EFFECT OF DIFFERENT CERAMIC TILE CHARACTERISTICS UPON ITS ADHESION STRENGTH TO CEMENT MORTAR SUBSTRATES.

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SYNOPSIS

The aim of this paper is to analyze the effect that different ceramic tile characteristics have upon its adhesion to cement mortar substrates.

A study has been carried out of the effect of such variables as the type of body used, the absorption of water by the biscuit, the form and distribution of the ribs, the increase in the surface area due to these raised patterns and the roughness of the tile back.

For the purpose of this study we have used adhesives from the mid-market range: cementitious adhesives with hydraulic binders and cementitious adhesives with mixed binders. For the main fixing background we have chosen a cement mortar substrate, seeing that it is the most widely used background in the relevant national and international regulations. The test specimens were debonded basically by shear stresses.

1. INTRODUCTION

The success of all surfaces covered with ceramic tiles depends on numerous factors. The selection of the most adequate materials (tiles, adhesives, grout...) for each particular situation (substrate, atmospheric conditions, use it will be subjected to...), employment of the most appropriate fixing method in each case, carried out by qualified professionals, are all aspects with which great care must be taken, and which need to be observed to the very last detail.

It will therefore be necessary to achieve high degrees of optimization in designing and executing all the elements involved.

With this aim in mind, adhesive manufacturers set out a series of recommendations. Some of the aspects widely dealt with by these professionals are: the selection of the appropriate adhesive for each type of background subject to particular atmospheric conditions and use, installed by employing a particular fixing method.

There are also recommendations on the use of tiles considering some of their characteristics (water absorption by the biscuit, abrasion index...) in particular situations (outdoors, in public buildings...).

It is the aim of this study to elaborate upon the recommendations regarding the adhesion of ceramic tiles and the manner in which the different characteristics of these tiles affect this phenomenon.

The optimization of these characteristics, with regard to the whole ceramic- fixing system (substrate-adhesive-tile) can lead to higher levels of reliability and durability, which are always critical aspects when dealing with tiled surfaces.

2. THE PHENOMENON OF ADHERENCE

2.1. DEFINITION

Adherence can be defined as the action of the forces that oppose the separation of different bodies. When we refer to the ceramic-fixing system, we are talking about adherence as the strength of the bond between the ceramic tile and the adhesive, and between the latter and the substrate.

The two aims of good adhesion are: on the one hand it must ensure that the tiles are firmly fixed to the substrate, while on the other, it must ensure the durability of the bond throughout time and against the conditioning factors for which the join has been designed.

2.2. TYPES OF ADHESION. MECHANICAL ADHESION. CHEMICAL ADHESION.

There are different theories which allow us to interpret the complex phenomena that appear in adherence. However, with regard to the fixing of ceramic tiles, there are basically two types of adhesion: mechanical adhesion and chemical adhesion.

Mechanical adhesion can be defined as that in which the adhesive liquid flows or is forced toward the cavities or pores in the surfaces to be joined where, once hardened, the adhesive and the surface to be joined are firmly bonded. The strength of the join obtained by using this type of adhesion is greater with those surfaces which have a larger number of «potential» anchoring points. Thus, in principle, we can say that in mechanical adhesion, porosity (water absorption by the biscuit), surface roughness and ribs (raised patterns on the back of the tile) are characteristics which contribute to increasing the strength of the join between the tile and the adhesive.

The cement mortars used in thick-set fixing and the cementitious adhesives with hydraulically hardening binders (used in the thin-set method) basically employ this type of adhesion.

Chemical adhesion is basically due to chemical and electrostatic forces between active groups of the adhesive and the surface to be joined, these forces being probably similar to those which bind the atoms and molecules of the surfaces to be joined.

The cementitious fixatives containing mixed binders (hydraulic binders and organic binders, of which the latter can be in dispersed powder or liquid solution form), and the organic reactive polymer adhesives, use this type of «chemical» bond in greater or lesser degree, to obtain the final adherence between the surfaces to be joined. These adhesives must be employed with the thin-set fixing method.

2.3. OTHER FACTORS THAT CONDITION ADHESION

Apart from the above-mentioned factors, the obtention of a correct bond will also depend on other aspects: the physical contact between the adhesive and the surface to be joined, and the chemical compatibility of the two.

2.3.1. Physical contact between adhesive and the surface to be joined

The adhesive must have good physical contact with the surfaces to be joined (ceramic tile and substrate). This means that it will need to be sufficiently deformable through creep or flow. There are two objectives to be attained with this requisite: that the adhesive should be able to reach the pores and cavities, thus permitting a mechanical-type anchoring, and that the necessary close contact should take place to bring about the chemical linking characteristic of chemical adhesion.

