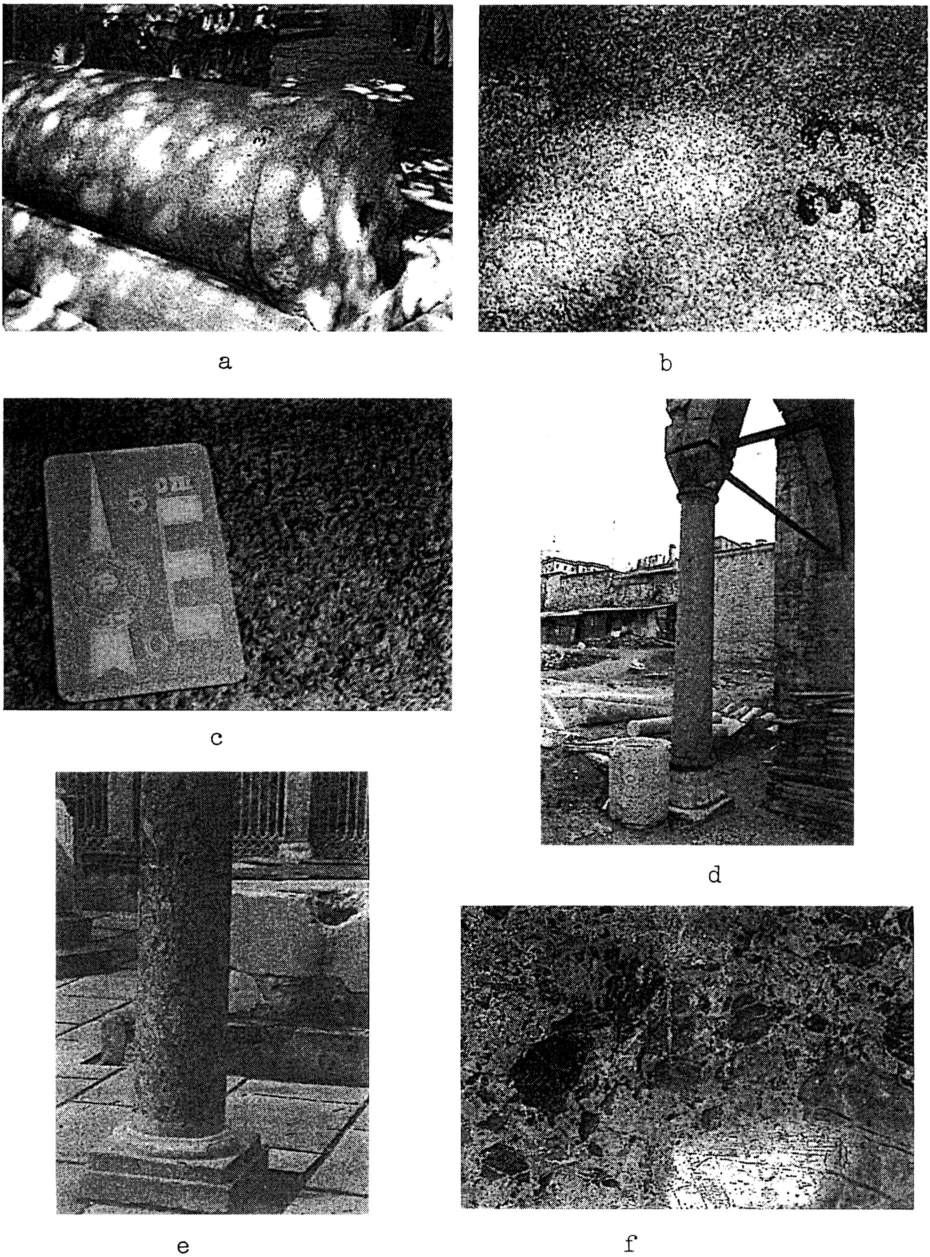


Figure 2: Old granite columns (a,b,c,d) and others substituted later by ophiolitic breccia (e,f). Plagioclase alteration and fissures are apparent in the granite weathering (b), whereas Ophiolitic breccia suffers from localised alteration to talc (f).

