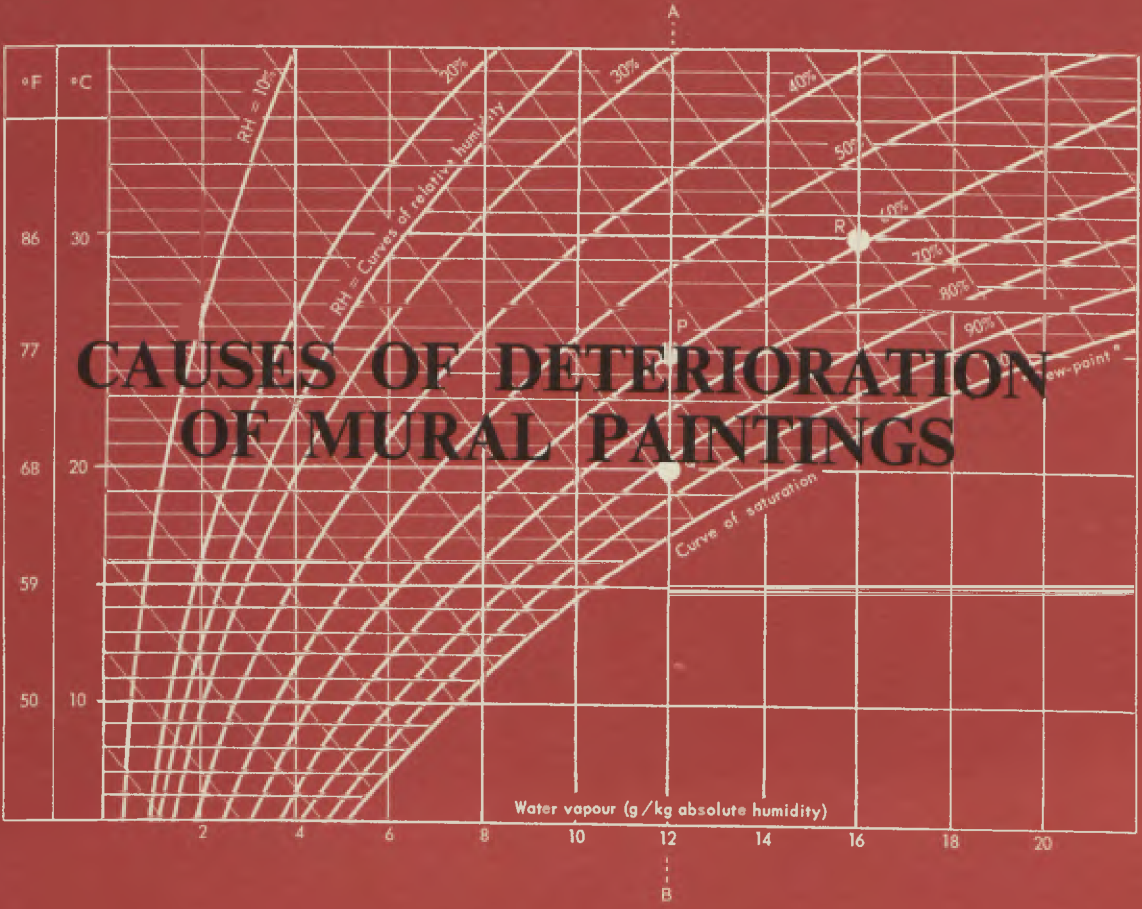
INTERNATIONAL CENTRE FOR THE STUDY OF THE
PRESERVATION AND THE RESTORATION OF CULTURAL PROPERTY

PAOLO MORA

CAUSES OF DETERIORATION OF MURAL PAINTINGS



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SUMMARY

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GLOSSARY

ARRICCIO	first layer of mortar applied directly on the wall for the purpose of creating an even surface that will receive the finer layer of rendering called intonaco.
INTONACO	layer of mortar covering a wall and on which the paint layer is applied.
FRESCO	technique of wall painting on wet lime plaster, according to which the pigments are applied with water — or sometimes with lime water — so that they are fixed on the surface of the intonaco by carbonatation of the lime hydroxyde of the rendering.
A SECCO	technique of wall painting on dry rendering, according to which the pigments are mixed with an adhesive, called medium, which on drying fixes them on the surface.
CRAQUELURE	cracks that appear in the rendering or ground of a painting and in the paint layer as a result of contraction during the drying process or of movement of the surface.
STACCO	method of removing a wall painting together with its layer of intonaco.
STRAPPO	method of removing the sole paint layer of a wall painting by stripping it from the intonaco.

CAUSES OF DETERIORATION OF MURAL PAINTINGS

A survey of the various causes of deterioration with notes on methods of control where possible.

Introduction

There are many possible causes of the alterations occurring in mural paintings and several of these are commonly found to be in operation at one and the same time; indeed, the presence of some make possible the action of others. It is right, therefore, to give prominence to such causes as may be regarded as fundamental, because in their absence the secondary causes lose much of their significance. To this end we will examine first of all the alterations that can be traced to the materials used by the artist and to faulty techniques, then we shall examine those changes arising from external causes including unsatisfactory methods of conservation, and finally proceed to study changes caused either by humidity or favoured by the presence of moisture.

Of all causes of change, clearly, the most significant are due to high humidity, whether judged by its frequency of occurrence or by the secondary reactions that may follow in its train.

We have to face the vast problem of dampness in buildings but this, however, cannot be developed in detail here [16]. On the other hand it has seemed logical to include reference to biological forms of attack (fungi, algae, lichens, etc.) as well as to certain kinds of chemical attack that are of frequent occurrence but which only manifest themselves under conditions of dampness.

These matters are all dealt with under their appropriate headings in the text.

I. CAUSES OF CHANGE

1. Instability of the Materials

The materials employed in the execution of a wall painting may have inherent defects which manifest themselves in time either by causing specific alterations or promoting deterioration.

1.1 *THE SUPPORT*

The support may be too weak to resist long exposure to the atmosphere. Such is the case, e.g., in walls of unbaked brick or of poor quality material containing soluble salts. Moreover, heterogenity of the wall (as when composed partly of brick and partly of stone differing in porosity and in thermal conductivity) can give rise to zones in the painting which respond promptly to surface condensation thus occasioning the formation of light and dark stains.

1.2 *THE RENDERING*

The general properties of the principal rendering materials will not be considered in detail and may be summarized as follows: those having a clay base are generally friable and sensitive to water, (mud, loess, adobe); those on a basis of plaster may be equally sensitive on account of their hygroscopic nature. When plaster is present as a constituent of a lime rendering it makes it sensitive to moisture and sulphatation may the more readily result, — sulphatation being defined as the transformation of calcium carbonate in calcium sulphate under the influence of sulphur dioxide gas, a frequent impurity of contaminated air.

When a rendering is too friable it will not adhere adequately to the wall whatever its composition and when painted upon, the paint layer will tend to exfoliate, especially if the binding medium is so strong that it shrinks on drying.

The quality of the rendering materials is particularly important in the case of the fresco technique of painting. It is composed of lime plus a filler which may be sand, pozzuoli earth, powdered limestone, ground brick, etc.

Straw and other vegetable fibres as well as animal — hair bristles frequently used to give cohesion to a rendering can be very effective but they may be dangerous if exposed on the surface because of their affinity for water. In these instances they enable moisture to penetrate and this may give rise to expansion in frosty weather as well as providing favourable conditions for biological attack.

1.3 *THE PIGMENTS*

The pigments chosen for mural painting must be able to resist attack from the atmosphere and its pollutants and in the case of fresco, from the caustic action of lime. We will not go into the tests that are applied to control such pigments here but rather content ourselves by listing those suitable for fresco work.

(a) *Pigments used in fresco*

Bianco di S. Giovanni	calcium carbonate
Slaked lime	calcium hydroxide
Ochres, siennas and caput mortuum	iron oxides, anhydrous or hydrated, natural or artificial
Terre verte	celadonite and glauconite
Egyptian blue	calcium, copper and silicon oxides
Ivory or bone black	carbon and calcium phosphate
Wood charcoal	carbon
Malachite	basic carbonate of copper

(b) *Pigments used in fresco but liable to alterations on exposure*

All organic pigments	
Lead white (basic carbonate of lead)	changes to black dioxide by a mechanism as yet unexplained.
Minium (oxide of lead)	
Azurite (basic carbonate of copper)	in damp conditions changes to green malachite frequently used in the past but normally ground in a binding medium and applied to the dry wall.
Cinnabar (mercuric sulphide)	frequently used in the past but sometimes has gone to black metacinnabarite. This is a physical change for which the exact cause has yet to be discovered. The older texts recommend vermilion exclusively for indoor use.

2. **Faulty Application of Techniques**

Instability may arise due to mistakes or to carelessness on the part of the artist, the chief examples of defective techniques being the following.

2.1 *DEFECTIVE PREPARATION OF THE SUPPORT*

Whether new or old, but especially if old, the support must be subjected to the most careful cleaning before the rendering is applied. All traces of mildew, smoke and dust must be eliminated and the surface roughened if necessary by picking in order to be quite sure that the rendering when applied will adhere well.

Before the rendering is applied the wall must be soaked with water as recommended by the classical literature and this must be thoroughly done especially when it is very porous and absorbent as in the case of brick. The reason why this is so important is that otherwise the support would absorb water from the rendering on its being applied and this would hinder the setting of the lime. Obviously the same precautions are required when *intonaco* is applied over *arriccio* and, generally, for all superpositions of rendering coats.

2.2 *FORMULATION OF THE RENDERING*

A correct composition is essential in making a permanent rendering. Excess of binder involves the risk of getting eventually a craquelure that in time would result in cleavage between support and rendering: insufficient binder would result in lack of cohesion with the risk of a powdery disintegration. For fresco renderings the normal proportions are sand two to three volumes for one volume of lime. The sand can always be replaced in whole or part by other inert matter or by chopped straw or animal hair as used notably by Byzantine artists, but in this case there must be due adjustment of the quantities given in the standard formula. The particular function of the organic constituents is to compensate for the strains involved in the "setting" of the lime, to ensure good cohesion of the rendering by prolonging the time of drying.

2.3 *WETNESS OF THE RENDERING WHEN PAINTING IN FRESCO*

When painting in fresco a certain degree of humidity in the rendering is essential. When the rendering is too wet the colours, under the mechanical action of the brush, tend to mix with the rendering and the tone is changed. When too dry they are imperfectly fixed, the calcium hydrate is not sufficiently diffused into the water in which the suspended pigments are applied and so the cohesion and adherence of the paint layer is considerably reduced.

2.4 *SECCO TECHNIQUES, DISTEMPER, OIL, LIME*

When the painting is done using a binding medium, the colour tends to scale off whenever the binder is too strong compared with the cohesion of the rendering. On a rendering that is too glossy or too absorbent, oil paint, moreover, may contract on drying and form a premature craquelure. As for painting in lime there will be insufficient adhesion and it will tend to scale if applied to a rendering that is dirty, greasy or inadequately wetted.

3. **Lime Washing and Over Painting**

Mural paintings have often been covered with lime wash for hygienic reasons (disinfection) or religious requirements ("anti-iconism"). Such washes are sometimes more compact than the painting itself and threaten to detach it. Sometimes, however, for several centuries they serve to preserve the underlying paint layer from destruction whether by natural or human intervention.

Certain kinds of white washing have been applied in distemper, in which case they generally still retain their solubility in water.

A special case, but one that certainly is not exceptional, is that of several different paintings having been superimposed one over the other, each having its own preparation or *intonaco.* The under paintings have generally been subjected to picking in order to ensure good attachment of the new painting ground or *enduit.* When prudent to do so, a skilfull application of the method of *strappo* allows one to separate the different layers. But in such matters one must consider the monument as a whole of which these paintings are an integral part as, for example, in the problem presented in S. Maria Antiqua in Rome. This consideration may well justify the preservation of the palimpsest *in situ,* the successive superpositions documenting important historical considerations.

4. **Exposure to Extremes of Humidity**

The maximum humidity that can be tolerated in a wall lies between 3 and 5%. In very wet walls (20% and over), the percentage of humidity is equal in bricks and mortar. In walls of medium humidity (6-10%), the proportion is different: 16.7% in tufa for 6.4% in the mortar. In walls less humid (up to 6%) the proportions are very different: brick 0.3%, rendering 5.7%. The normal percentage of humidity arising from the effects of capillarity in brick walls is between 9 and 15% over the first 3 metres while above this limit it reverts to normal (3%). In more serious cases the figures 5 - 9% are registered instead of 3%. [16] Fig. 1 reproduces a diagram illustrating the different types of humidity.

When it is not coming from the ground or the foundations, moisture *tends always to descend.* Drying begins at the top and is completed when the water is cut off at the base. In the case of humidity arising from capillarity the faster the surface evaporation takes place the greater the drying effect and in consequence reduction in the capillarity effect. On the contrary, moisture rises highest when there is no evaporation.

One must beware of judging by appearances. One can get an idea of the thermal conductivity by touch and this is one of the specific characteristics but it is not possible by such means to determine the thermal resistance or the degree of humidity of the surface. It may even happen in the case of condensed moisture that the measuring instruments fail to record the phenomenon for it is intermittent. At interior temperatures between 5-20°C it may only require a lowering of temperature by half a degree for condensation to take place where the relative humidity of the atmosphere is around 95% and a lowering of each degree of temperature corresponds to an increase of about 5% of relative humidity. Condensation takes place on a surface when it is in contact with saturated air (100% RH) at the same or a lower temperature.

The statement that a mural painting should always be executed on a surface which allows it to "breathe" is quite wrong and misleading. This should be obvious, because if air and water vapour can penetrate through the paint layer it means that moisture can also, and this would bring atmospheric contaminants into intimate contact with the paint and result in chemical action.

In absence of moisture and at normal temperatures such reactions cannot take place. It follows, therefore, that as all chemical reactions damaging mural paintings need water we must protect them from damp whether coming from the wall or from condensation. This, incidentally, will save them from biological attack.

The concept of walls breathing should thus be considered as a condition that facilitates the transfer of moisture in gaseous or liquid phases more than a passage of air. Indeed, tests have indicated [6] that ordinary walls of brick, tufa or sandstone of medium thickness as used in civic constructions allow the passage of some 300 g of water/square metre daily when not protected by a coating to render them impermeable.

The opaque appearance of old dry painting is due to an irregularity of surface caused by abrasion and/or the action of moisture. When the surface is wetted the appearance is no longer one of opacity because the water re-establishes a continuity of surface and the light is no longer scattered. The same improvement of appearance is obtained by the use of a permanent fixative or impregnating medium which, incidentally, forms a moisture barrier and to a degree protects the paint layer from deterioration.

Where particles of pigment are found to be adhering but feebly to the ground ("dry areas") the condition may also be corrected by the use of a fixative.

It sometimes happens, especially in churches, that old porous brick pavements are replaced by an impermeable layer of asphalt or marble and there may even be an impermeable rivetment or impregnation of cellar or crypt walls, etc., so that the accommodation may be brought into service. Such measures, in preventing evaporation encourage capillary action and water rises in the wall with consequent deterioration in conditions! A characteristic common in all such cases is that stagnant air in immediate contact with the damp surfaces reaches the point of saturation irrespective of the amount of water in the walls and this condition obtains to a distance of some 6 or 8 cm distance from the walls.

It should be empasized that all types of humidity favour the growth of micro-organisms.

5. **Water Soluble Salts**

As already mentioned many times humidity is the principal cause of alterations in mural paintings from the fact that it sets in motion different processes or promotes secondary reactions resulting in the disintegration of structures or of paintings which may cover the walls of buildings.

We will examine in the first section the general processes of alteration that apply to all types of rendering and of mural paintings and proceed later to study the more specific types that act on different specific types of rendering and support.

5.1. *MIGRATION AND RECRYSTALLIZATION OF SOLUBLE SALTS*

This is the most characteristic process that threatens murals and there are four aspects to be considered as follows:

(i) Surface evaporation and crystallization.
(ii) Process of disintegration by the recrystallization of salts.
(iii) Superficial incrustations.
(iv) Nature and provenance of salts.

5.1.1 *Surface evaporation and crystallization*

The surface of walls decorated by painting are always, in relation to humidity movement, in a particular state of instability that is different by comparison with that of the mural structure itself. The painted surface is especially vulnerable because, though an integral part of the wall, the constant interchange required between the wall and its environment to humidity equilibrium produces local variations in the region of the painting and hence the changes that are seen within and round it. It is in these local areas that evaporation, condensation, and transpiration of water are most likely to be present, giving rise to disintegration. [23, 24].

The water coming up from the soil and bringing with it salts in solution, may be further contaminated by dissolving salts from the wall in making its way towards the surface of greatest evaporation. The same series of events occurs in the opposite direction if we consider water infiltrating from above.

Leaving aside for the moment the direct solvent action of rainwater on the rendering (see below section 13) we will now consider the phenomena that occur in the critical zone of evaporation.