2.3.2. Chemical compatibility between adhesive and the surface to be joined

Chemical compatibility -i.e. the grade of affinity between the adhesive and the surfaces to be joined- must exist between the elements that constitute the join. Simplifying, it can be said that the surface energy tells us the state of the electrons situated on the surface, that is, whether they have a high excitation energy level, whether they are being attracted in various directions by atoms situated close by, or whether they are at rest. Surfaces which have low surface energy are non-polar, whereas those with high energy are usually polar. An adhesive will only «wet» well the surface to be joined (by «wet» well, we mean suitable moistening) when its surface energy is lower than that of the latter (13).

This is the reason why it is inappropriate to employ hydraulically hardening cementitious adhesives (of a mineral nature) upon backgrounds of an organic nature (plastics, paint...), whereas adhesives of an organic nature may be used on substrates of the same nature as well as on those of a mineral nature (with higher surface energy).

3. METHODOLOGY USED FOR TESTING

3.1 PREPARATION OF THE TEST SPECIMENS

3.1.1. Obtention of the ceramic tiles used for testing

The origin of the tested ceramic tiles was two-fold.

The great majority was prepared by ourselves in our own laboratory. We employed for this purpose spray-dried powders from firms situated in the province of Castellón. The spray-dried material was pressed within the pressing ranges used industrially. After oven drying (at 110º C), the tiles were fired in a rapid-fire laboratory kiln, using short cycles, as in the industrial firing operation. With this type of procedure we were able to control most of the characteristics of the tiles obtained and these became the basis of the study carried out.

We also tested ceramic material obtained from numerous firms located in our country. On the one hand, this allowed us to study different models of rib, and on the other, to study the real ceramic material on the market. For example, the latter permitted us to detect the importance of «surface roughness» in the case of products with low water absorption.

3.1.2. Obtention of the substrates used in testing

There were two types of background or substrate used for testing: a cement mortar substrate -used in numerous national and international regulations (3), (19), (24)- and a rendered brick background -in imitation of the typical rendered brickwork wall with a layer of cement mortar.

We used the cement mortar substrate to carry out the main part of the investigation. Using the proportions specified by the regulations, and following the necessary curing period, this type of background was subjected before use to mechanical surface abrasion. Through this procedure we were seeking to attain two objectives: to eliminate any grout from the surface (result of the process of trying to attain an even surface) which was impairing the adherence between adhesive and substrate; and to increase the roughness of the substrate and thus improve the adherence between adhesive and substrate, a fact noted and proved by different authors (9), (MCR Method) and (10).

The rendered brick substrate was used to analyze behaviour compared to a different type of substrate (and thus with different characteristics).

Different types of analyses were carried out of these substrates, such as measuring thermal expansion, setting shrinkage, moisture content and the surface water absorption (suction).

3.1.3. Adhesives employed

We decided to use adhesives to fix the tiles to the substrates. Due to the increasing use of this type of materials in Spain -in the rest of Europe their use is already widespread (8)- we felt that this would be the best method.

Of the various types of adhesives from which we could choose, we decided upon those to be found in the mid-market range: cementitious adhesives with hydraulic binders and cementitious adhesives with mixed binders.

While the adhesive described in this experiment as **TYPE A** refers to material where the hydraulic binders predominate, the one described as **TYPE B** constitutes a mixed binder adhesive, where adherence is due to the combined action of hydraulic and organic binders. These adhesives were subjected to different tests which permitted the identification of their particular characteristics as well as the explanation of the difference in the behaviour of the two.

3.1.4. Fixing the tiles to the substrate

The mixing of the adhesives with drinking water was carried out according to the various specifications surveyed (19), using the proportions stipulated by the manufacturers. Control of the working temperature and the complete elimination of lumps required special attention.

We used the thin-set method for fixing, with floating and buttering, that is, applying the adhesive to the background and the back of the tile. After installing the tiles upon the fresh adhesive, we proceeded to verify the parallelism between the tiling and the substrate surface, and to check the thickness of the resulting adhesive layer (with which the greatest of care must be taken if one is to obtain valid results). These facts were later verified during a process that we could call «individualization», and which consisted of eliminating the excess adhesive from around each individual tile, each of which was adhered to the same substrate. The aim of this procedure, carried out when the consistency of the adhesive was appropriate, was to obtain conditions where the debonding of one tile would not affect that of its neighbour, an occurrence caused by the transmission of stress throughout the layer of adhesive.