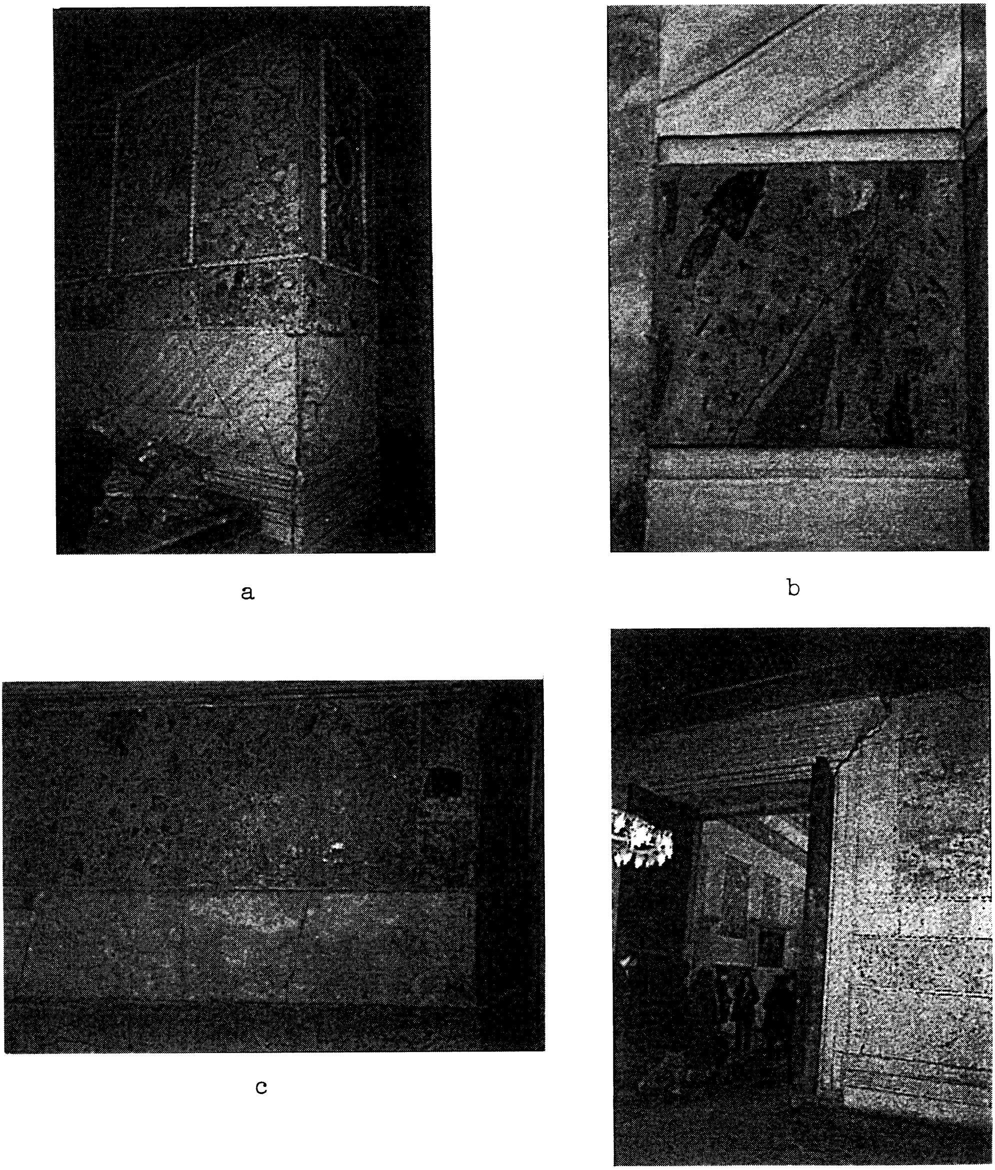


Figure 3: Marble coverings of the Dome columns (a-d). Grey - white marble presents fissures and detachment (a) Ophiolitic breccia (c,d) suffers from decolouration and intense alterations to serpentine and talc.