The factors determining the drying of a porous body are the following:

(i) The characteristics of the immediate surroundings - temperature, relative humidity of the atmosphere and amount of ventilation.

(ii) The particularities of the structure of the material have an effect upon the movement of water towards its surface. Indeed, the porosity and the density of a material can in themselves provide indications as to the probable effects of humidity. Heavy, compact materials such as marble are normally characterized by abundant condensation whilst light and porous materials favour the ingress of humidity by capillarity and infiltration, but are little affected by condensation.

In order to dry a solid body of a certain thickness it is evident that the moisture by one means or other must be displaced from the interior and moved towards the surface where it can evaporate into the air. If the moisture movement is triggered by capillary forces the surface will receive a continuous supply. But if the forces are weaker and do not reach the surface, it will dry and the evaporation front will then lie immediately below it so that the evaporating water vapour will be forced to traverse the porous section, between the evaporation front and the true surface of the wall before evaporating into the air.

The drying of a saturated solid takes place on the surface at the same rate as that of a watertable exposed to the same atmospheric conditions. But when the supply of water is insufficient the surface is no longer completely wet and the speed of evaporation diminishes. When the supply is constant the drying takes place mostly on the surface where there is no lack of water supply, whereas, in the latter case, after a brief period, the rate of evaporation is diminished and gradually recedes to continue slowly from levels beneath the surface so that one must be prepared to come across walls in which the immediate surface is apparently dry whereas the mass of the structure is still quite damp.

Given that the supply of water is constant, different materials behave differently when exposed to it, depending on their porosity (number and dimension of the pores), as they exhibit different resistance to alterations. Small pores in the material and an adequate water supply provide least resistance. Large pores are more resistant and materials that are only slightly porous for the same types of pores are the most resistant of all to alterations of humidity.

On the other hand, the conformation of the surface (as corners or thick brush strokes) and its exposure to different conditions can augment the speed of evaporation and act in such a way as to lead the evaporation to take place in a directional fashion towards certain zones rather than others.

To sum up, one may meet in one and the same structure different types of degradation and different degrees of degradation which will be influenced even by the nature of the saline matter that is transported. According to the conditions which are manifest on the surface, the salts will crystallize there or in the zone immediately below and it is not an uncommon occurrence to find that they actually extrude from the surface in filamentlike crystalline threads having somewhat the appearance of cotton wool. When evaporation takes place almost entirely at the surface one can expect to find external efflorescences; if on the contrary, after a brief period of evaporation from the surface, it continues from a level further within the wall the salts will crystallize also at the deeper levels. This phenomenon has been verified by experimentally accelerating surface drying.

One distinguishes, therefore, two main types of crystalline formations, *superficial or external efflorescences and cryptoflorescences in the interior of the pores.*

The location of crystallization depends first of all upon the conditions of evaporation and the nature of the material and secondly on the nature of the salts.

5.1.2 *Decomposition caused by crystallization of salts*

The forces causing the decomposition exerted by crystals in the course of their growth can be attributed to capillary forces which act in the interstices — the openings between the crystal surfaces and the internal walls of the capillaries — under the stress of thermic expansion. These interstices are continually being supplied with additional salt solution that is sucked in. This process encourages the further growth of crystals even when they already apparently completely fill the pores.

Another possibility in studying the decomposition of the rendering, is to be found in the fact that certain crystals are grown in the dehydrated condition. When, however, conditions permit, tha salts become hydrated, the crystals increase in volume and in the force they exert, causing disintegration.

In each case there is a trial of strength between the expanding crystals and the material composing the pores: one of the two must yield. If the rendering is the more resistant the crystals are extruded as an efflorescence. If, on the contrary, the walls of the pores are the more feeble they disintegrate and decomposition of the rendering results. Given that surfaces of walls are not always homogeneous and that the salts are almost always of varied compostion one can find simultaneously examples of each phenomenon existing side by side on the same wall surface.

If one takes into consideration the fact that the capillary forces of deterioration vary with the temperature and that salt hydration implies an augmentation of humidity it should be possible to control deteriorations of this nature by maintaining a constant RH and temperature. This, indeed, is demonstrated by the state of conservation of the mural paintings in very wet surroundings where the temperature is constant as in the tombs of Tarquinia and the Lascaux caves before their being opened to the public.

5.1.3 *Provenance of salts*

Salts forming on the surface or beneath it may have the following provenance.

(I) They can exist or be formed in the actual materials of construction or result from their decomposition (e.g. bricks that have remained for some time buried in the soil), and are: calcium carbonate, sodium sulphate and sulphates of potassium, calcium and magnesium as well as silicates.

(II) They may actually come from the soil. In this event the salts are usually sodium, potassium and calcium nitrate. Salts are formed in the ground as a result of the action of certain microorganisms on organic nitrogen compounds which transform them first into ammonia which is oxidized to nitrous acid then to nitric acid which attacks constituents of the soil converting them to nitrates.

Nitrogen can also be absorbed in the ground following atmospheric precipitations either by the action of nitrogen fixation bacteria or by bacteria in the rootlets of leguminous plants which ultimately operate in the same direction.

(III) Certain salts may be present in the atmosphere, e.g. sodium chloride in sea air.

(IV) They may emanate from the animal kingdom: the excreta of birds and bats when transported by water may eventually deposit salt on other sites.

(V) They may result from residues of material employed in an earlier age with the idea of effecting conservation (calcium sulphate, silicates).

5.1.4 *Composition of salts and their action on the rendering and on the painted surface*

(I) The salts that are considered to be potentially most dangerous to the rendering and to the painted surface of a wall are the *sulphates of sodium, potassium, magnesium and calcium*, because according to where they crystallize they cause serious disintegration owing to the failure of cohesion of the materials. Calcium sulphate can form a white veil over the surface or it can be crystallized within the rendering by the sulphatation of calcium carbonate to which a polluted atmosphere contributes [10].

(II) The *nitrates of sodium, potassium and calcium* are the soluble salts which normally give rise to thick efflorescences easy to eliminate and of which the disintegrating action is inferior to that of the sulphates.

(III) *Calcium carbonate* is a main component in constructions, and grottos in limestone. For data on its behaviour see the remarks referring to the stability of the rendering that is composed on a basis of lime (p. 13). Calcium carbonate has not by itself a disintegrating effect after it has once crystallized, but it forms incrustations that are very hard and intractable.

(IV) *Sodium chloride* is normally a surface deposit, having been transported by sea air and in itself does not cause disintegration. However it is able by a process of hydration and dehydration to promote the disintegration of surfaces by its action on other salts that may be present under the effect of varying temperatures.
It may also be found in the rocks on which pictures are painted and it may migrate towards the surface where there is occasional humidity as in the tomb of the Valley of the Kings at Luxor, Egypt [18].

(V) The *silica* contained in certain rocks, in clays and in cements is in a form that can be transported very slowly towards the surface by infiltrating water. A long-term effect is the formation of white incrustations of silicon dioxide (opal) or of silicate mixed with other substances notably calcium carbonate.

Types of saline deposit

Different types of saline formation are laid down over the zone from which water has evaporated.

— when the surface is continuously damp one finds veils of salts or even surface incrustations;

— when water comes slowly to the surface or when evaporation takes place rapidly one is inclined to find that disintegration is progressive, — first in the painting, then in the rendering according to the depth of the evaporation zone and the crystallization zone moves from the surface inwards.

As we have seen, the salts which form on the surface have sometimes a disintegrating potentiality that can operate to push away from the surface fragments of the rendering and the paint film as well. If, on the other hand, they are more feeble in strength than the materials that surround them, the salts themselves can be extruded from the porous surface of the wall in filamentous form.

5.1.5 *Superficial incrustations*

Superficial incrustations can be formed in the following ways.

(I) By passage of water through the rendering and paint layers.

(II) By trickling of water streams over the surface of the paintings.

(III) By condensation moisture fixing dust deposits.

In cases (I) and (II) the water in which salts are dissolved evaporates from the surface leaving the salts behind in amounts depending on the quantity of water which collects the salts from the interior or from the surface of the wall respectively. Case (III) is exemplified by conditions in basements below ground where it is possible for air to enter bringing dust with it, which in due course is fixed by the salts crystallizing from water condensed on the colder surfaces. Vaults and the higher registers of a building structure are prone to exhibit such condensation phenomena, because the warm air rises and the high ceilings and vaults under the roof are normally colder in winter and this creates conditions favourable for this phenomenon.

As to the humidity that arises when a crowd of people are gathered together, it has been calculated [12] that in the chapel of Kings College, Cambridge, the walls had absorbed in the course of the summer of 1961 about 16 tons of water vapour! (Fig. 9).

Condensation favours salt hydration and water containing dissolved gases gives rise to chemical actions on the surface.

Hygroscopic salts such as sodium chloride when deposited on the surface tend to give rise to a liquid layer even when the RH is below 100% (Na Cl = 75% RH).

The particles of fixative do not coalesce to form a completely impermeable layer and they are traversed by humidity so that they are unable to prevent the actions causing disintegration.

6. **Exposure to Dehydration**

It has not been established that in drying a rendering or a wall completely in a normal climate it will exhibit lack of cohesion at normal ambient temperatures if composed of mixtures such as lime plus inert substances. The enfeeblement of renderings and of painted layers after drying is normally due to a process of disintegration coming from evaporation and deposit of salts whilst still in the pasty condition. On the other hand certain organic binding materials such as animal glues and gums become vitreous and contract on drying.

7. **Atmospheric Pollutants**

The atmospheric agencies that give rise to the disintegration of art objects in general and of mural paintings in particular can be divided into two categories, natural and artificial i. e. resulting from the activities of man.

Natural Agents of Pollution

Carbon dioxide: this is in part of natural origin and in part results from the respiration of human beings in confined spaces such as rooms and grottos where there is limited circulation of air. The mechanism by which mural paintings are altered will be described in paragraph 13. 3.

Natural aerosols: particles that are so minute and light in weight that they can remain in stable suspension in the air are called aerosols, and they normally contain fine silica and calcium carbonate from the ground and chlorides and sulphate of alkali metals derived mainly from the sea.

Artificial Agents of Pollution

Sulphurous anhydride: this comes from the combustion of materials containing sulphur such as coal and mineral oils. It is readily oxidized forming sulphuric anhydride which the moisture in the atmosphere converts to sulphuric acid. This acid attacks calcareous materials (limestone, marble) and also renderings having a basis of lime and these are all transformed on the surface into calcium sulphate with increase in volume. Such sulphatation is the forerunner of disintegration which is soon evident on the surfaces. In the case of mural paintings on interior walls the phenomena are of limited importance. One must remember, however, that it is always the presence of water, from whatever source, that makes disintegration possible.

Artificial aerosols: the aerosols that form in the atmosphere of towns and especially of industrial areas contain in addition to the characteristic constituents already mentioned particles that are contributed from combustion.

These aerosols are responsable for fine deposits of solid matter on the surface of objects.

Ammonia: ammonia which is present in the air has the property of being able to promote the conversion of sulphurous anydride and sulphuric anhydride into their respective acids and to neutralize these acids when they are formed in contact with water.

8. Frost Action

The phenomenon of gelivity is a well known factor in causing the disintegration of stony materials exposed to frost and to sudden changes of temperature. The action of frost on damp walls is particularly rapid and destructive, the rendering is weakened, it disintegrates and becomes detached as the water in the wall freezes and expands in volume. Strong oscillations of temperature to which walls are sometimes exposed in certain regions or alternations of night frost and daily sunshine cause slow disintegration of surfaces fortunately rather rarely.

9. Biological Action

Micro-organisms of the nature of fungi, algae and lichens develop rapidly when exposed to air that has a relative humidity of over 65% and so one has always to be on the look-out for their presence in places that are persistently damp [4]. They may take the form of staining or may be spotty in character and of varied colour and they change the appearance of the paint layers and the rendering. There is a certain surface loss which after cleaning is revealed in the form of little holes at first almost invisible, but which are capable of spreading until whole areas of the painting are destroyed. No curative treatment can hope to be durable if one does not get down to a thorough treatment and to ascertaining the origin of the damp and finding a cure for the same.

10. Minor Physical Causes

10.1 *WIND EROSION*

Wind charged with sand or dust is a factor to be mentioned in this section as it causes the erosion of exterior murals. One can sometimes remedy this by planting a curtain of trees in a strategic position or constructing a palisade or applying some form of transparent protective material in front of the paintings. This latter solutions is generally the simplest, but usually the least satisfactory from the aesthetic point of view.

In other cases the wind may favour evaporation which is increased by ventilation and crystallization will take place in the wall rather than on the surface. This can be aggravated by the phenomenon of cavitation shown when the wind is canalised or focused towards the areas attacked, intensifying evaporation and crystallization.

10.2 *LIGHT*

Light, and in particular sunlight, even when it does not attain high temperatures, as in previously described cases, can in time cause fading of colours. The infra-red constituents of sunlight provoke differences of thermal expansion in the binding materials of pigments and those similar elements in the preparation or rendering, causing exfoliation of the paint layer and, indeed, the wearing away of fixatives applied in the course of restoration. It is the ultra violet radiations that are mostly responsible for the bleaching of organic pigments and also for the oxidation of painting media which become vitreous and detach themselves from the picture.

10.3 *DUSTS AND DEPOSITS*

Among extraneous alterations one cannot exclude such things as dust deposits, soot, insect excrements and the damage done by wasp nests, by bats and other animals. Deposits cause darkening and they are often difficult to eradicate. In bad cases the painting may be lost under a permanent black stain. Moreover, where, as often happens, the deposit is alkaline or acidic in nature it promotes corrosion of the surface which may only be apparent as regards the seriousness of the attack after the painting has been cleaned.

10.4 *FIRE*

The heat from fire can convert the calcium carbonate back to quicklime with change of volume and this in due course will become hydrated; the rendering will break away but even before this happens there will be colour changes, yellow and green oxides becoming red or brown in tint simply from candles placed too near a painting. Such transformations are frequently to be seen in the vicinity of altars or where church candles are too near paintings and have caused reddish and dark halos. Sometimes even the reverse action can take place for humidity, may convert certain red ochres to yellow in the course of time.

Yellow ochres become reddish in colour around 250°C - at 300°C. The tone is a reddish-brown and darkening continues up to 750°C above which no further colour changes are observed.

10.5 *VIBRATIONS*

One tends to neglect the effect that vibrations may have on the painting whether due to traffic, to organ music or to the ringing of bells. Such vibrations may, indeed, if not actually cause detachment at least promote deterioration that has been initiated from other causes.

11. **Uncontrolled Artificial Heating**

The heating of churches until a few years ago was inconceivable. The temperatures considered adequate for congregations were relatively low and indeed one can hardly claim that these have been a serious cause of change to mural paintings. But records show that while in 1954, an air temperature of 12°C was considered reasonable, in 1963 the demand was for 15°C and today, the figure is 20°C [20].

Not only is the trend to increase the temperature but also to heat an enormous volume of air only a few hours before religious services. We have therefore a sudden rise in temperature and when the congregation is assembled a sudden rise in relative humidity which, as we have seen, puts a serious strain on works of art of all kinds aggravated when heating is discontinued by the inevitable condensation of the excessive moisture that follows. The walls are therefore subjected to a series of intermittent shocks liable to affect the stability of mural paintings profoundly.

Measurements taken in certain warmed churches have shown that the internal conditions of temperature may rise to more than 45°C in the higher parts under the roof vaulting - depending on the duration of heating and this despite the use of ventilators which ought to have ensured air circulation.

To plan a heating project for a church guaranteed to be free from danger to structures such as wooden ceilings or frescoes, or to furniture such as organs and screens, one must accept the principle that each place has its own particular problems. There is no such thing as a scheme that is applicable in all cases: individual problems require individual solutions.

As in all problems of conservation, collaboration is required between the architect, art historian, climatic expert and conservator. It is not sufficient to pass the problem to a firm of specialists; the problems must be examined together with the proposed solutions from all aspects. It is necessary, for example, to consider what influence new works might have on the acoustics and other things. Another aspect is that of the colour of the walls. It has been observed that while in a large church warm colours give the impression of comfort and warmth, in small churches, if the walls are finished in cool colours - though the actual temperature is identical with that of the large church, there is a feeling of frigidity.

Before beginning to design a project it is advisable to arrange to take readings of temperature and relative humidity throughout one entire year so as to study the natural variations and establish a mean so that heating can be designed to maintain the figures slightly above these mean figures. One must, moreover, examine very specially the objects that are of particular interest so as to adapt the heating or conditioning to the exigencies required for good conservation.

The choice of a source of heating is of the very greatest moment and one is limited to the use of equipment that will increase the temperature gradually (not brusquely) to the required figure and that will not be of intermittent operation. Experience has shown that for all practical purposes one cannot rely on results obtainable from static installations and that it is almost imperative to incorporate forced ventilation with a booster fan in reserve. Nevertheless, one must remember that the circulation of air is liable to introduce new problems. The rate of displacement of air which must be relatively high above the vaulting in order to attain the necessary circulation is liable to cause currents of air at ground level which may be disagreeable to the human subject. One possible solution consists in planning the system in two circuits: above, the air is supplied at a speed of about 6 m/s which, however, is reduced to 3 or 4 in service, while below, a second circuit of air is supplied at about 1.2-1.5 m/s. The recovery is evidently made at the opposite end of the building. Smoke tests on such installations have demonstrated their efficiency and temperature tests have recorded a difference between pavement and vault levels of only 1.5°C.