After permitting the appropriate curing time for the adhesive to elapse (specified by the manufacturer), still using laboratory conditions, we proceeded to debond the tiles. However, due to the important effect of the variation in climatic conditions upon the durability of ceramic tilings, we also carried out climatic tests which permitted us to verify the behaviour of the adhesives under such conditions.

3.2. DETERMINING SHEAR STRENGTH

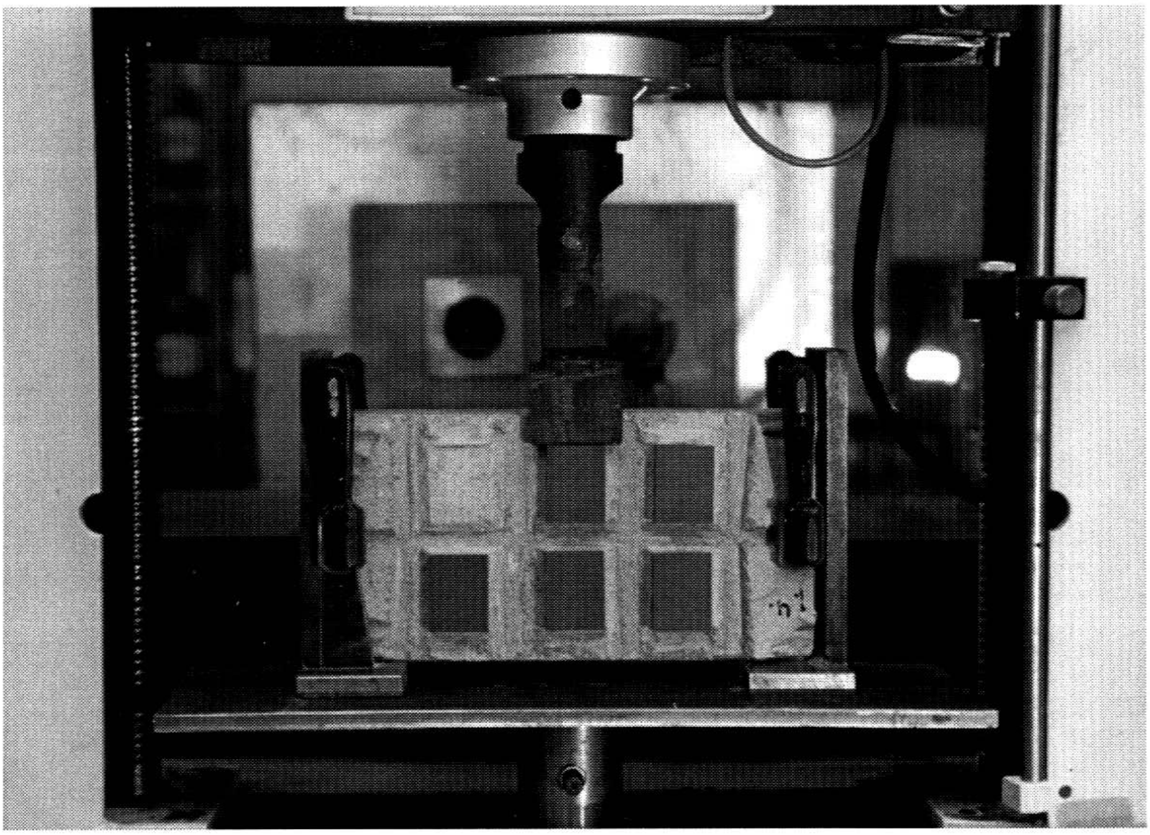
3.2.1. Debonding procedure

After different initial trials, we decided that we would test adhesion failure caused by shear or peeling. Tests were also run on adhesion failure caused by tensile stresses, which showed that there are correlations between the two (16). The shear or peeling was accomplished with the testing machine shown in **Photograph 1.**

The original instruments of the machine were modified by the inclusion of a frequency regulator (which permitted the modification of the loading speed and its setting at the ranges specified by the regulations) and a digital reader of the applied force, the value of which was obtained to an accuracy of a 0.1 kg.