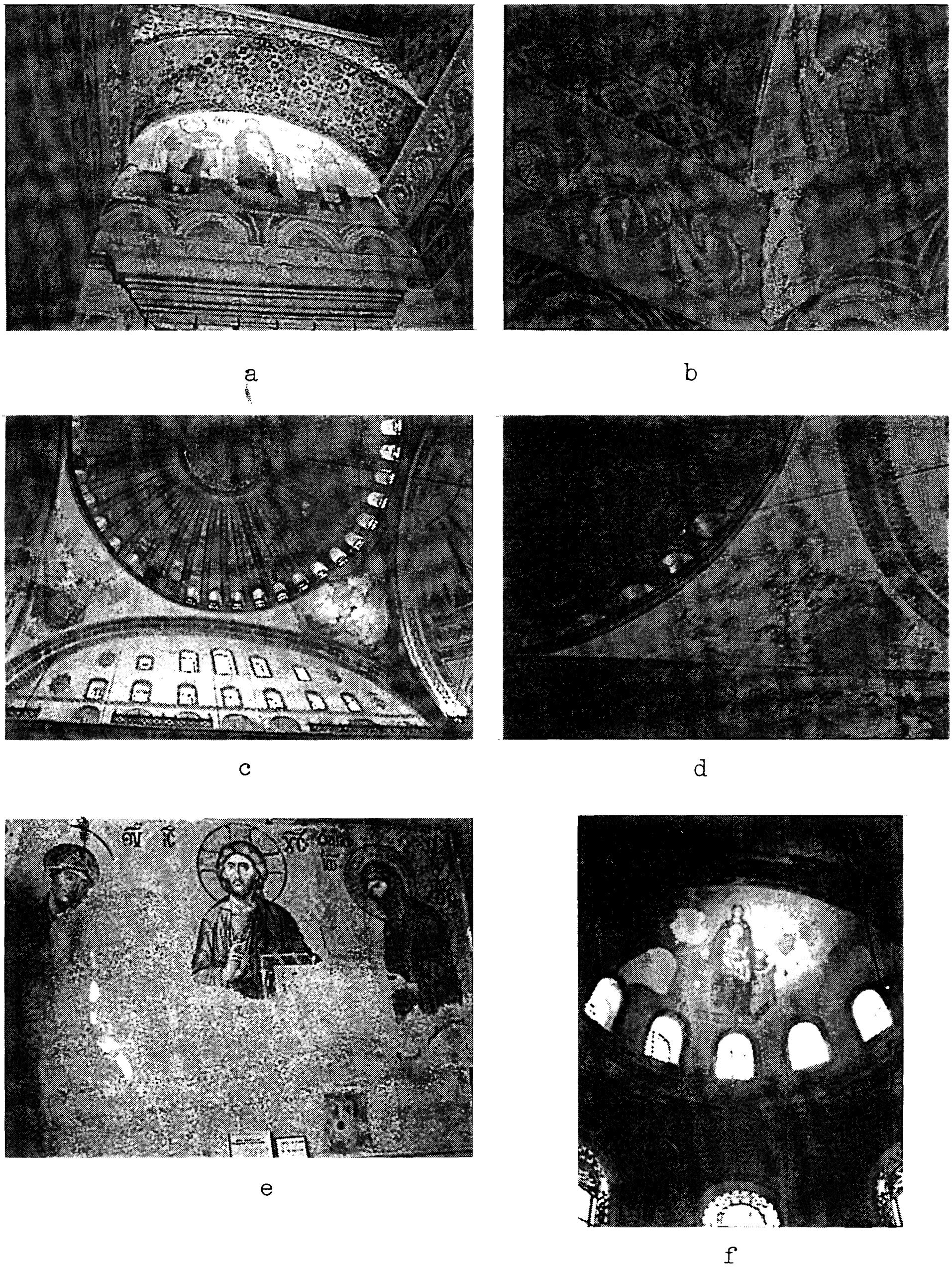