Normally, the maximum temperature to be aimed at should not exceed 15°C. The temperatures of emission which sometimes attain 80°C must be reduced to about 45°C and compensated for by prolonging the heating. On commencing operations do not try to attain the maximum. Work slowly and progressively towards it. Regulation must be under the most strict control and be accompanied by tests and, when once successfully in operation, there should be a thorough hygrometric and thermometric survey test carried out at six monthly intervals.

Another method of heating that, with some modifications, has given good results is that of the ancient Roman hypocaust system. It frequently requires the addition of an auxiliary service of heat and the provision of slight ventilation along the walls to obviate stagnation and to neutralize the tendency towards cold strata parallel to the wall. The heating of the pavement can be conveniently achieved electrically or by warm water or low pressure heated air and the same type of energy may be used for the subsidiary service. As to the design of the canalization it is generally found to be more effective to utilize a whole series of small diameter conduits rather than just a few of larger diameter. Those used to heat the pavement may be utilized to effect by arranging occasional grids to the surface in such a manner that these are closed or opened to the interior air by a command thermostat, thus making it possible to ensure that the temperature of the building will not fall below the desired figure. An additional advantage of such a system is the complete absence of radiators or other such plant.

12. **Defective Restorations**

Besides overcleaning, all too commonly noticeable in the case of distemper painting, the following may seriously alter the condition of the paint layer: varnishes, oils, waxes and fatty substances. These may have been applied in the first instance to fix paint or to brighten or darken unsatisfactory areas but eventually they falsify the colour; there is lack of balance, over-brilliance or the reverse, - sombre patches that unite to destroy the aesthetic effect. Moreover, fixatives that are inadequate or that are badly applied can exfoliate the paint on drying and contracting, cleavage taking place at the boundary between paint layer and rendering; or they may act as a moisture barrier preventing evaporation of humidity from the wall with grave consequences to rendering and paint layer alike.

Gum arabic, white of egg and such substances do not seriously alter the visible appearance of paintings to which they are applied, but they are nutrients that attract the growth of micro-organisms and such things may do serious damage to wall paintings.

Alkaline silicates, formerly much in vogue for use as fixatives, form white veiling very difficult to remove.

Finally waxes, which at one time were much in favour, have a tendency to darken both fresco and distemper, giving them a fatty and sombre aspect which falsifies both the texture and the tonality.

The consolidation of walls which is often accomplished by grouting with cement can give rise to serious alterations:

(i) Because the water essential for injections may eventually reach the surface and cause damage as it dries.

(ii) Because rivulets of cement may form in unseen cracks reaching the pictorial layer and either appearing on the surface or forming zones of varying density beneath it, thus promote unequal condensation with resulting staining or disintegration of the rendering.

(iii) Because if moisture should appear at a later date this would dissolve the soluble salts present in cement; these would find their way to the surface eventually and cause the usual damage on crystallizing [14].

Apart from the difficulty of getting rid of cement, there are other serious objections to its use for reinforcing the boundaries of lacunae or of the mural painting itself, notably because ambient humidity tends to condense preferentially on cement wherever it occurs — to be absorbed eventually by the painting — or, if the wall itself should be damp, evaporation takes place preferentially through the painting rather than the cement, carrying with it the salts that cause disintegration. This can readily be observed in the deterioration of bricks that have been built together with cement; it is the bricks that suffer and their surface may be deteriorated to the extent of several millimetres of thickness.

13. Changes Characteristic of Different Types of Rendering

To the general processes of alteration that are caused by the combined action of water and salts one must add the types of alteration that are characteristic of the different types of rendering depending on the materials that are used in their formation.

As in Chapter 1.2 we distinguish three categories:

(i) Basis of clay, usually with the addition of organic fibres.

(ii) Basis of plaster.

(iii) Basis of lime and inert material, sometimes plus some organic fibre.

13.1 *CLAY*

These are extremely sensitive to moisture and are mainly found in regions of low rainfall. They are decomposed not by chemical but by physical action becoming softened and swollen by water so that they are simply washed away by any water trickling over the surface. Therefore all decoration is eventually lost.

Water often collects near the base of the wall and remains there stagnant, disintegrating the rendering and even the wall but with a limited rise of water and of soluble salts it contains.

Alternating humidity and desiccation are likely to be just as devastating.

13.2 *PLASTER*

Where conditions are dry, especially in desert lands, one has found and still finds today paintings having a rendering based on plaster. As we have seen this is a material that is very sensitive to humidity and contact with water causes rapid disintegration of the rendering and loss of paint.

Plaster renderings are also sensitive to excessive dryness. Indeed, the plaster formed by the hardening of the bi-hydrate can at a temperature above 30° and a moderate RH (30-40%) gradually lose its combined water becoming anhydrite and this weakens the rendering. The studies made by Van't Hoff [26] have revealed the instability of calcium sulphate at 30°C and at relative humidities lower than 75% and such a process of alteration has been found taking place in the Tomb of Nefertari in The Valley of the Kings, Luxor [18].

13.3 *LIME*

Renderings formulated with lime and especially those of fresco and other lime techniques where the pigments are fixed by the calcium carbonate, can suffer disintegration by chemical change due to the action of water containing dissolved carbonic anhydride as well as by the physical mechanism of decay involving the crystallization of salts.

In the course of the setting of a fresco rendering, water progressively evaporates from the surface that is exposed to the air and the relatively fluid mortar is transformed into a mass that becomes more and more compact. Gradually a crust of calcium carbonate begins to form on the surface. But the formation of this crust lessens the absorption of carbon dioxide within the body of the rendering. In consequence one obtains, in very dry ambience, a hard crust of calcium carbonate on the surface overlying a weaker core of incompletely carbonated matter because its moisture has been absorbed by the wall before all the calcium hydrate has had time to be carbonated like the surface. Thus one may sometimes come across calcium hydrate in a dry state within an apparently sound rendering: this causes weakness and moreover is extremely sensitive to fog, to damp and of course to rainwater for, when moisture is present, the hydrate in enabled to react anew with the carbon dioxide in the atmosphere and on re-drying it comes to the surface and is carbonated on exposure, hardening the ground and paint layers.

The process will continue so long as there is any undecomposed hydrate remaining on the wall. But when all has been finally used up, increasing humidity is likely to provoke a reverse action, causing disintegration this time since the carbonic anhydride can no longer react with calcium hydrate and is free to exercise its acid action on the calcium carbonate transforming it into soluble bicarbonate.

Carbon dioxide which is contained in the atmosphere reacts with water to form the very weak acid carbonic acid. Solutions of this acid slowly dissolve calcium carbonate giving rise to the soluble bicarbonate which when washed away, soon decomposes again by loss of water to deposit a layer of the insoluble calcium carbonate and this often accounts for the white veil found covering mural paintings.

An analogous phenomenon is produced sometimes in paintings that are underground (e.g. cave paintings) whatever the technique used. Infiltrating water containing bicarbonate can give rise to surface carbonate deposits on drying. Hard water, as we know, deposits salts readily and it is the calcium constituent of such salts that is the main cause of the hardness that is familiar to us in heating installations and pipes, kettles, etc.

In conclusion, the action of water depends mainly on the relationship between calcium salts and carbonic anhydride. When water is present, solution and hence deterioration takes place as well as redeposition with the formation of a white veil of calcium carbonate covering areas where the aqueous solution of bicarbonate dries to leave the carbonate behind. An ideal equilibrium is impossible in practice, perfect conservation of surfaces being in such conditions almost unattainable.

14. **Pigments**

Humidity makes possible certain chemical actions which modify the composition and in consequence the colour of certain pigments. Such pigments are rather unsuitable for fresco painting.

Leadwhite (basic lead carbonate) and *Minium* (red oxide of lead) are transformed into brown lead dioxide. This can be very localized [9, 11].

Azurite (basic carbonate of copper - blue) is transformed by the action of humidity into the green carbonate (*malachite*) which is more basic in character. It has been claimed that in the presence of moisture and sulphuric acid certain copper blues are decomposed to black *copper sulphide* [3].

Cinnabar (red mercuric sulphide) sometimes changes to a black metacinnabarite under the combined action of light and moisture, a transformation that profoundly modifies the appearance but does not change the chemical formula [15].

II. CONTROL

1. Water the Universal Catalyst

Humidity, as has been stated, is by far the most important cause of deterioration in mural paintings. The first measures to be taken, therefore, are to find out the source of the humidy and having done this to take steps to eliminate it. If this confronts us with the problem of the conservation of the building itself we shall be forced to accept the larger problem and for the sake of the murals study it in detail (1) [16-17-27].

The humidity of walls can be the subject of an analytical classification in five types according to its origin.

(i) Humidity due to infiltration caused by defects in roof or guttering or by exposure of walls to driving rain.

(ii) Humidity due to capillarity where walls are in contact with damp ground.

(iii) Humidity arising from condensation on cold walls.

(iv) Humidity caused by the presence of hygroscopic materials, characterized by instability.

(v) Humidity arising from damp air in basements.

2. Survey and Measurement of Humidity and Temperature

Determining the causes of humidity in a wall implies making a survey and interpreting systematically an assembly of often complex facts. In general, one has to guard against prejudging the issue or making decisions that are claimed to be based instinctively upon common sense. One can only hope to make a correct diagnosis following a careful study of objective data collected by the use of instruments that register the conditions by measurement.

After studying the structure and the condition of preservation of a building, one proceeds, as the case demands, to measure and to record a series of characteristics such as those described below.

(i) A statement of the RH (2) and temperature of the air outside and inside the monument covering one entire year will allow one to take account of the magnitude and the variations in the two figures and decide as to whether conditions are ever likely to favour condensation. One uses simple equipment for obtaining such records. (Par. 3.1.)

(ii) The measurement of the superficial humidity of walls is

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(1) For further information see bibliography.

(2) Relative Humidity.

probably that of most immediate interest to the conservation of mural paintings. It is done with direct-reading instruments recording percentage humidity, but a rather special instrument is required for continuous documentation.

(iii) By measuring the concentration and the distribution of humidity in the walls one can establish whether the moisture comes from the ground (capillarity), the roof (infiltration) or the wall surfaces (condensation). For this type of measurement one generally takes samples which are weighed before and after desiccation. One can also introduce into the wall at different points and at different depths probes that are connected to a registration instrument, but this involves the use of complex and very expensive apparatus.

(iv) The temperature of walls may be obtained by the use of different non-registering instruments which implies that here, as before, continuous documentation is a separate investigation. By comparing the temperature of walls on the exterior and interior surface one can assess their efficiency as heat barriers and this is essential in order to establish if the conditions are such as to promote condensation.

The interpretation of the facts thus collected will be based upon familiarity with the characteristics of the different types of humidity to be examined later (Par. 4.1) and the results will then be examined together with the list of alterations to which the painting has been subject and notably to the various manifestations of cleavage as between strata and wall. In such an enquiry it is useful to make a graph externally and internally showing curves uniting different zones that have the same humidity — relating these with damage on the painting and noting particularly at which points the humidity is excessive, i.e. more than 2-4%. In the majority of cases such a confrontation will enable one to understand very easily the source of the humidity responsible for the alteration of paintings. One can see in Fig. 2 an example of such an early stage, but it suffices to show the zones of humidity excessive for the good conservation of a painting.

We may remark in passing that the staining to be seen on old walls has not necessarily arisen from continuous exposure to humidity. Very often the phenomenon has had its origin in exposure to moisture during some restricted period long past. The dark stains to which we refer form quite quickly — in the laboratory one can reproduce them on bricks in the course of two or three days — and they are probably due to the migration towards the surface of certain mineral or organic colouring matters derived from the wall.

3. **Instrumentation**

It should be possible by simple means to make a record of the measurements required in order to determine the origin of humidity and of the causes of alteration and these measurements should be designed to cover a period of one year for it is clear that certain types of humidity are of a discontinuous nature, — such as humidity caused by condensation

— appearing only occasionally. One cannot, therefore, rely on isolated observations as the seasonal variations of humidity are quite as important. Measuring and continuously recording instruments are both required and if the latter type is not available it will mean that more frequent readings must be taken with the former in order to be able to compile a satisfactory graph illustrating long-term variations in the conditions.

Precise figures are difficult to obtain and, indeed, with some instruments it is necessary to regulate the instruments for each measurement or at least once a month.

We have no intention of attempting to record here all types of instruments or all existing systems of measurement and will limit ourselves to describing below those that are simple to apply and that provide data with sufficient accuracy for our requirements [16].

3.1 *MEASURING THE RELATIVE HUMIDITY OF THE ATMOSPHERE*

This measurement can be made by using one or other of the following instruments:

- psychrometers;
- dew point hygrometers;
- hair hygrometers;
- hygrometers based upon various other principles.

(a) *Psychrometers*

Psychrometers consist of two ordinary thermometers so arranged that while the bulb of one is in direct contact with the atmosphere the other is covered by a textile sock kept moistened with water. The water in the sock exaporates at a certain rate depending on the relative humidity of the surrounding atmosphere. The major part of the heat necessary for this evaporation being furnished by the bulb of the thermometer, the temperature falls and a difference between dry bulb and wet bulb readings may be observed and recorded.

Movements of the air in the neighbourhood will obviously affect the rate of evaproation, but this can be corrected by ensuring that a current of air, say 4 —10 metres a second is made to pass over the bulbs. This largely reduces the error and allows one to obtain by this instrument an accuracy of some 4% in the RH. In actual use one subtracts the temperature recorded on the wet bulb thermometer from that on the dry, obtaining a figure that can be converted by using a hygrometric table to give the required relative humidity of the air.

The principle sources of error in reading the psychrometer are in the proximity of the observer. Water vapour is exhaled on breathing (about 60 g/h and more) and this affects the thermometers, especially if reading should be difficult owing to the scale of the thermometers being too short. Indeed, an error of 1°C in the reading may make a difference of 8 or 10% in the RH figure obtained. In more refined instruments where the scale is long and clearly read and the bulbs adequately screened a precision of ± 2% can be obtained.

Psychrometers must be kept scrupulously clean. Only distilled water should be used to moisten the sock which must be washed in distilled water at all times and replaced if it shows the slightest sign of contamination or if it becomes unravelled for this would be likely to affect the rate of evaporation and so vitiate results.

Psychrometers exist as static wall types (which must be fanned by hand or they do not work) or dynamic portable types which incorporate a small fan operated by electric battery or clockwork and provide a constant current of air over the bulbs. There is also the simpler form of whirling psychrometer so arranged that when held at arms length the thermometer can be made to spint round the handle extension functioning as axis and are thus adequately aerated.

Certain types of psychrometers are designed to be read at a distance or even to be self recording. For further details the specialized literature must be consulted [16].

Instead of using mercury thermometers those having thermometers of the electrical resistance type are available. These have the advantage of greater precision; they are easier to regulate and can be controlled from a distance.

(b) *Dew-point apparatus*

The essential part of the dew-point apparatus is a mirror, the temperature of which can be measured and which can be cooled progressively to a point when the moisuture in the air begins to condense upon its surface. This is known as the dew-point. It corresponds to the temperature at which the air is saturated. The higher the RH the smaller the degree of cooling required.

The most accurate results are obtainable when the difference between the temperature when the dew forms and the temperature when it disappears does not exceed 5°C. The mean of these two temperatures is actually taken as the condensation point and a table then furnishes the figure for the tension of acqueous vapour that corresponds to this temperature. This indicates the amount of water present in the atmosphere being tested. What is required, however, is the RH and it is obtained by dividing this by the temperature of the air in question.

This system which may appear somewhat complex has been found of great value, however, in making measurements in places inaccessible to other forms of instrument.

Continuously registering instruments have been designed on the basis of the dew-point apparatus but they are even more complex and they require constant maintenance. For details one must consult the literature.

The successful application of all these instruments requires a certain experience on the part of the operator. They must be filled with a sample of air that is representative of that to be measured and the main difficulty is in determining the exact moment when condensation takes place.

Under the best conditions one can obtain figures correct to ± 3%.

(c) *Hair hygrometers*

Hair hygrometers are based on the property of certain organic materials to expand or contract when the humidity varies. In practice small bunches of degreased human hair are used, the bunch being stretched between a fixed point and a lever operating as a needle or an actuating pen that records movements.

The reaction of this kind of instrument to variations of humidity is rather sluggish and may take up to 30 minutes to attain equilibrium. Hair hygrometers, moreover, are subject to contamination by grease or fatty fumes which in isolating the hairs may reduce considerably their sensibility to humidity.