It is necessary to state the importance of ensuring total alignment between the driving unit and the tile to be tested, as the slightest error in this sense could seriously bias the

PHOTOGRAPH 1: ADHESION TESTING MACHINE



PHOTOGRAPH 2: DETAIL OF DEBONDING BY SHEAR LOADING

results. In the same way, and in order to avoid the shear stress's turning into something different and undesired (basically, ripping) (13) or the occurrence of higher- than-normal scattering, the driving unit was always applied to the same point in the tile, as close as possible to the tile-adhesive interface. See **Photograph 2.**

3.2.2. Calculation of shear strength

Each tile-adhesive-substrate set tested -also called a model (16)- involved six individual test specimens with similar characteristics. After the six individual test specimens were debonded, we proceeded to determine the average of the resulting values (which represented breaking strength/contact area), rejecting those that exceeded by approximately 20% this average -according to the above-mentioned different specifications (19). If four or more values were found to be within the specified margins, the test was considered to be valid and the final value was calculated as the new average of the values that had not been rejected.

4. CERAMIC TILE VARIABLES THAT AFFECT ADHERENCE

The identification of the tile variables that can affect adherence was one of the trickiest phases of this study.

We decided to use experimental design statistical techniques, more concretely, a fractional factorial design. These techniques (which save a great deal of time and material) permit the identification of those variables -and the interactions between them- that are truly important in a process or phenomenon. Their main drawback is that a selection must be made beforehand of the variables to be tested. The selection was made by consulting the literature as well as studying the adhesion phenomena and processes, as much at theory level as in specific circumstances in different fields (such as that of synthetic industrial adhesives).

During the actual investigation process new variables came to light -for example the surface roughness of the back of the tile- which had not been taken into consideration at the outset.

All these variables can be classified in two groups:

- Variables that depend on the composition of the body:

- Composition of the ceramic body
- Thermal expansion of the biscuit (*)
- Water absorption of the biscuit

- Variables of a geometric nature

- Water absorption of the biscuit
- Form and distribution of the ribs. Increase in the contact area
- Surface roughness of the back of the rib
- Size and thickness of the ceramic pieces (fixing with joints) (*)

The water absorption (WA) of the biscuit is a variable that -for different reasons- can be considered as much of a geometric nature as dependent on the composition of the body. On the one hand, the WA depends on the size, quantity and location of the internal pores of the biscuit, all clearly geometrical questions. However, on the other hand, the obtention of a WA value for a specific biscuit will also depend upon the type of body we are working with and the firing range that is industrially viable for that composition.

4.1. COMPOSITION OF THE CERAMIC BODY

In traditional tile fixing, employed world-wide until a few years ago (and still widely found in Spain) (8) - i.e. thick-set fixing with mortar on substrates of a mineral nature- a fundamentally mechanical adhesion is used to fix the tiles to the walls and floors. We have already stated in section 2, that this is the prevailing type of adhesion for this type of adhesives with hydraulic binders. This is the reason that it has traditionally been thought - and this is truly the case- that with porous products a better adhesion can be obtained than with vitrified or semi-vitrified products (with lower water absorption values, and therefore, a lesser number of open pores, authentic potential anchoring points).

(NB: We have mentioned a WA characteristic, even though we are analysing the effect of the composition of the body, due to the undeniable interrelationship and interaction between the two).
(*) N.B: These characteristics have not been implicitly analyzed during the investigation and the respective statements are the result of minor tests, assumptions based on logic and literature surveys. It is due to this fact that they are referred to in section 4.5 «Effects of other characteristics».

This theory, used for centuries, has been confirmed by the tests carried out with the adhesive we have called «type A», a cementitious adhesive with hydraulic binders, used for thin-set fixing. In the industrial and commercially viable WA ranges for each of the different bodies, in every case greater adhesion is found in the porous than in the stoneware products.

With the appearance of new adhesives in the market, where the importance of organic binders is on the increase, the traditional theory has been upset. With these new adhesives, chemical adhesion is given more relevance, and whether the tiles have a greater or lesser number of open pores is no longer of such great importance. As the manufacturers of adhesives themselves extol in their advertisements: «...suitable for fixing tiles with very low water absorption»!

In the tests carried out with the «type B» adhesive -cementitious adhesive with mixed binders- this theory has been confirmed. Where adhesion is concerned, the stoneware products are comparable to and even exceed, in absolute value, the porous products.