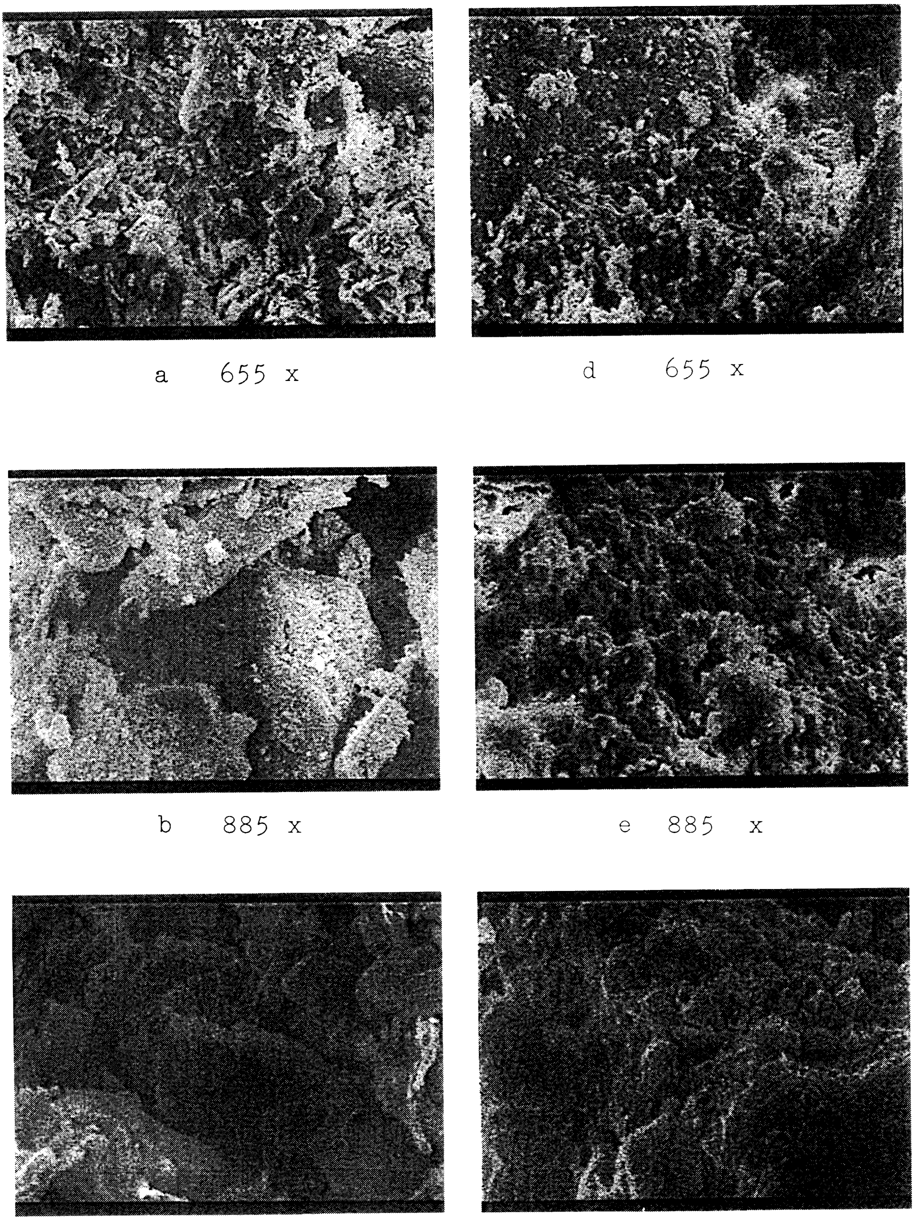