The principle of the hair hygrometer has been adopted in a series of instruments from the pocket size with a needle, to tiny forms to introduce into small places or tubes, etc., to pen-recording types for use in obtaining continuous documentation, and to controlling alarm systems and air conditioning equipment.

For temperatures lying between 15° and 21°C and relative humidities from 30-80% the precision of reading is between 3 and 4%. At lower or higher temperatures readings may vary from 10% too high at —5°C to 10% too high above 35°C. For this reason they cannot claim to be precision equipment and, indeed, if the operator is not familiar with their behaviour significant errors may be introduced. On the other hand they have the great advantage that they can be positioned for local recording even in a closed room and can be read immediately and with ease. When employed judiciously and given the necessary time to function properly in reacting to the ambiente atmosphere they are extremely useful.

It is essential, however, that they be calibrated regularly by using a psychrometer or dew-point apparatus and this should be done at least every two months or more often if they are ever moved.

If one has not the control instruments at hand a rough and ready form of calibration is obtained by wetting the hairs carefully with a soft camel-hair brush using distilled water. This should give a reading of 95% RH and not as might have been supposed 100%.

(d) *Hygrometers based on other principles*

It remains to describe certain other hygrometers coming within this category that give fairly accurate readings, are easy to use, and that can be read at a distance.

Electrolytic hygrometers are used to measure the RH of the atmosphere by recording the variations in the electrical resistance of a material that is sensitive to changes of atmospheric humidity when it is subjected to an electrical current of high frequency. Suitable materials may be tissues of cotton fibre, inorganic fibres impregnated with hygroscopic salts or certain synthetic resins. They must be carefully protected from dust and replenished annually.

A special new apparatus based on this principle and designed for work on condensation moisture has been brought to attention by the Italian Commission for the Study of Humidity in Walls [1]. As condensation is an intermittent phenomenon it is necessary to have an apparatus that can be relied upon to remain sensitive to changes and to record conditions over a lengthy period of time if one wishes to document the manifestations of condensation. The principle of operation is based on the variations of electrical conductivity in relation to the quantity of water contained by the hydrolyzed salts that are present in most materials used in building construction.

In practice, the sensitive element is constructed on a support for printed circuits covered over with copper and divided in two parts along its length by a groove with the shape of saw teeth about 1 mm in width. The whole thing is gilded to ensure that the surface is insoluble. Thus two electrically — isolated electrodes are obtained of known length.

At the back of the plaque a layer of the material constituent of the wall that is under test is built up to about a depth of 1 cm whilst the groove in front is filled with a paste made from material taken from the surface of the wall and reduced to powder.

This scheme enables one to determine the moment when water is first condensed on the surface and whether this arises by simple condensation or is affected by the presence of salts that are more or less hygroscopic.

By applying an alternating current of some milliamps through the element in order to avoid complications by polarisation one can obtain a resistance that varies with the humidity that is present.

By connecting the element to an instrument that registers the condition one can observe the critical moments when the first pellicle of condensed moisture is forming on the wall under test and hence by collating this with the other relevant climatic factors one can determine the causes leading to the condensation. This apparatus also can be used for controlling the operation of equipment designed to control the humidity of the atmosphere and thus protect the painting from exposure to excessive damp.

Capacitor hygrometers have a pair of pure gold electrode plates separated by a dielectric of some mms. thickness that is capable of absorbing humidity. The amount of humidity that is absorbed determines the capacity which can be measured by an electronic circuit at high frequency and recorded on specialized equipment.

Hygrometric indicator papers can be prepared from special tissue which has been impregnated with a solution of cobalt thiocyanate (0.55 mg/cm^2) which causes it to change colour when exposed to different humidities. By comparing the colour with a key chart covering the colour range one can get a rough estimation of the RH of the atmosphere (approximation ± 10%).

Conclusions

As the atmosphere to which works of art are normally exposed never varies to the extremes that are of interest in meteorology or industry the restorer can be content with a limited number of simple instruments such as the following:

— a pocket sized hair hygrometer provided with a thermometer;

— one or several self-recording thermohygrographs for continuous recording;

— an electric psychrometer of good quality, — the key instrument used to calibrate the above mentioned equipment.

Instruments other than the precise psychrometer need not read more accurately than to ±4% RH at normal temperatures.

3.2 *MEASURING THE HUMIDITY OF WALLS*

To determine the origin of the humidity it is necessary besides recording the relative humidity and temperature of the air to study both the superficial humidity and the internal humidity of the walls.

(a) *Measuring superficial humidity*

Several instruments used for the measurement of superficial humidity are based on variations in the electric conductivity of the wall constituents which depends upon the amount of moisture present. The contact models have a window. applied directly to the wall behind which are the two electrodes maintained at a known distance one from the other. The *electrode-insertion* models have pointed electrodes that have to penetrate into the wall and this causes damage if the wall is painted. The electrodes may be held at a fixed distance apart by their support or if separate, they must be carefully inserted at a pre-established distance the one from the other.

Recent models are provided with a scale on which one can read directly the RH of different materials, masonry or for example, wood. As walls are composed of different materials (partly limestone, plaster, cement, etc.), there are auxiliary tables that allow one to calculate with greater precision the actual conditions from the data furnished by the instrument.

The above types of apparatus must be calibrated on each occasion prior to use. In general they furnish information that is very useful but not always very precise.

(b) *Measuring the concentration or the distribution of humidity within the wall*

For such investigations it is necessary to take samples of the wall by drilling holes with a low number of rotations to avoid heat (Fig. 3). The first

20 cm of extracted matter is jettisoned and then proceeding to drill more deeply one collects the sample for analysis (25-30 g), placing it immediately inside an airtight weighing bottle and weighing it at once. The bottle is then opened and placed in an oven in which the sample is heated for seven hours at 100°C in a current of air. This is standard laboratory practice subject to slight variations where it is a question of dehydration; and after cooling in a dry atmosphere (desiccator), and reweighing, the results are expressed as a percentage of humidity in the original material.

The percentages obtained by testing in this manner at various places and at various depths make it possible for one to prepare concentration diagrams.

3.3 *MEASURING THE TEMPERATURE OF WALLS*

The temperature can be measured by using an optical thermometer that is able to capture the infra-red radiations from the surface by means of a series of thermoelectric couples recording instantaneously without inertia. Rapid assessments are thus possible, but as there is no continuous recording there is the possibility of missing phenomena that are intermittent unless frequent observations are made.

Records of temperature should be made of all surfaces within the room, ceiling, floors and walls as such measurements can supply extremely useful information on the mechanism of alteration.

If this type of equipment is not available one must have recourse to an ordinary thermo-couple type of thermometer in which the thermocouple is put either in direct contact with the wall by means of a clay cone that gradually acquires the same temperature or is furnished with a pastille attachment that gives equally good result.

Failing this one must use an ordinary mercury thermometer, preferably of long scale and easily read. The bulb is exposed to the temperature of the wall by dipping into a series of small clay "buckets" that have been attached to the wall and filled with mercury. Inevitably, however, there is some loss of mercury when the buckets are eventually detached.

Thermovision

A recent system for measuring the external temperature of objects uses an instrument that intercepts the infra-red radiation within its field by means of a special counter [25].

This device converts the signal picked up into an electric impulse that, amplified, controls the electronic band of a cathode ray tube of a television monitor.

The image or thermogramme indicates within approximately 0,2°C the external temperatures of the objects focused on.

The hot areas show up as white and darken progressively through greyish tones until black is reached indicating cold areas.

A single instrument can measure temperatures ranging from —30°C to +2000°C and visually indicate, in black and white, measurements up to two isotherms, with colour equipment up to 8.

The images can be registered on photographic plates, motion picture film and magnetic tape.

While the system has not given positive results up to now in indicating plaster detachments or non-homogeneous zones, it is very useful in the study of micro-climates in large monumental complexes.

In fact, it is difficult to effect normal measurements of the superficial temperatures of mural structures, however with thermovision it is possible to see and evaluate differences of 0,2°C with the greatest of ease, even in very large ambients.

On the accompanying thermogramme it is possible to note areas with a temperature difference of up to 3°C, which can obviously cause condensation, with its known consequences for the film of paint, to form on the coldest spots.

The instrument used was an AGA Thermovision 680.

The system also offers the possibility of discovering, through temperature differences, hidden structures and structures in reinforced concrete, or, in any case, areas of low inertia and high thermic conductivity.

4. **Humidity Control**

4.1 *DETERMINING THE SOURCES OF HUMIDITY*

4.1.1 *Infiltrating moisture*

This may be due to defects in the roof, in terraces, guttering or it may arise from leaking drainage systems. Despite appearances the point of origin is not always easy to determine as the water may run along cracks within the wall and only come to the surface and cause damage a long way from the sources. Nevertheless, systematic study usually leads in the end to a satisfactory diagnosis and identification of the cause.

4.1.2 *Humidity caused by driving rain*

4.1.2.1 *Direct action of rain*

The direct action of rain on a painted surface causes damage especially by trickling, where the effects are more in evidence the more sensitive the surface ingredients are to water. Having regard to the extreme thinness of the paint layer (10-30 microns) damage soon occurs. Painting which employs an organic binding medium and grounds having a basis of plaster or of clay soon show signs of disintegration, whereas frescoes and grounds containing calcium carbonate are subject to attack by water in which carbon dioxide is dissolved (see par. 13.3). To these direct effects of rain must be added those types of damage resulting from the presence of soluble salts — migrations and recrystallisations — occasioned by solution in the excess moisture (see par. 5).

It is evident that for paintings exposed to weathering the orientation of the walls with respect to prevailing winds will constitute an important factor as regards conservation.

4.1.2.2 *Infiltration through walls*

This case is not frequently found in ancient buildings, but when it does occur it applies usually to one or two sides of the building only, because in any given situation the rain-storms tend to be directional in their action. Moreover, they are by their very nature seasonal and thus the damage to which they give rise is likely to be limited at least in temperate climates.

The amount of water that is absorbed depends less on the force of the gale than on the capillarity characteristics of the wall. The appearance of moisture on the inner surface will depend naturally to a large extent on the thickness of the wall, but it may also result from condensation provoked by cooling of the outside of the building caused by rain-storms and the infiltration of the rain into the external surface.

When the wind is blowing with a velocity of 45 km/h this corresponds to a pressure on a vertical wall at right angles to the direction of the wind of 12 kg/m^2, the pressure of a column of water of 12 mm i.e. about 1/1000 of an atmosphere. This is a very small figure and it can do little more than to ensure the wetting of the surface, penetration being due to the results of capillarity operating on the mortar and other constituents of the wall. In the case of a wall constructed of stones that cannot absorb moisture by capillarity, the damped areas of the mortar joints cannot dry by the water soaking into the surrounding stones and it is obliged to find its way inwards carrying with it any soluble salts encoutered in its passage, these being deposited on the inner surface of the wall as the water evaporates. (Fig. 4).

Even the wind in certain cases can prevent the normal drainage of water from windows and gutters so that it finds its way into the interior.

4.1.2.3 *Cooling and condensation*

Whether from rain or from other causes, the damp soaking into an exterior wall lowers the temperature on evaporation. If this wall is too thin or if it presents feeble resistance or high thermal conductivity the external chilling may be the cause of condensation inside (see par 4.1.2.3) — condition not at all common in ancient buildings in which walls are normally too thick for the phenomenon to occur.

4.1.3 *Humidity arising from capillarity*

Capillarity humidity is normally recognizable by the presence of persistent dark stains on the pavement and the walls stretching from the ground upwards for a certain height and by the formation of efflorescence and sometimes even erosion of the upper part of the humid zone following a line approximately parallel to the ground. Examination of the wall in depth by taking samples at different heights and depths should reveal that the humidity is of the same magnitude throughout the area in question tailing off towards the top. Capillarity humidity causes the destruction of surfaces and of mortars by the dissolving and recrystallising of salts in the zone of evaporation.

This type of humidity is chiefly found in pavements and walls that are made of porous materials and are in contact with the soil.

The water rises much higher in a thick than a thin wall when the factor of evaporation is at a minimum because of lack of ventilation and when the temperature is low. It mounts higher in walls exposed to the north and in the walls of enclosed courtyards than in walls having a southern exposure. The maximum height may reach two or three metres and this level is not greatly modified by seasonal changes.

The moisture that impregnates walls that are in contact with the soil may arise from water that has accumulated superficially in a limited zone. In this case it will usually attack an isolated building or even only part of a building. Should we be confronted with the major problem of moisture coming from an elevated watertable a whole building or even more than one building may be affected in the zone in question. One knows that the height of the watertable may rise as a result of construction work, the construction of retaining walls and such like nearby and that the effect may not be in evidence for quite a time thereafter. The impermeable paving used in some modern structures may well be a contributory factor.

4.1.4 *Humidity and condensation*

When humidity is due to condensation the walls become covered with a uniform veil of whitish crystalline fluorescence which may sometimes disappear during periods of active condensation. At the angle made by vertical walls with a pavement slight erosion is usually to be observed due to the condensed moisture trickling down to the ground.

Measurements of humidity will reveal that the surface areas are much wetter than the interior of the walls and that at similar depths in the wall the humidity figures correspond irrespective of the height above ground.

It seems that the phenomenon of condensation is noticed especially in countries in which the mean January temperature is as low as 2°C.

Humidity resulting from condensation is encountered very commonly in underground rooms (cellars, crypts) in spring and summer, whereas in winter it may be seen in buildings above earth level on the inside surfaces of walls of moderate thickness or of considerable, thickness, if these are of dense siliceous rock or limestone and in consequence good conductors of heat.

In spring and summer it is due to the thermic inertia of walls and of the neighbouring ground and of pavements that remain cold in winter.

This chills any warm air entering the locality with consequent elevation of the relative humidity. In winter the thinner walls become chilled by the cold outside and by the evaporation of rain water from external surfaces.

Condensation tends to be more prevalent in the absence of internal winter heating. It is influenced to no small extent by the use to which rooms are put, kitchen premises being exposed in the normal course to water vapour and assembly rooms likewise when crowds of people are present. (Fig. 9). It should be added that, when heating is only occasional rather than regular and ventilation inadequate, condensation phenomena are only to be expected. Humidity arising from capillarity or infiltration on evaporating into a room may eventually be redeposited on the colder surfaces.

4.1.5 *Variable humidity*

This arises when a heterogeneity of material is used in the construction of a wall and in consequence is not a common phenomenon where mural paintings are concerned, as the soundness of the structure will have been assured before painting commenced. Old or re-used bricks or stones may sometimes slow down the evaporation of moisture absorbed from the wall or the atmosphere by reason of a kind of superficial cementation. Other materials of high specific weight and good thermal conductivity such as metals and marble transmit more cold and so favour the condensation of atmospheric humidity. And, finally, there is the contribution that is made by any hygroscopic materials that may be present, which also give rise to the dark staining characteristic of local dampness.

4.1.6 *Humidity from the sub-soil*

The underlying soil between the foundations and the water-table when very porous may contain up to 50% of air and this being humid can give rise to surface condensations when there is a fall of atmospheric pressure and the surroundings are cold. Irregularity is a characteristic of this phenomenon. It tends to disappear in summer and affects only the cellar premises.

4.1.7 *Humidity exchange between atmosphere and walls*

In order to understand the mechanism of the interchange of humidity between the walls and the air in a room we must first consider the various cases that are presented in a very simplified way.

(i) Wall normally dry; air normally dry and temperature of the two in equilibrium. Result — no movement of humidity to cause damage. These are the ideal conditions (Fig. 5).

(ii) Wall very wet in a closed damp room; temperature of the two in equilibrium (Fig. 6). When the air is once saturated at a given temperature the moisture in the interior of the wall no longer evaporates. It is quite possible for no apparent damage to ensue, save that from trickles of water running down the walls, charged probably with bicarbonates or nitrates. Moreover, there is a possibility that slow disintegration may be occurring as a result of gases dissolved on the surface water.

(iii) Walls humid; ambient air dry; temperatures either varied or identical (Fig. 7). Water evaporates from the wall into the air. If it contains soluble salts or any acids that attack the calcium carbonate with the formation of soluble salt, the salts take the form of a white veil over the painting or may form a layer of crystals or efflorescence. In certain cases as in grottos a thick incrustation may be formed, apparently without enfeeblement of the surface, but these tend in time to become detached taking with them fragments of the paint layer. Acids may also be formed on the surface of the wall by the action between atmospheric pollutants (sulphur dioxide, carbon dioxide) and the moisture. Should this happen it is likely to affect the stability of the surface layers or if it takes place in depth the acids, little by little may be neutralized by the carbonates in the course of their migration towards the surface. The intonaco functions as a filter so that only the soluble salts reach the surface.

(iv) Walls dry and warm; air humid and cold (Fig. 8). No condensation takes place; no deterioration anticipated.

(v) Walls dry and cold; air humid but warmer than walls (Fig. 9). Humidity condenses on the surface of the wall if this wall surface is sufficiently cold to lower its temperature below dew point. If not it may be colder beneath the surface in which case water may be formed beneath the painting.