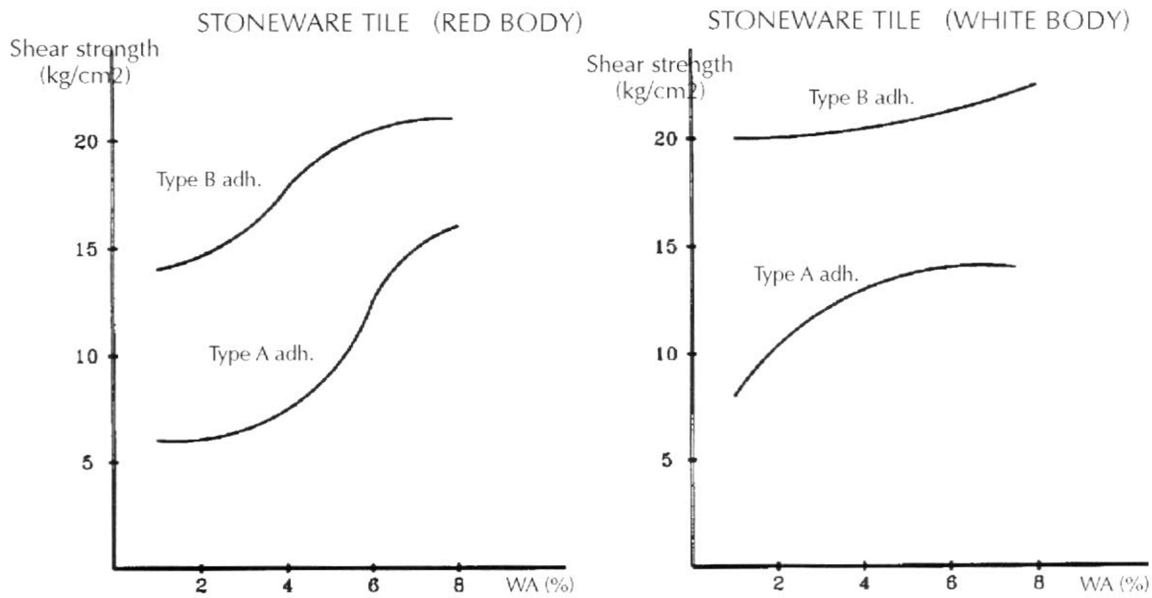
In the following section (effect of WA) we shall continue with the explanation, in a parallel way, of these two variables whose interrelation is undeniable.

4.2. WATER ABSORPTION (WA) OF THE BISCUIT

The water absorption of a ceramic tile measures the apparent porosity of the product, that is, the total amount of pores in contact with the exterior and capable of being filled by a liquid under atmospheric pressure (16).

This characteristic depends on several factors: the mineral composition of the bodies, bulk density, firing cycle, peak firing temperature... Basically, we have used this last factor

GRAPH 1
SHEAR-STRENGTH - WATER ABSORPTION



TYPE OF SUBSTRATE: CEMENT MORTAR

to obtain variations in the water absorption, once the mineral composition and the bulk density had been set (within the industrial ranges for each type of body).

Right from the beginning this variable had been considered as possibly one of the most influential. The results confirmed the earlier suppositions, also stated by different sources (5).

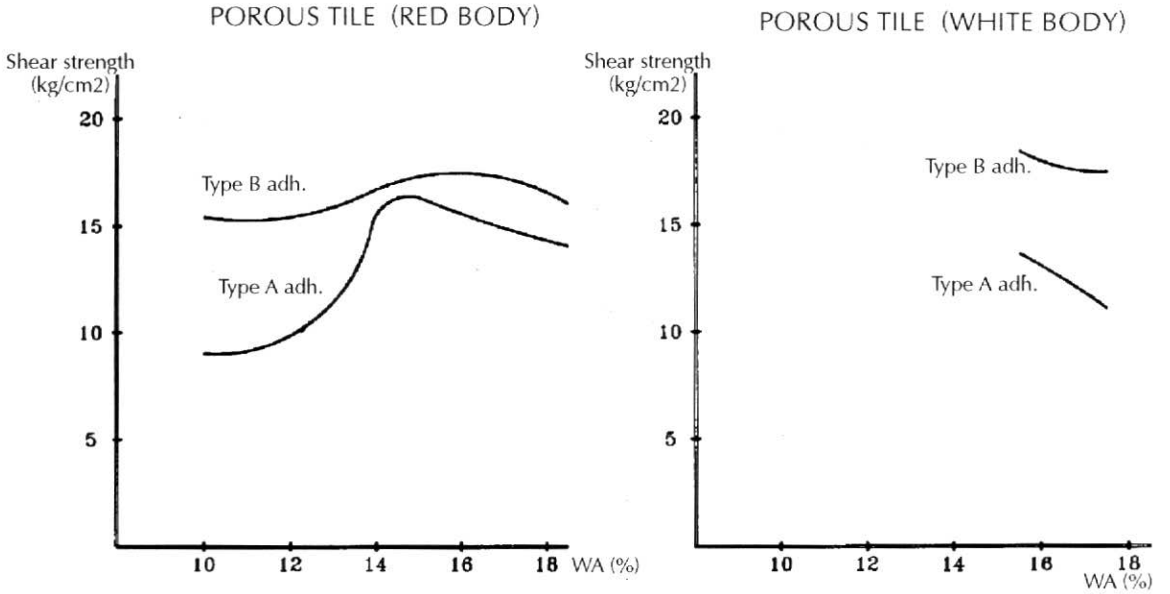
We shall now go on to comment upon the tendencies observed once the tests had been carried out. The curves we are going to analyze have resulted from averaging a large number of adherence tests, which inherently entail certain degrees of scatter -scatter which is recognized by the relevant specifications (19).