Figure 4: Serious problems of water penetration around the Dome, decolourating iconographies (a,c,d) damaging the mortar substrate (b) and weathering to deterioration famous mosaics (e,f).



a 655 x

d 655 x

b 885 x

e 885 x

c 2620 x

f 2620 x

Figure 5: SEM micrographs.
a,d : x 655, b,e : x 885, c,f : x 2620. Buff bricks (sample 4-A) of low vitrification and obvious porosity (a,b,c) as compared to other buff (e,f) or red (d) samples higher vitrification and lower porosity.

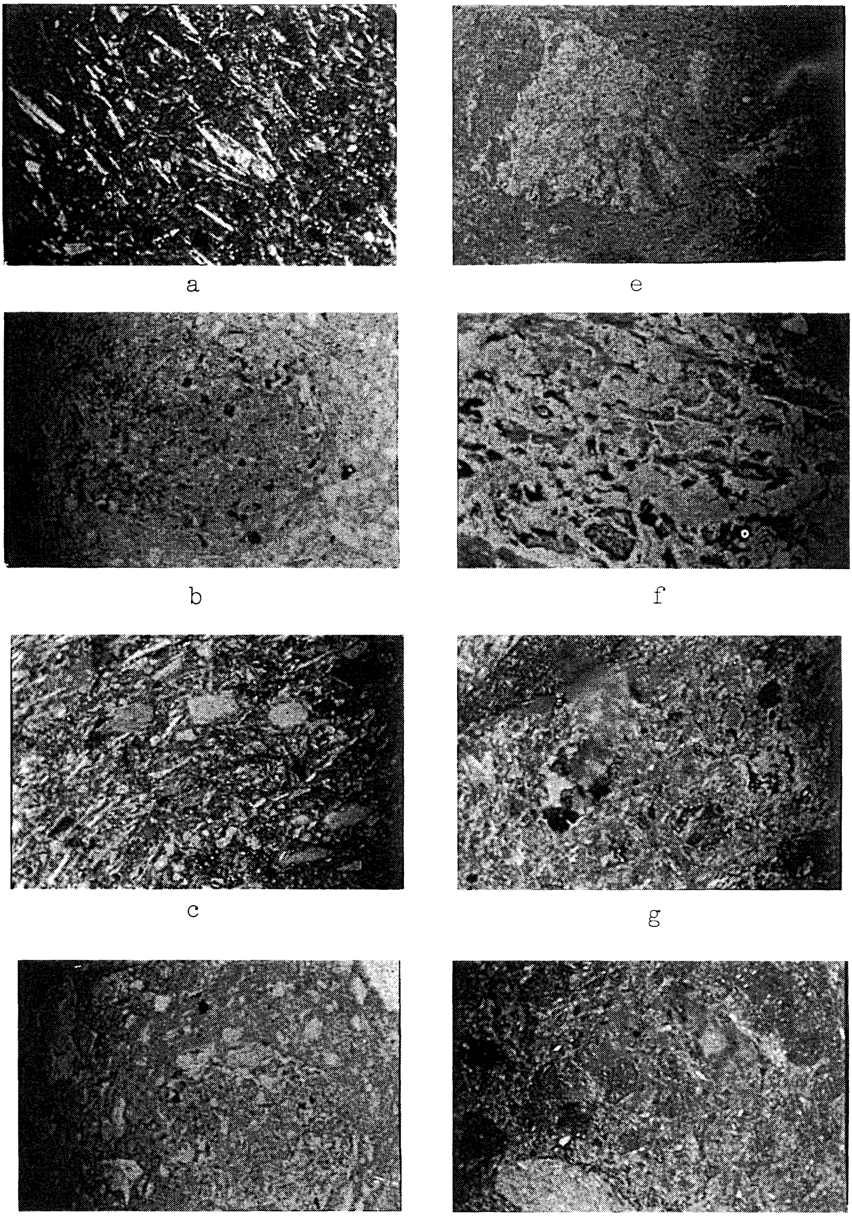


Figure 6 : Optical microscopy x 100 (a-h) Buff bricks, sample A-4 (a,b//) presents an homogeneous finely crystallised matrix with oriented prevailing muscovite, in comparison with other buff brick samples like 5 and 3 (c,d //) where larger inclusions of quartz, mica, but also calcite are met. Red bricks samples 2-B, 1-B and 4-B (e,f, g, h //) present large inclusions of calcite (e, f) in an intensive Fe oxidised matrix with large pores (g, h).