In the case of superficial condensation the gases formed by interaction between the moisture and air pollutants attack and weaken the calcium carbonate as described above. Soluble salts resulting from the action penetrate into the rendering where they are eventually deposited in solid form. If they are compact they may actually reinforce a weakened area, but if the deposits are weak, discontinuous and lacking in cohesion the tendency will be to threaten to disintegrate both the painting and the rendering. A similar phenomenon can be observed on walls exposed to rain. On the contrary, if condensation takes place in depth, the reactions will be the same and will disintegrate the rendering beneath the paint layer. Should there be a reversal of conditions wherein the walls are damp whilst the surrounding air becomes dry, damp will come to the surface and evaporate as in case (iii) described above.

(vi) Walls that are wet as a result of capillarity effects. When water rises by capillarity from damp ground and permeates a wall, it climbs to a level determined ultimately by the effects of evaporation and at this level soluble salts crystallize on a line roughly parallel to the ground causing mechanical disintegration of the rendering and the pictorial layer. When, for reasons that are connected with seasonal changes the humidity becomes less intense the effect on capillarity water is that the crystallization zone retracts and the long-term result of these rhythmic movements of salts and water is to form a wide zone of corrosion.

4.2 *CONTROLLING HUMIDITY*

4.2.1 *Infiltrating moisture*

The treatment in this case is to overhaul and repair the roof and drainage systems.

4.2.2 *Moisture due to driving rain*

4.2.2.1 *Walls not painted on the exterior surface*

Cover the walls with a layer or rivetment that will protect it without introducing capillarity risks and will allow the rain to run off without collecting at any points during its passage. One effective system is to use tiles or slates attached with metal hooks. If the wall has an artistic quality that must be respected it should be cleaned and repointed using a hydraulic mortar. If the wall has a rendering this should be remade with a lime mortar containing hydrophobic material.

Renderings made entirely of cement are only suitable for walls directly on the ground. For the repair of joints it is better to use a mortar of hydraulic lime that will not prevent the natural breathing of the surface. Of the many possible formulae, the following have been found satisfactory:

Lime	1	—	1	
Cement	2	1	1	
Sand	9	—	6	(Hydrophobic addition of cerasite)
Powdered brick	—	3	—	

4.2.2.2 *Walls having external paintings*

The most difficult problem to solve in a satisfactory way is certainly that of the durable protection of paintings on outside walls that are exposed to weathering. This presents a dilemma. The only protection that could be guaranteed would be to make a stable construction over the building or at least in front of the walls that are exposed. But such an intervention would alter completely the architectural value of the monument and would thus be considered as ultima ration and only applied if after a complete study no other solution could be found to be satisfactory.

In certain cases when the procedure is acceptable from the architectural standpoint the eaves may be extended so as to afford greater protection for the walls. This is what was done for certain churches in Moldavia that are decorated with frescoes on the exterior and the results seem to a point to have been quite successful. Indeed, it would seem that the greater part of any deterioration must have occurred shortly after their completion in the exposed parts, whilst in parts more protected by the roof and not exposed to prevailing winds the frescoes are in excellent condition. The following ideas suggest themselves:

(1) To establish the minimum angle with the horizontal that rain and snow make when driven by the wind and to examine the degree of protection that would be afforded by any proposed enlargement of the roof.

(2) If this is not sufficient one might imagine further protection being given by a series of laminated slats of aluminium on the lines of the ordinary vitronic or venetian blind to break the direction of the wind and that could be arranged to pull up out of the way in seasons of good weather. In this connection, the presence or the reconstruction of a wall of the complex at a suitable distance and reasonable height would operate to give results of the same kind. (See Fig. 10).

On the other hand one should study the results obtainable in controlling the micro-climate by planting curtains of trees or using protecting screens of large mesh and with hinged or adjustable sections designed to break the wind and to reduce it to a sufficient degree so that rain and snow could not beat against the walls.

The idea of providing mechanically a vertical current of air projected upwards parallel to the walls on the side most exposed to storms and coming automatically into operation when the wind attained a certain velocity would perhaps be worthy of study by experts.

The construction of temporary screens of transparent materials near to the walls cannot be considered seriously, because it would present too many risks of damage during mounting and remounting.

The fixing or consolidation of the paint layer by the use of organic or inorganic impregnants cannot be relied upon for long to give definite protection. Indeed, it has been established on the basis of practical experience that the maximum duration of protection by such treatment is of the order of five years for the most effective of the organic fixatives. As for inorganic fixatives one has not the practical experience to judge whether they would be effective in cases such as those under discussion. There are, moreover, good reasons for believing that inorganic consolidants, being of the nature of fillers rather than adhesives, could aggravate the situation rather than improve it when exposed like the paintings to the process of weathering and changes in temperature.

At all events, whatever procedure seems to be warranted it should be at first examined on the site in an experimental way before being definitively adopted. On the basis of experience to date it may be stated that the product that has afforded the best results or prospects of success has been the synthetic resin known as "Paraloid B 72" a product supplied by the firm of Rohm and Haas, Philadelphia. Continued observation is essential and this involves regular inspection of the areas and maintenance of the frescoes in good condition.

4.2.3 *Controlling humidity resulting from capillarity*

The only means of protecting mural paintings from ascending humidity is to adopt the best means possible for isolating the wall at the base and on the sides too, if it is in contact with other damp walls. But this is only a limited measure and a more profound treatment would be to isolate the building itself from the source of the water contamination as soon as this has been identified satisfactorily.

If the humidity is arising only from exceptional humidity in the soil one may be able by a suitable network of land drains to achieve the desired result. (Fig. 11). If, on the other hand, one is confronted with the problem of a high water-table or of excess water of uncertain origin the only possibility of control is to adopt one of the following lines of procedure.

— isolation of the wall throughout its entire thickness (damp proof course) (Fig. 12);

— reduction of the absorbent section of the wall in order to diminish the intake of water and lower the level of the water rising by capillarity (Fig. 13);

— exterior isolation of the wall with a view to drying the foundations by constructing an impermeable rivetment in case of (Fig. 14) superficial water or a protective wall or by drainage (Fig. 15).

4.2.3.1 *Isolation of the wall*

Without any doubt this is the most effective system; but it is not always possible to apply it because of the great thickness of some ancient walls. It consists in cutting the wall at the base throughout its entire thickness slightly above the pavement with a view to inserting an impermeable layer (Fig. 16). The operation is carried out in two stages in order not to compromise stability. One first makes a series of slots at most 60 cm long (provided the stability will allow) and 20-30 cm high at horizontal intervals apart of the same length as the cuts. The maximum thickness of wall which one can thus cut into satisfactorily is about 1.20 metres, if one can work from both sides. One then inserts in the slots the isolating material which may be warm liquid tar, lead sheeting of 1.5-2 mm thickness covered on each side with bitumen, aluminum sheeting specially prepared in sandwich form with bitumen, begnets of compressed asphalt, etc. The walls is then made good by breaching taking care to compress the material so that it can be relied upon to support the weight of the wall and leaving on both sides a free space of 3 or 4 cm to allow the superposition and welding in of the successive elements of the isolating layer. Mortar must be used in correct proportion and in minimum quantity with a small addition of cement, sand and a good waterproofing material.

When the slots have been finally filled up and made good and the material has hardened one can proceed to the second stage of the operation which consists in cutting the wall that is still intact between the slots and inserting isolating material as before. If conditions require, the slotting can be to some degree curved (arched) as a further contribution to stability.

When the isolating layers are being positioned care must be taken to make them cross through the rendering in order to avoid all risk of contact between this and the damp wall that lies below.

Another system of cutting and of isolating walls has recently been devised and carried out on several buildings by the engineer, G. Massari. The principle is the same as in the case of cutting by hand through the entire thickness of the wall, but in this system the cutting is done mechanically. One uses a small electric drilling machine provided with a power of 1 HP, which will not break the wall and produce debris and which avoids serious vibration that might damage painting and wall. The cutting crown of the tubular tool which penetrates by rotation is made from little diamonds arranged with less than 1 mm of projection around the edges. The depth of the cut, which by hand cutting can not normally exceed 70 cm (or working from both sides 120 cm), can in this process be extended to 150 cm and more. The width of the cut is 3.5 cm only corresponding to the exterior diameter of the crown of the trepan which eventually extracts a cylindrical "carotte." By proceeding to make a series of juxtaposed holes one obtains a slot having clean edges without debris. (Fig. 18).

Procedure - The length of cut is normally 42 cm and it is convenient to work to a standard dimension so as to have always the same quantity of material to put into the hole without waste! The plan of operations must be studied so that the system of cuts do not introduce instability in the structure. In certain cases it will be necessary to proceed to reinforce structures before cutting into them — in the case of pilasters for example. The cut must be situated the lowest possible near but below the pavement level, or slightly above if necessary, and the first series must be given ample time after filling to ensure the mechanical solidity of the building before embarking on the second part of the work i.e. making cuts in the structure that connect with the first series.

Infilling - The mastic mixture that is used for pouring into the holes consists of powdered marble or sand of known granulosity which acts like a skeleton for the calcium carbonate, polyester (or better epoxy resin) and a diluent used to fluidify the mixture.

As for all thermosetting resins the proportions of resin, catalyzer and diluant depend on the temperature. In general one should operate above 15°C. It is wise also to dry the slot thoroughly by ventilation (say for 15 minutes) and to warm and dry the inert components in the first place so as to facilitate polymerization of the resin. The mastic mixture must be homogeneous and of such consistency that it will thoroughly penetrate into the hole, an operation that is facilitated by first stretching on the bottom surface a sheet of polythene about 1/100 mm in thickness. The mastic is poured while warm to ensure fluidity, but never above 40°C.

To run without forming seams, two reservoirs on both sides of the wall are maintained at the same height above the hole and joined by a pair of cramps to hold them in position (Fig. 19).

After running-in the mastic guillotines are inserted with the object of getting rid of excess of resin remaining on the wall. When polyester is employed polymerization is completed in about 3 hours.

In the case of walls that are curved or where the sides are not parallel the impregnation is carried out from one side only, the other side being covered with a little board fixed by plaster leaving an opening at the top to allow air to escape and allow one to check the level of the filling.

4.2.3.2 *Reduction of absorption*

The porous wall can be considered as an infinity of tiny narrow tubes and it will be understood that in reducing the surface of a horizontal section and in augmenting the surface of evaporation with regard to the volume of water absorbed one will reduce the height to which the capillarity water will rise. The method of reducing the surface of the horizontal section is usually to make a series of openings at the base of the wall, so arched as to sustain the structure above and not impair its stability. (Fig. 17).

4.2.3.3 *Exterior revetment and construction of isolating walls*

When isolating revetments are applied to exterior vertical walls from the foundations upwards they are useful only for intercepting superficial water; they are not able to deal with water rising from below.

They are not to be used where there is subterranean water, as their action in preventing superficial evaporation is merely in the end to cause the capillary water to rise higher so aggravating the conditions.

On the other hand, the construction of an isolating wall allows one to keep superficial water away from the foundations without impairing evaporation and this is essential particularly where there is a low water-table against which the action of the isolating wall would be useless. However, the isolating wall can help to increase evaporation from below soil level if one can maintain it in contact with the open air and this may be made more effective by hastening the air circulation with vents.

It should be made clear that all impermeable revetments of whatever nature (cement, asphalt, etc.) whether on walls or on pavements, far from ameliorating the position, aggravate it by their action in preventing evaporation. In fact, they cause the humidity to rise higher than the vertical revetment. Cement, moreover, encourages condensation and also the accummulation of salts as clearly seen in certain Etruscan tombs of Tarquinia where deposits are found along the edges of lacunae that result from modern efforts at consolidation and restoration. Cement was never employed in constructing ancient monuments; it only appears as an unfortunate intervention of the restorer.

Normally it is not sufficient to eliminate any external revetments in order to eliminate rising humidity. This reduces only the level of capillarity water because of the increase of the evaporation surface.

4.2.3.4 *Specialized systems*

(i) *Electro-osmosis*

There is no need to describe in detail the operation of this process which is effective in giving positive results when it is a question of dehydrating earth containing much moisture. But owing to practical experience the results are insufficient when applied to walls of masonry. This, however, does not exclude the possibility that it may be made more effective in future.

(ii) *Atmospheric syphons*

These consist of porous tubes that are set into the wall at such an angle as to be higher in the interior of the wall than externally. The hope is that the drier and lighter air of the atmosphere will find its way into the tubes and in so doing take the place of the humid heavier air coming from the wall and so promote drying, but the system has not been found to give any decisive improvement.

(iii) *Injection of isolating materials and moisture repellants*

With these methods of treatment, which have been in use already for several years, there is no absolute certitude of uniform distribution in the interior of the wall. They succeed, however, in reducing the absorbent cross-section of the wall and thus in reducing capillarity water and to this extent may be effective in lowering the height and amount present. The injection of moisture repellants operates in somewhat the same manner as in the case of the isolating layers (Par. 4.2.3.1). The injection of isolating products on the other hand can be used to intercept water in the soil around the foundations both in the interior and the exterior. A product of the firm Cyanamid (AM 9) has been used successfully for protection of tunnels agains running water.

4.2.4 *Control of humidity resulting from condensation*

One must first of all be alive to the importance of eliminating the causes of humidity resulting from the use of the premises and, in particular, anything that can give rise to water vapour: excessive crowds (churches, meeting rooms), lighting systems, kitchen premises, combustion of gas etc., and if in evidence, the humidity from capillarity or infiltration. This requires careful examination of the whole of the building.

If the humidity arises solely from deficient isolation of the pavement it will suffice to construct an isolating layer between this and the ground. Should it be a question of winter humidity caused by occasional warm winds these must be excluded or the room must be warmed or better still the walls must be kept warm by the use of electrical resistance tubes inserted in the thickness of the masonry. On the contrary, one does not advocate heating in an enclosed space without ventilation when moisture may be coming from the walls. It will be sufficient in this case to raise the temperature of the walls by 4-5°C (about 1000-1400 cal/m^3, using about 1-1.5 hW/h).

In the case of spring or summer humidity which concerns mostly the half basement type of room one should prolong the winter heating, but to a lesser degree to cover two or three extra months as by this means one may avoid the necessity for using forced ventilation without air conditioning which introduces the risk of aggravating still further the degree of condensation. As for the winter humidity that affects particularly walls that are too thin or are inadequately isolated thermically and from the cooling effects of rainstorms — a condition of affairs not commonly found where mural paintings are concerned, there are no means of protecting the interior short of constructing a protective wall on the outside to act as a thermal insulator.

4.2.5 *Variable humidity*

The only way of affording protection from variable humidity is to ascertain and to eradicate the cause, but this is generally not possible where mural paintings are concerned and where the damage is serious, one must consider seriously the question of transfer.

4.2.6 *Humidity from the sub-soil*

This type of humidity is not very common and can be eliminated by preventing the ingress of warm damp air that would condense on the walls, ceiling and floor. In certain cases it could be useful to insert in the pavement isolating ducts with the object of reducing thermic inertia. If interventions of this kind are not possible it would be useful to arrange to slightly warm the building and maintain the heating during the cold spell.

4.2.7 *The time necessary for the drying of walls*

The slow rate of drying in the case of a damp wall is due to the fact that during humidification it is the whole mass (complete as regards height and thickness from foundations upwards) that has absorbed the water, whereas drying only takes place and there is evaporation, i.e. on the exterior surfaces. If after elimination of the source of humidity there is no more capillary rise and if one supposes that the wall is composed of an agglomeration of capillary tubes, evaporation can only take place from de meniscus formed at the end of the tube and this total surface is very limited indeed. This points to the desirability of taking action on the exterior by the application of warm or even of cold currents of air in order to accelerate the removal of moisture.

The painted surfaces at all events must be protected during the drying so as to avert salt crystallizations and local disintegration. This can be accomplished by fixing the painted surface very lightly so as to allow the humidity to come out and then covering this with a compress of paper pulp of about 5 mm thickness. Crystallization of salts then takes place in the thickness of the compress rather than in the painting. One can also use a compress made from sepiolite, attapulgite or kaolin and powdered pumice (1:1) mixed with very little polyvinyl alcohol dissolved in water. If the compress must remain on the wall for a long time a fungicide should be added in order to prevent biological attack.