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Table 1
Mineralogical composition, according to X-ray diffraction data

Sample	*Composition*
1-A (red)	quartz, calcite, muscovite, anorthite
1-B (red)	quartz, calcite, anorthite, palygorskite (Mg,Al) (Si,Al)O(OH).8H_2O
2-A (red)	quartz, calcite, muscovite, anorthite, amphibole
2-B (red)	quartz, calcite, muscovite, anorthite, amphibole
3 (buff)	quartz, anorthite, augite, calcite, dolomite
4-A (buff)	quartz, anorthite, muscovite, augite, amphibole, dolomite
4-B (red)	quartz, muscovite, amphibole, calcite
5 (buff)	quartz, muscovite, anorthite, calcite, chlorite

Table 2
Electron probe microanalysis results - Energy dispersive analysis.
More than one specimen were analysed, when significant variations of composition were observed.

Total content %	Samples / Measurement (different speciments from the mass)										
	4-A		3		5			2-B		4-B	
	1	2	1	2	1	2	3	1	2	1	2
MgO	5.48	5.28	4.94	11.26	4.84	5.13	3.05	7.76	7.49	2.53	2.40
Al_2O_3	12.79	12.96	13.72	8.55	15.07	15.21	14.49	12.27	12.03	15.90	11.55
SiO_2	30.49	34.49	40.74	41.45	42.74	37.84	41.88	41.34	40.56	61.55	67.65
Cl_2O	-	-	7.59	7.00	-	-	-	-	-	-	-
K_2O	3.26	3.24	2.26	1.72	5.15	5.54	5.07	3.82	3.99	5.26	3.52
CaO	26.39	27.33	16.04	12.71	17.64	22.58	24.21	21.79	22.35	2.74	3.14
TiO_2	1.34	1.01	1.07	0.37	0.87	0.94	0.98	0.94	1.20	0.93	-
Fe_2O3	20.24	15.69	13.62	16.94	13.68	12.75	10.32	12.08	12.37	11.09	11.74