FIGURES

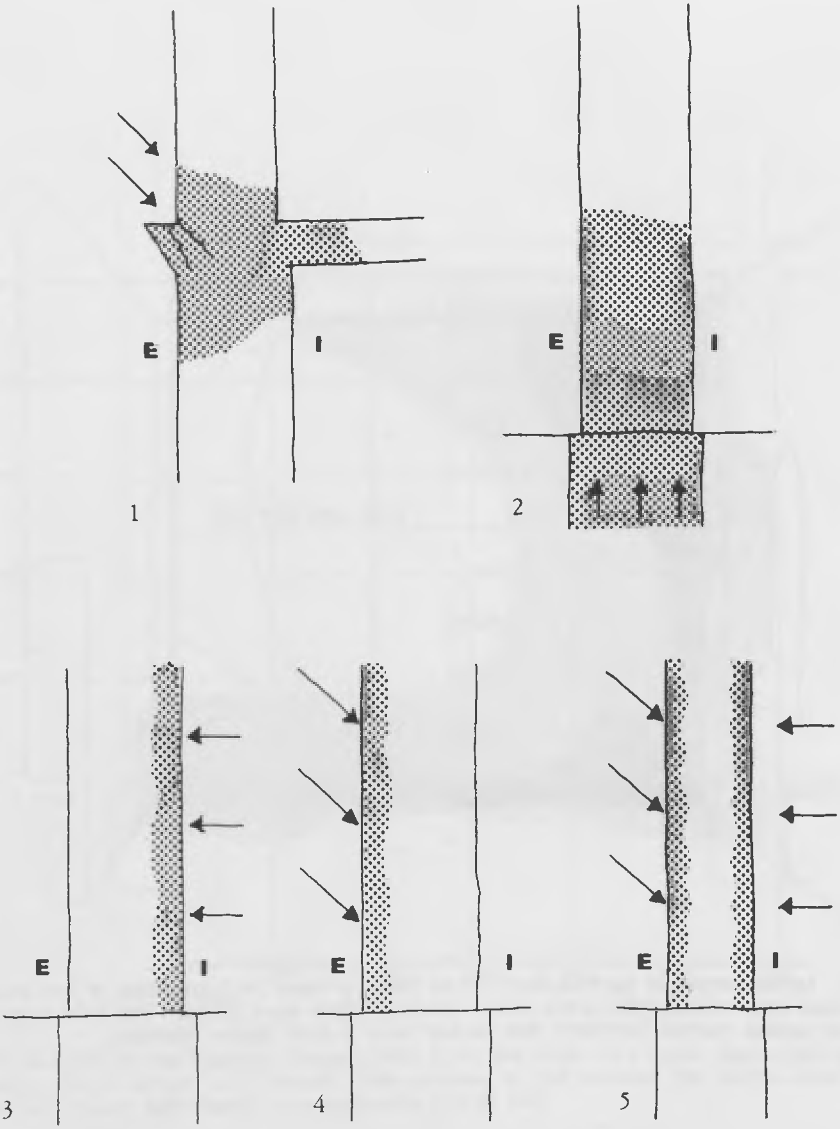

Fig. 1 - Sketch illustrating principle types of humidity in walls. 1. Infiltration; 2. Capillarity; 3. Condensation; 4. Rain and wind; 5. Rain and wind which provokes excessive cooling of the wall with consequent internal condensation. E. Exterior; I. Interior.

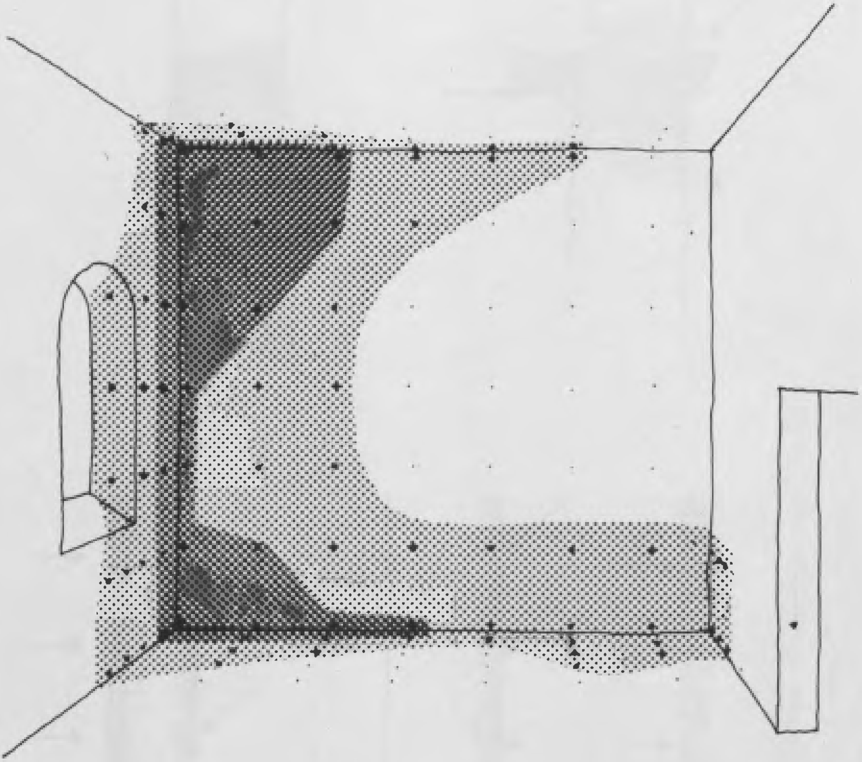

Fig. 2 - Measurement of surface humidity in order to have an initial idea of the situation. The black dots indicate the spots where measurements were taken. The light grey zones indicate above normal humidity, the darker zone a still higher humidity.

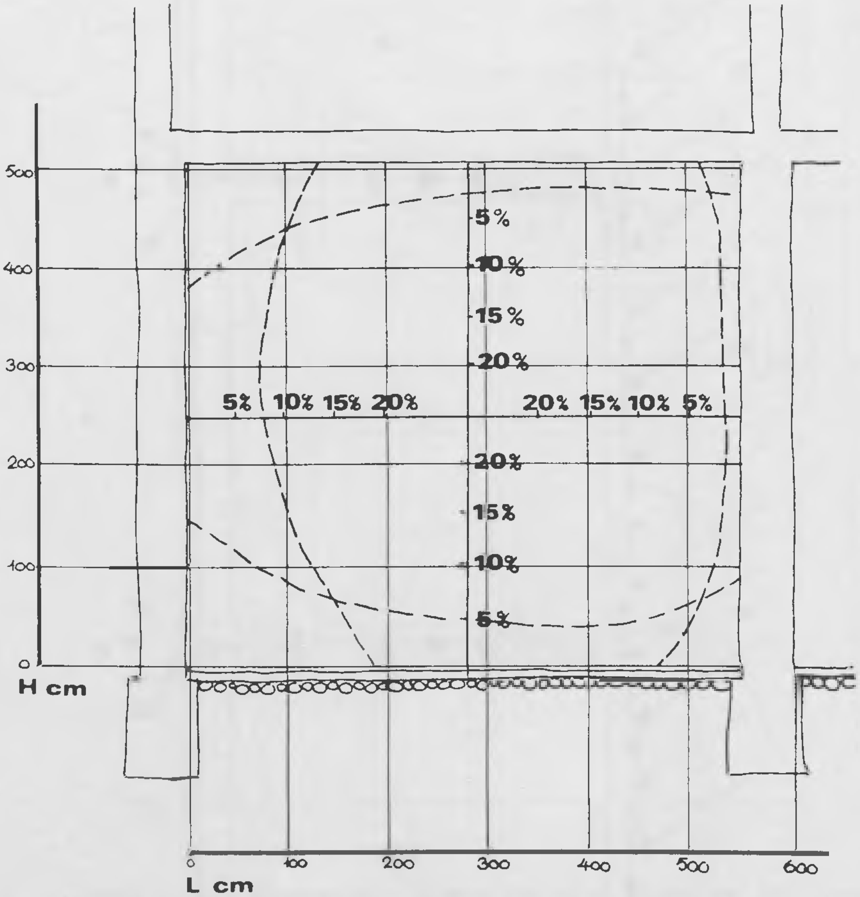

Fig. 3 - Scheme of the humidity survey taken from the walls of a room, represented upon a section. H = height; L = length. The numbers in red indicate the wall's percentage of humidity taken with depth measurements (15-20 cm).

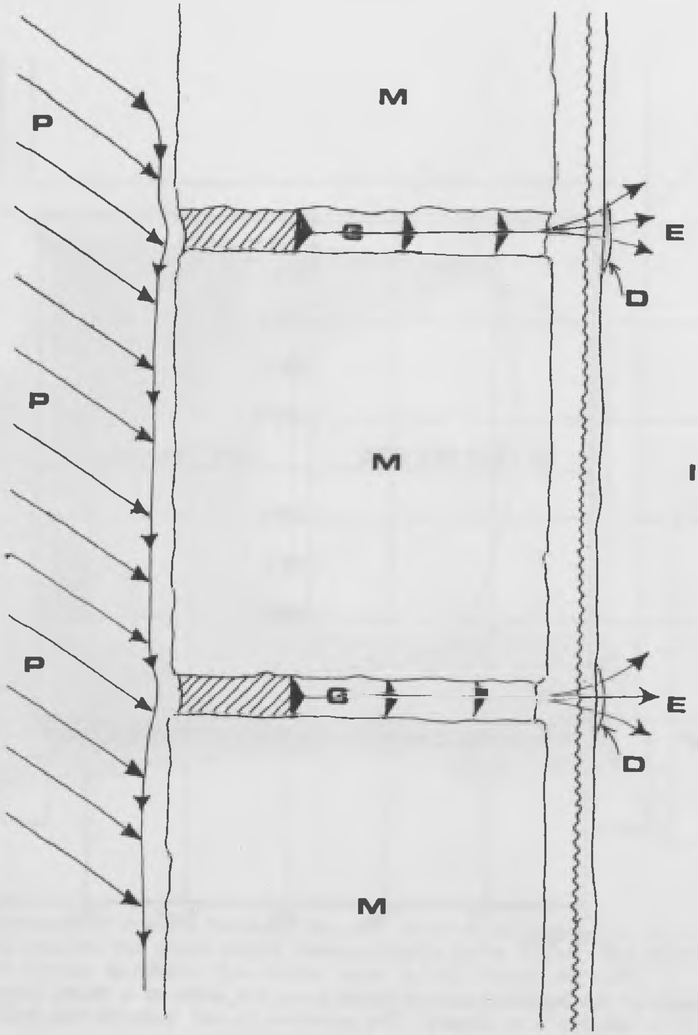

Fig. 4 - Effects of rain and wind on non-absorbent stone masonry. P: rain and wind; G: mortar in absorbent porous materials; M: stone ashlars; E: evaporation area of water that penetrates through the mortar and has brought soluble salts with it; D: salt deposit on the interior surface; I: interior.

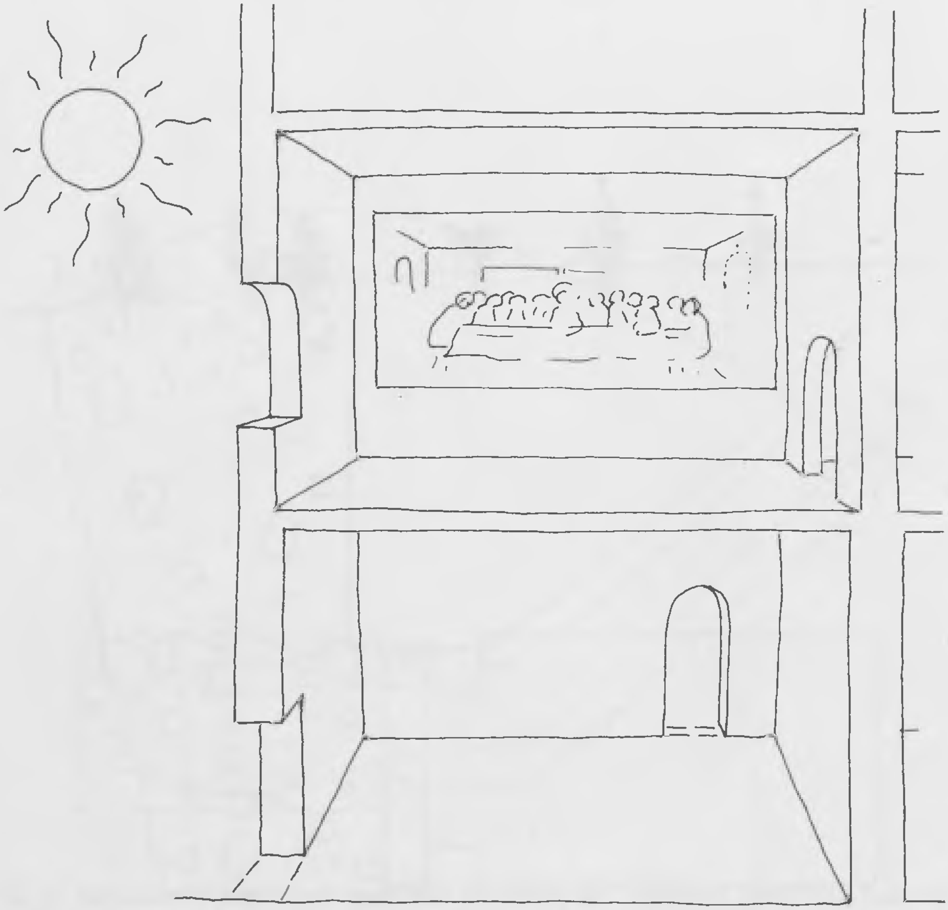

Fig. 5 - A normal healthy environment. Internal RH equal to external RH. Internal temperature equal to external temperature. Masonry temperature in equilibrium with internal temperature. No humidity movement.

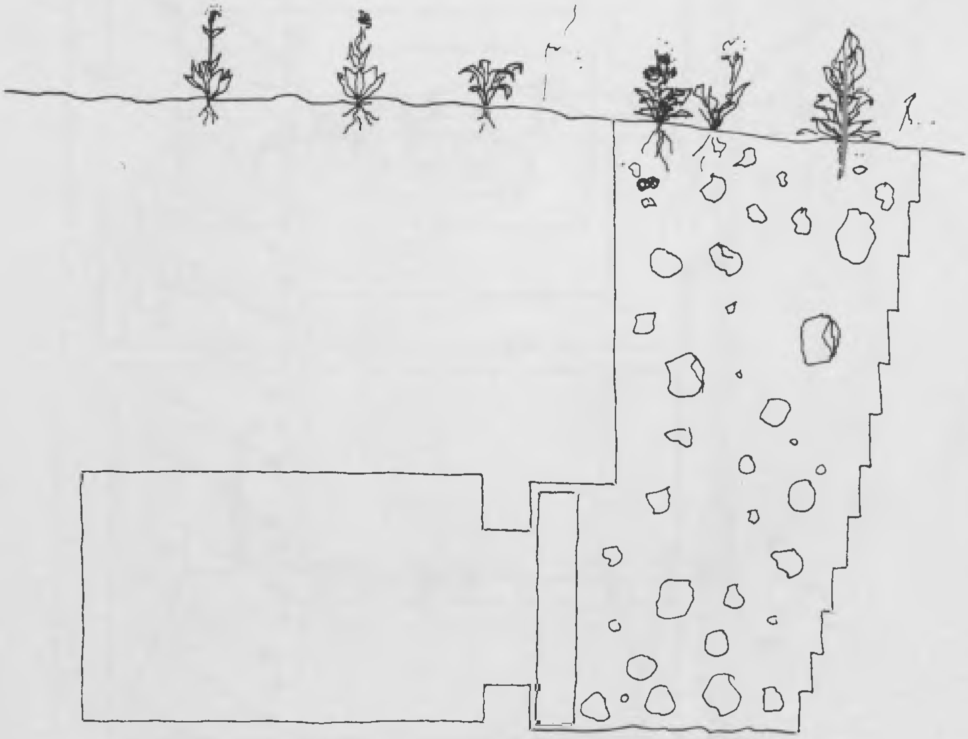

Fig. 6 - A closed very humid environment. Wall very humid, air saturated with moisture. Equal temperatures. No humidity movement. Only water dripping down the walls is possible.

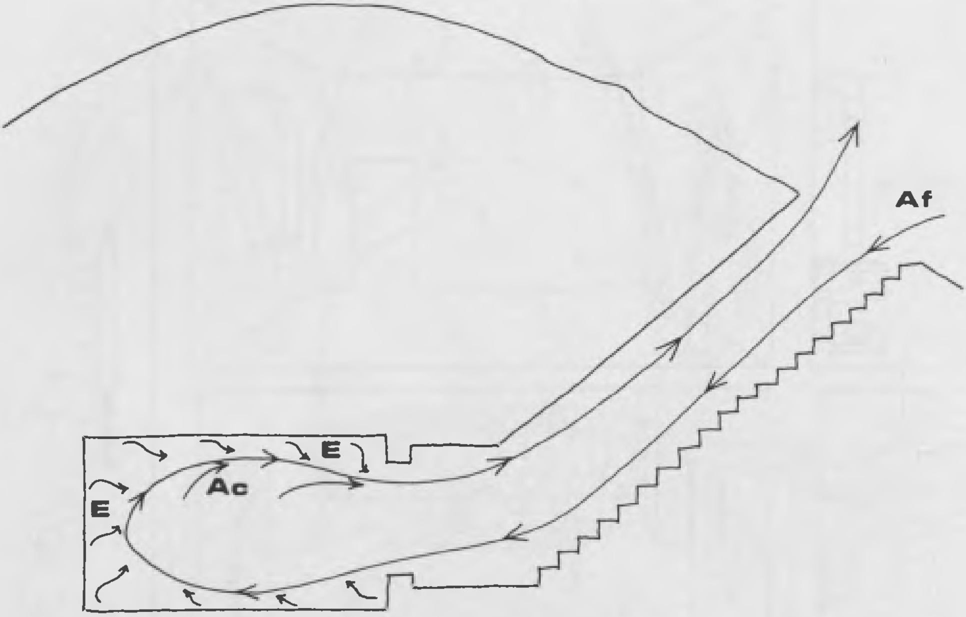

Fig. 7 - Environment with humid walls and circulating air. Humidity evaporates from the walls. Action must be taken. AF: cold dry air which enters the warmer environment; AC: warm humid air which goes out; E: the cold dry air which penetrates from outside causing the evaporation of humidity from the walls.