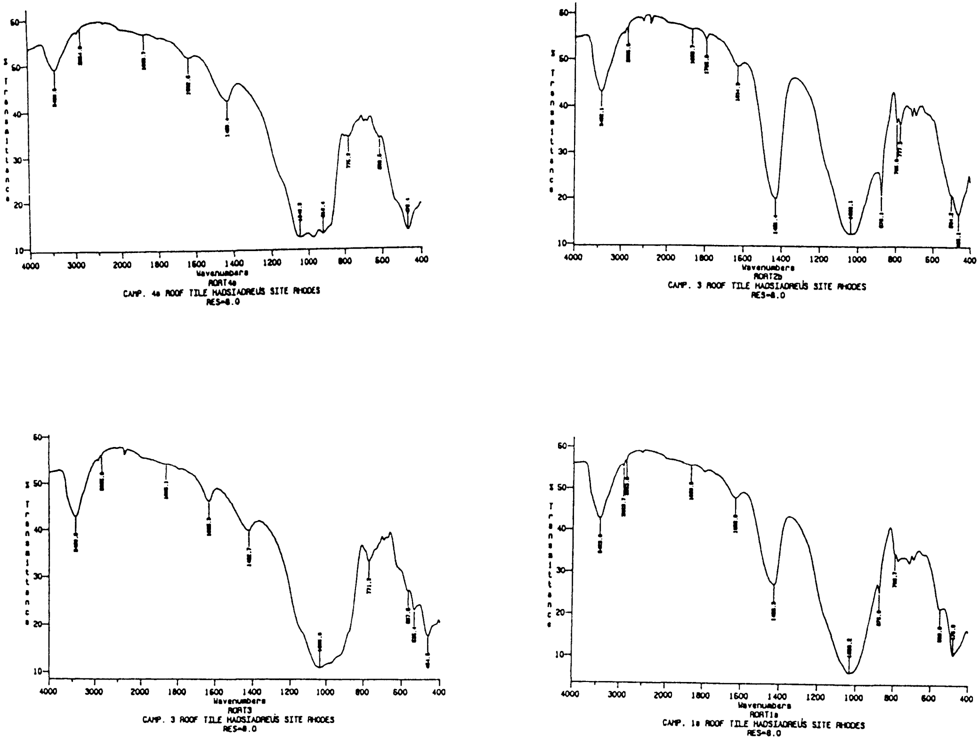

Figure 7 : IR diagrams (%transmittance per wavenumbers) for the buff (a,b) and red samples (c,d). The Al-Si compounts are obviously prevailing in the buff bricks, beeing more important in the case of the 4-A sample

Table 3
Infra - Red spectroscopy results

Sample No	*Composition*
1-A (red)	quartz, muscovite, calcite, silicates (plagioclase)
2-B (red)	quartz, calcite, muscovite, silicates (Plagioclase)
3 (buff)	quartz, dolomite, calcite, silicates (plagioclase)
4-A (buff)	quartz, muscovite, dolomite, silicates (plagioclase)

Table 4
Microstructural characteristics

Sample No	Pv	P %	rm	As	γ	pore<7.5μ
1-A red	27.76	42.89	7848	3.51	1.54	0
1-B red	13.36	26.85	3147	2.24	2.01	0
2-A red	14.89	28.55	1584	6.81	1.92	0
2-B red	15.75	29.86	1584	6.44	1.89	0
3 yellow	30.35	45.70	9841	1.76	1.50	0
4-A yellow	40.71	54.64	15254	1.99	1.34	0
4-B red	14.35	27.55	36576	3.84	1.92	0
5 yellow	25.97	40.82	6220	5.53	1.57	0

Pv : total cumulative volume (cm3/g %)
P%: total porosity (%)
γ : apparent density (g/cm3)
As : actual specific surface area (m2/g)
rm : medium pore radius (A)

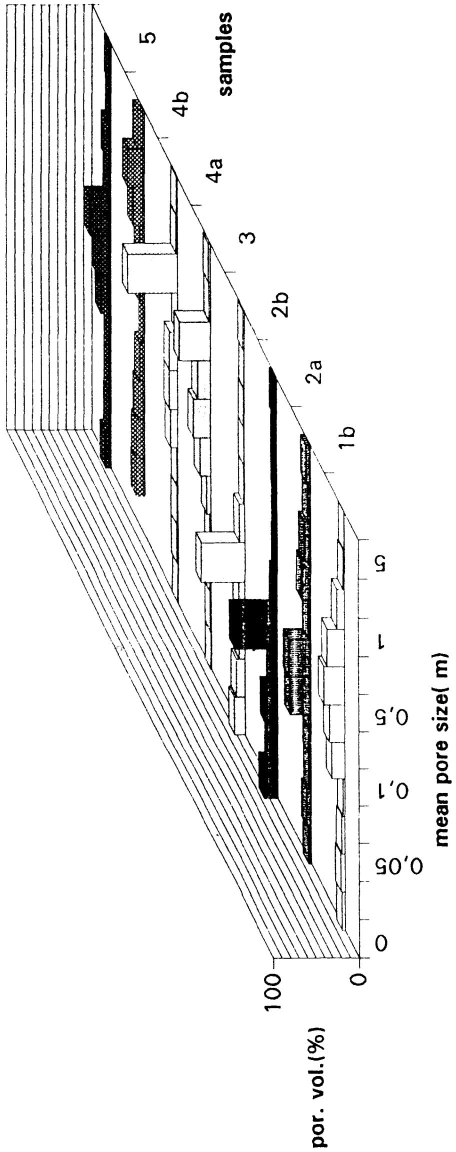

Figure 8 : Pore size distribution