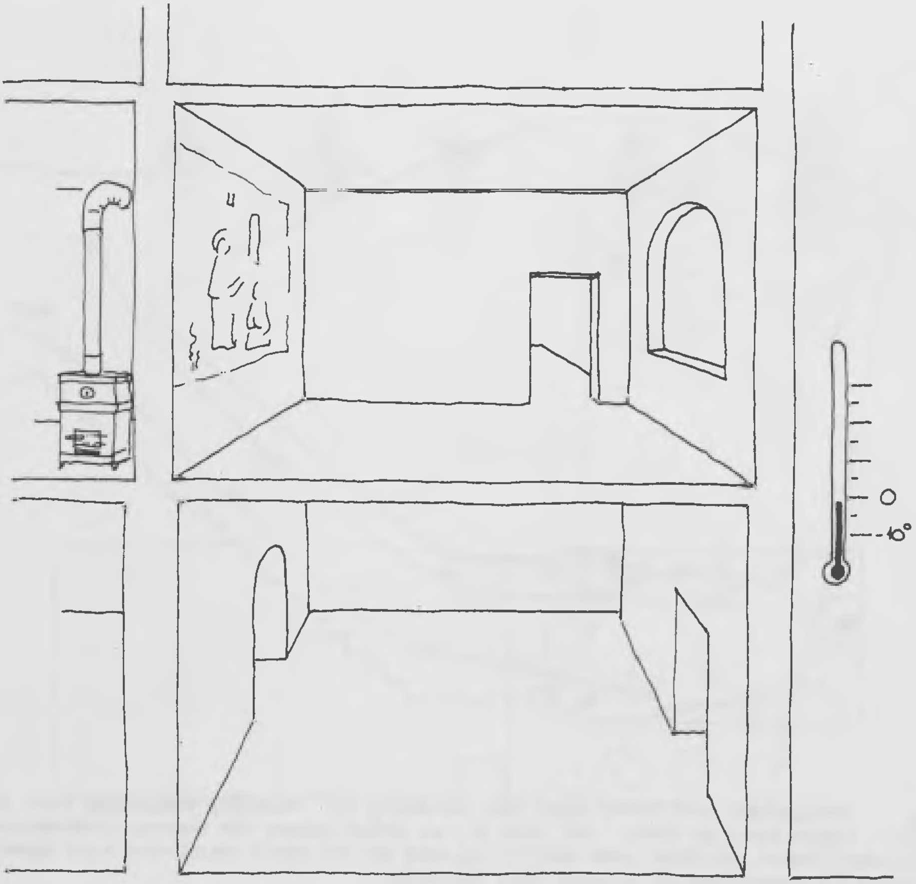

Fig. 8 - A warm dry wall - humid cold environment. No condensation therefore no alteration.

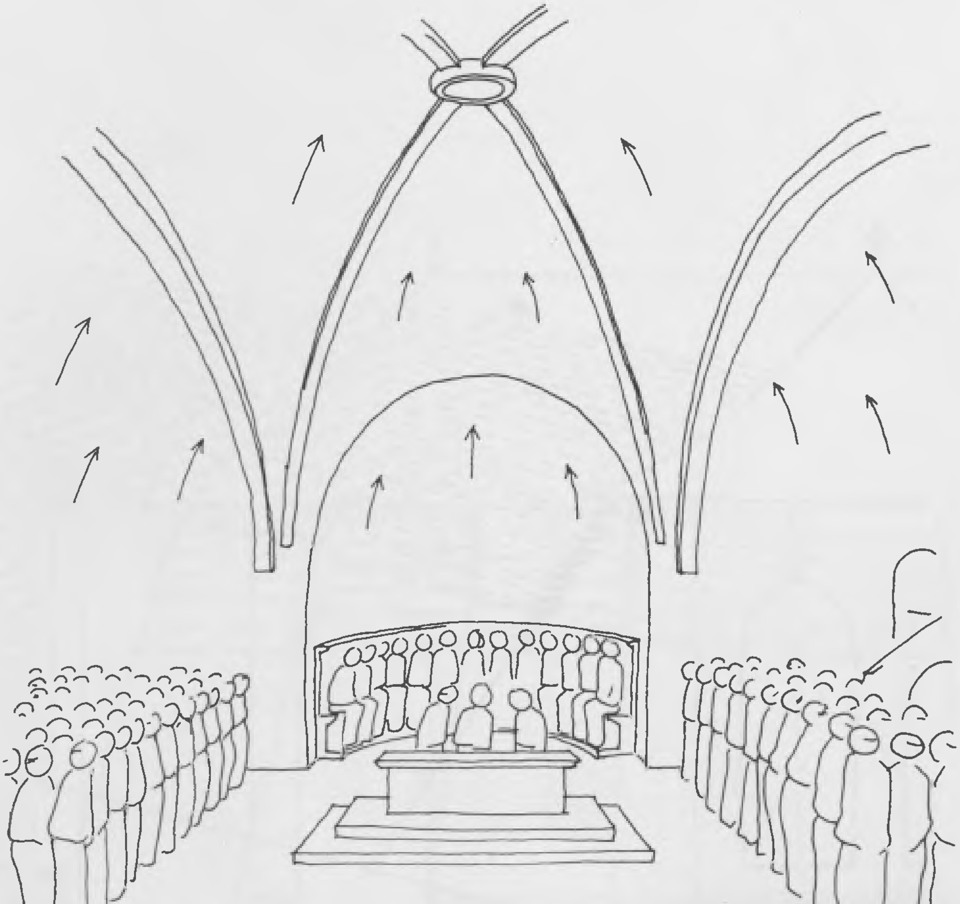

Fig. 9 - Cold dry walls, warm humid environmental air due in this case to excessive crowding (1 man produces approximately 50 to 80 grams of vapour per hour). Abundant condensation therefore, especially in high areas where heat is more likely to be concentrated. Steps must be taken to prevent condensation; often it is enough to improve air circulation.

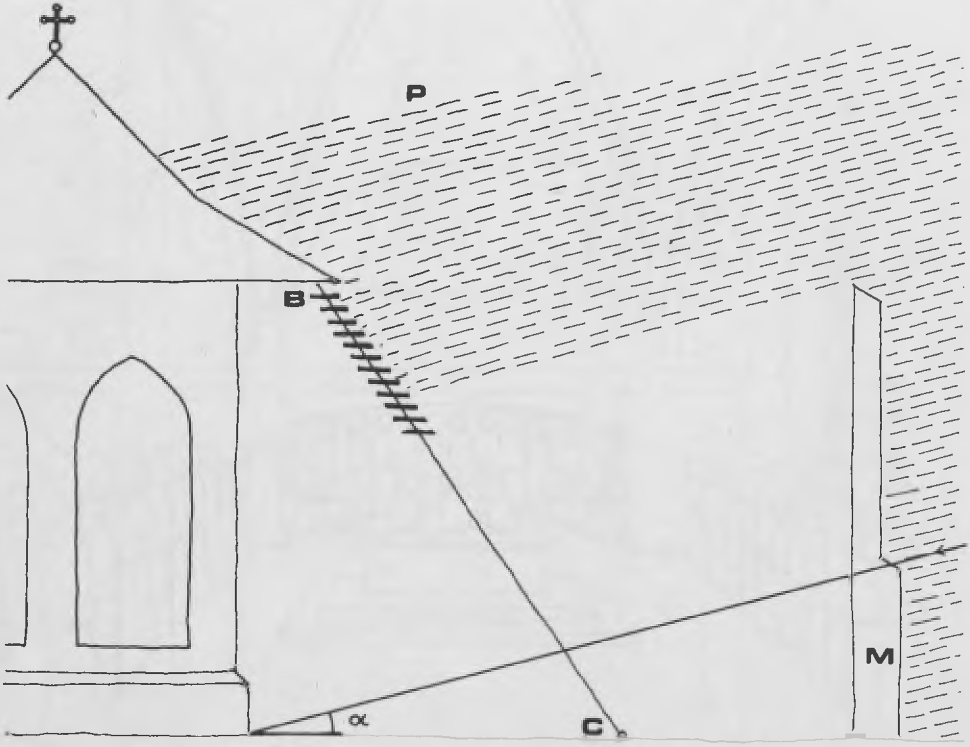

Fig. 10 a

Fig. 10 - α: Angle minimum of the rain and the wind with the ground; M: Fence existing or to be built; C: Steel cables on which are mounted, after a certain height, lamellas as persiennes (inclination to be established according to the case); P: Zone exposed to the rain against which the paintings must be protected; B: Screen in "perspex".

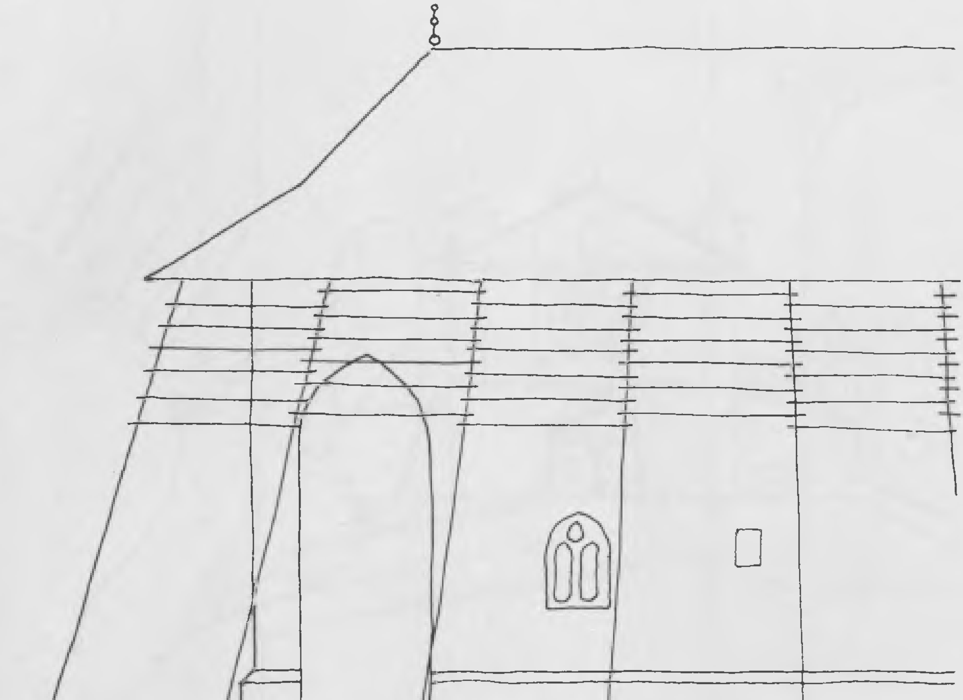

Fig. 10 b

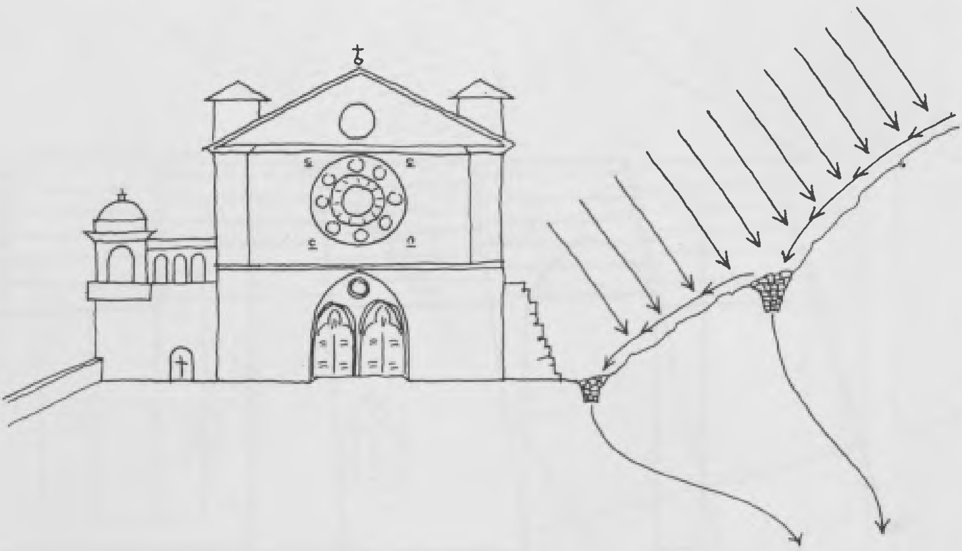

Fig. 11 - External drainage to divert surface water.

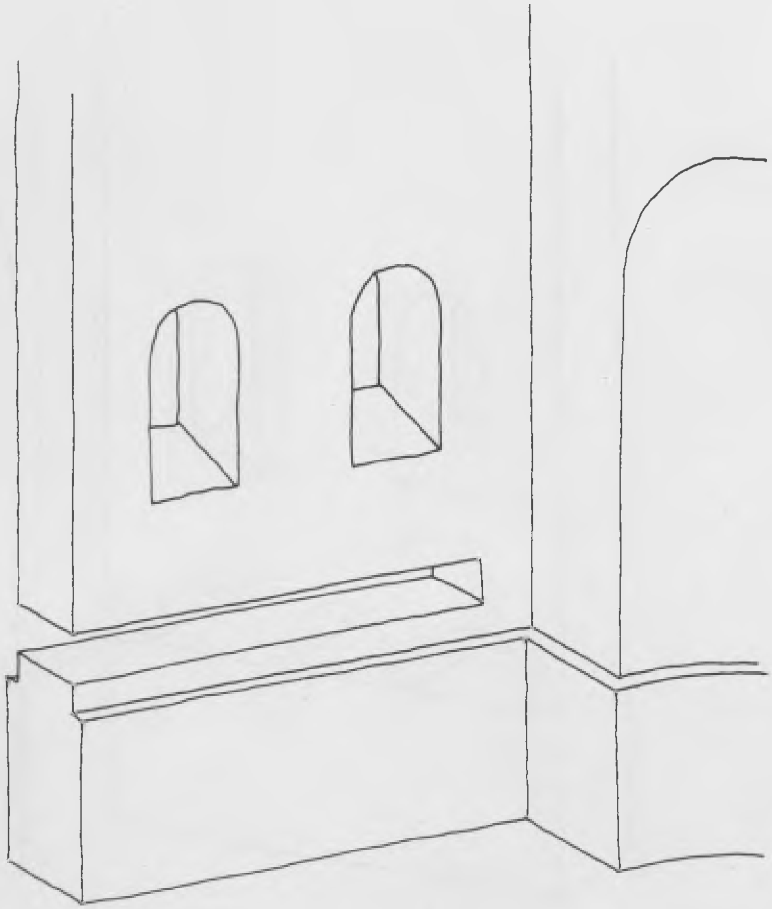

Fig. 12 - Isolation of a humid wall by means of cutting completely through the entire thickness.

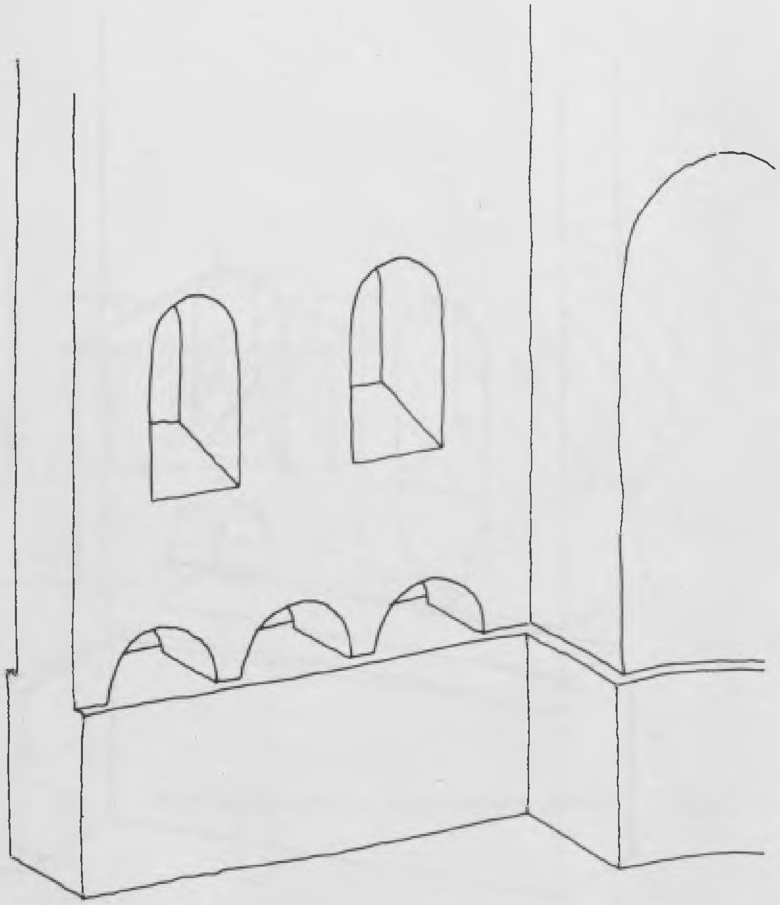

Fig. 13 - Reduction of the absorbent surface by means of arches.

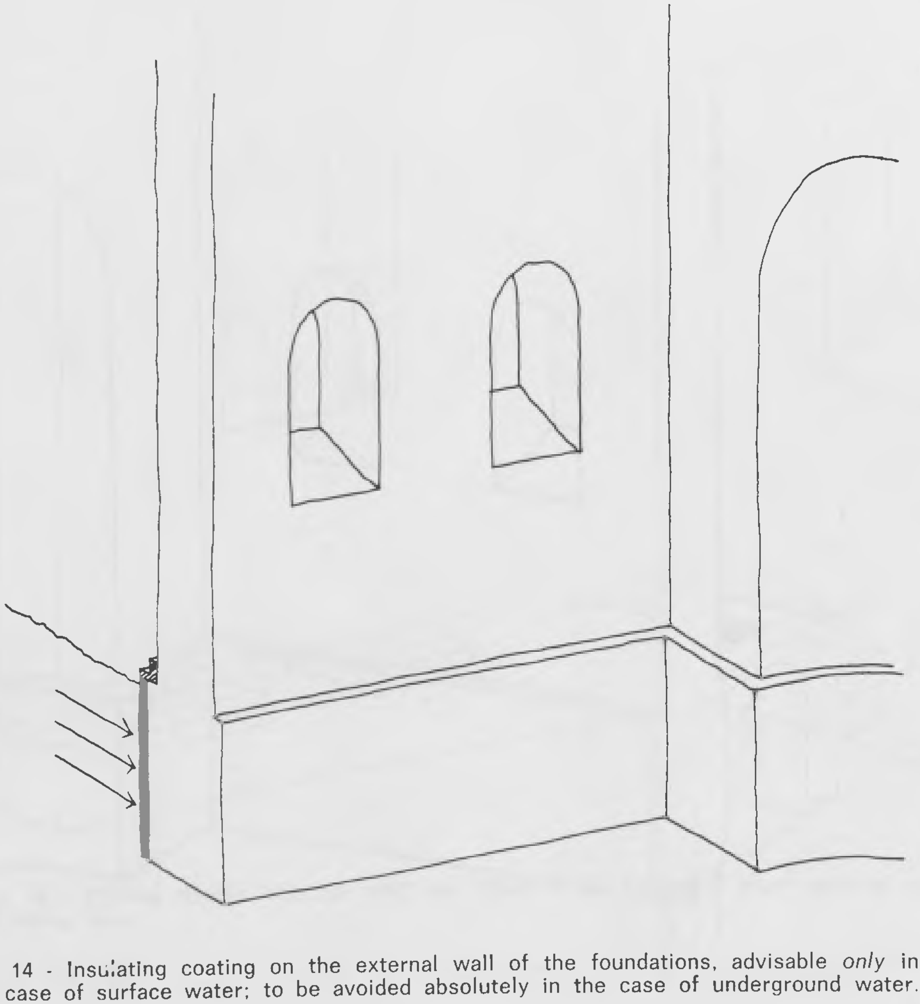

Fig. 14 - Insulating coating on the external wall of the foundations, advisable *only* in the case of surface water; to be avoided absolutely in the case of underground water.

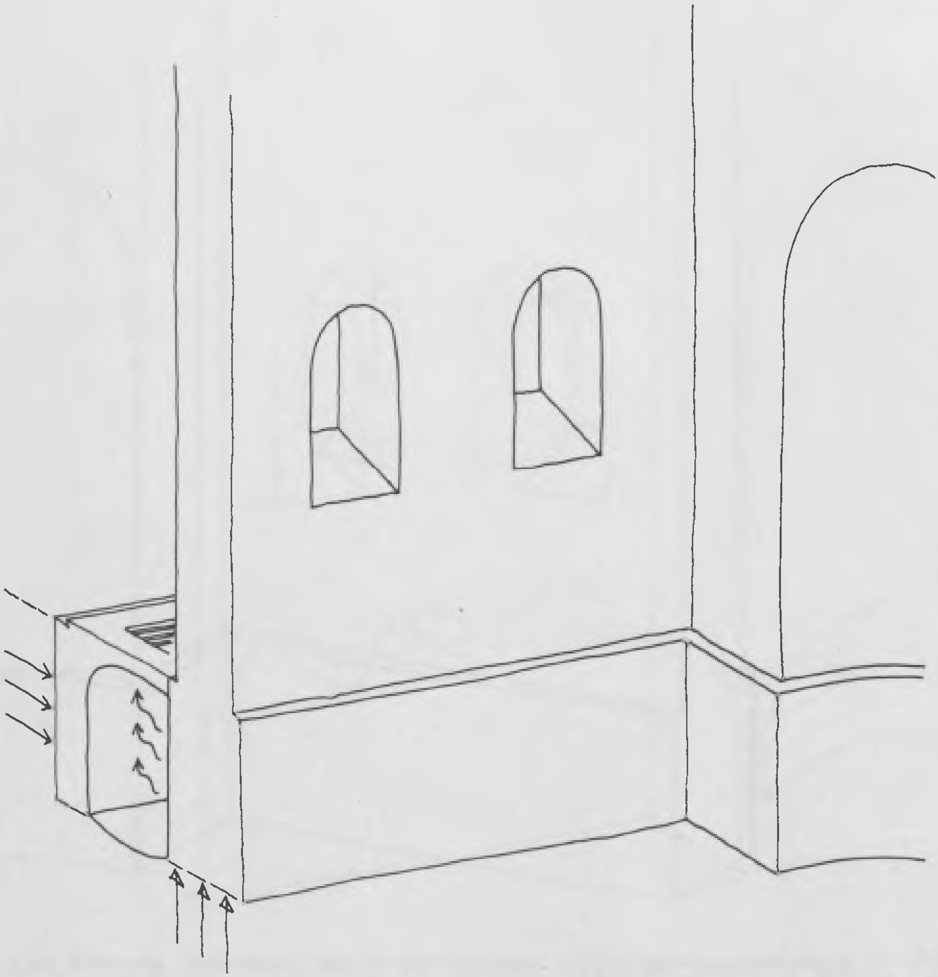

Fig. 15 - Exterior cavity wall to the foundations. It serves to intercept surface water to increase evaporation and lower the level of the evaporating surface. It is advisable to activate air circulation by vents.

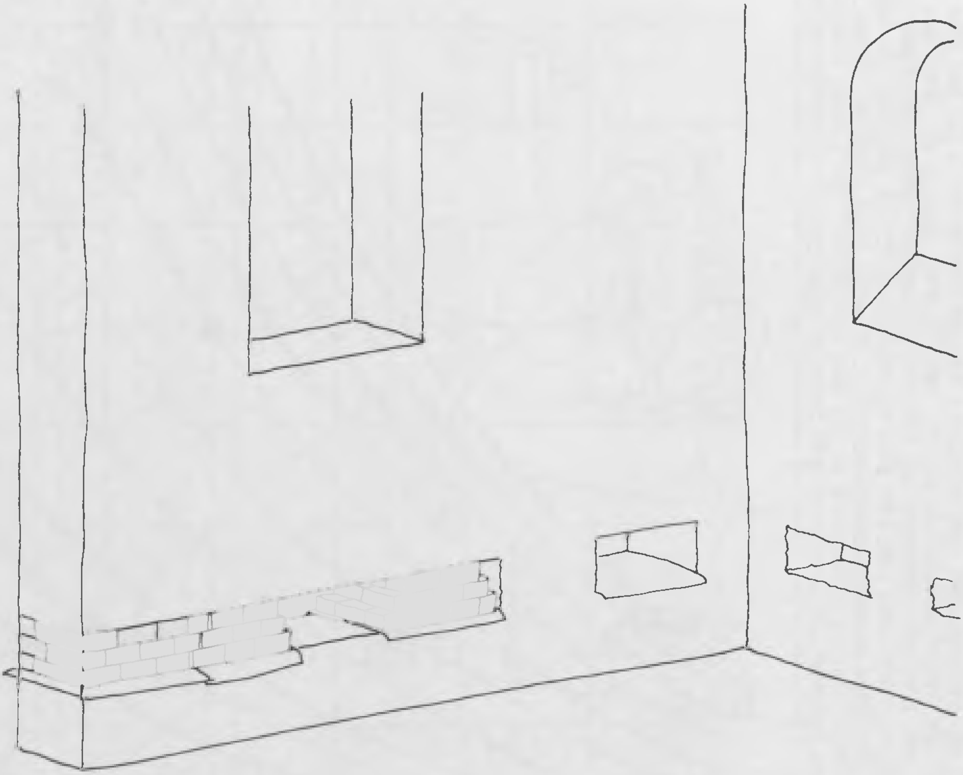

Fig. 16 - Cutting deeply into the wall and filling it by breaching after applying an insulating layer.

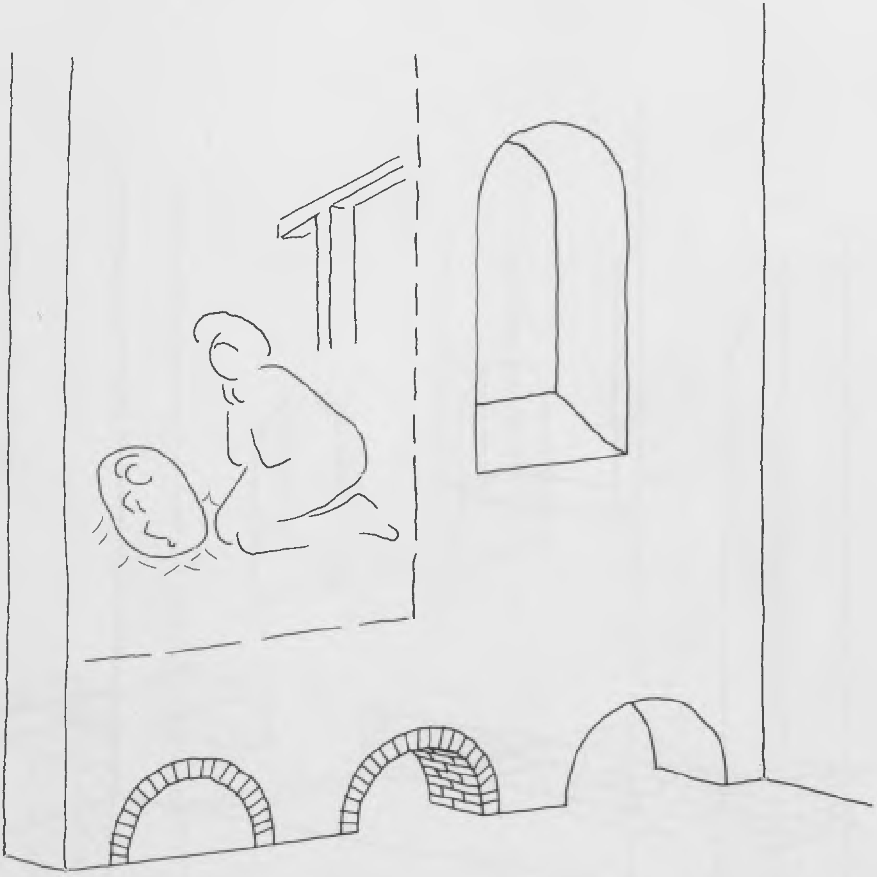

Fig. 17 - Reduction of the wall's absorbent surface and construction of small reinforcing and isolating arches.

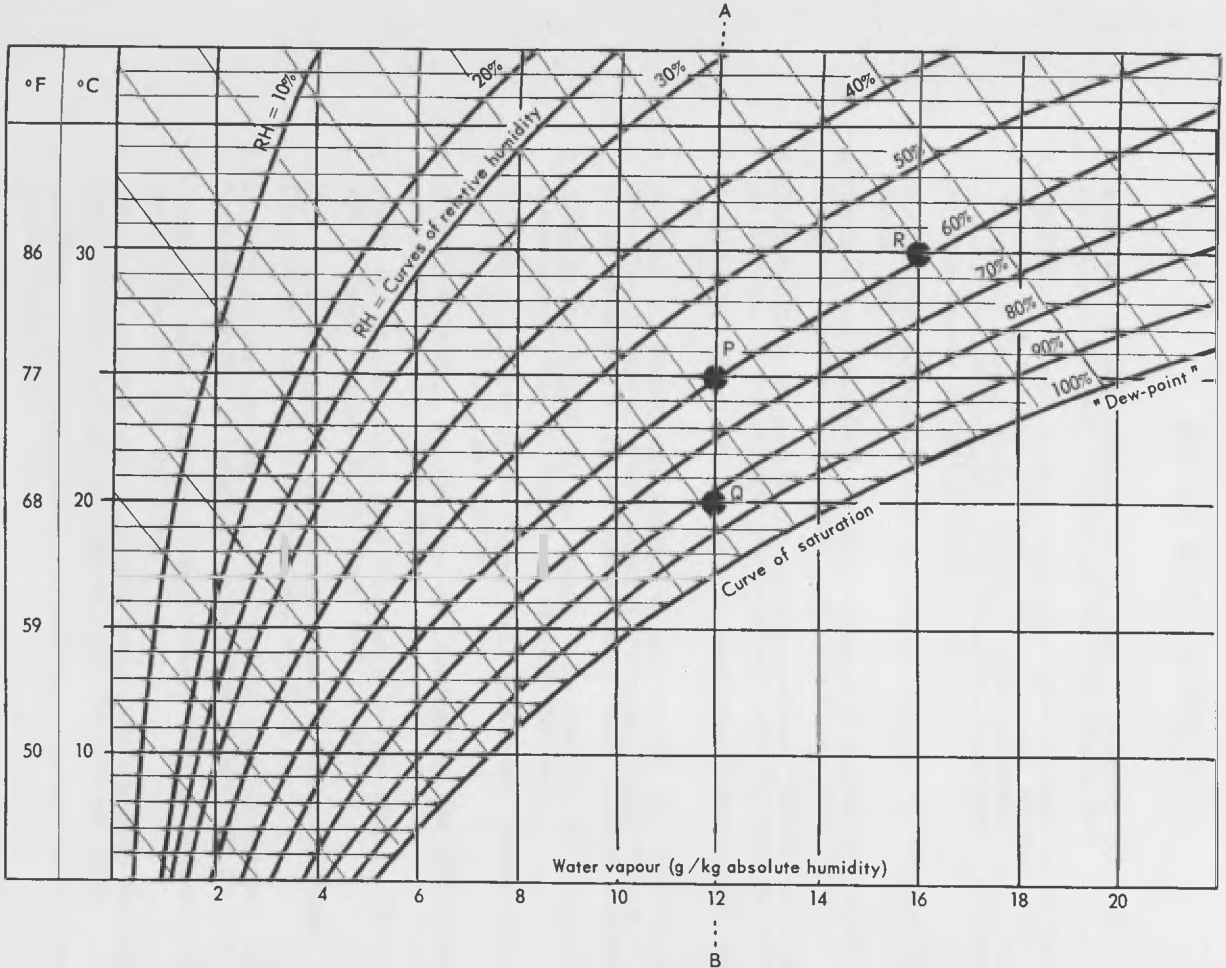

Fig. 18 - Hygrometric chart illustrating the relationship between temperature and relative humidity of the air. The shape of the hygrometric chart is determined by the fact that air can carry more aqueous vapour when warm than when cold. Thus, at a constant absolute humidity of, say, 12 g aqueous vapour per kg of dry air (line AB) the air is actually saturated (100 per cent) at 17°C, whereas at 25°C, it is only 60 per cent saturated and at 32°C less than half saturated (40 per cent). Heating, while not affecting the absolute humidity, always reduces the relative humidity of the air. Over a large area of the chart this is most useful, e.g. by heating air at Q (80 per cent RH), bad conditions can be brought to P (60 per cent RH) and conditions are then satisfactory. In cases where the absolute humidity is very high, e.g. 16 g/kg and over, the method becomes impractical. In the case cited the temperature would have to be raised to 30°C to reduce the relative humidity to the point R on the 60 per cent curve. It should be added that in actual practice one does not rely on heating alone but in conjunction with dehydration, ventilation, etc., to attain the desired conditions.

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