The curves which correspond to the different **STONEWARE TILE** bodies (**graph 1**, upon a cement mortar substrate) indicate a widespread tendency for this type of body: a continuously increasing, although not linear, shear strength with the WA of the biscuit. It can also be observed that in the white-bodied stoneware tile this shear strength value is somewhat higher for low WA values.

For the **POROUS TILE** bodies (**graph 2**, upon a cement mortar substrate) the tendencies shown earlier for stoneware tiles are only valid to a certain degree. The reason for this is the following: the initial tendency is an increasing shear strength, in proportion to the rise in WA. On the other hand, this increment is less pronounced, and begins at higher degrees of shear strength. At a certain WA value (different for each type of adhesive) the tendency is inverted, and a slight but continuous decrease in the obtained strength will begin. In the case of the white-bodied porous tile, it was the mineral composition itself (which showed a very flat vitrification graph), which did not permit obtaining a more extensive WA range and thus, only the final descending curve can be seen.

For the **PORCELAIN TILE**, tests were run within the industrial WA ranges. The results also showed a sligth, but perceprible, increase in shear strehngth with the WA (increase

GRAPH 2
SHEAR STRENGTH - WATER ABSORPTION



TYPE OF SUBSTRATE: CEMENT MORTAR

from values of 0.03 - 0.05% to 0.4 - 0.6%). For the «type A» adhesive we obtained a shear strength value was approx. 1.2 kg/cm^2 (a truly low value), while for the «type B» adhesive, this value was approx. 17.0 kg/cm^2 (corroborating the fact that it is a suitable adhesive for materials with a very low WA).

Different assumptions can be made to explain the tendencies indicated by these curves.

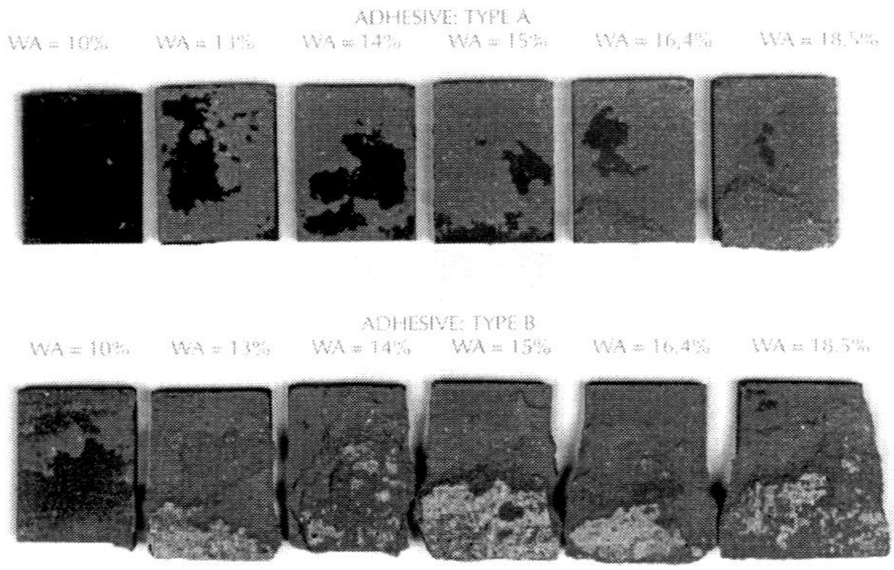
In each and every case the «type B» adhesive shows greater shear strength than «type A». The explanation is clear: the presence of organics binders. What is more, the curves obtained (with the «type B» adhesive) are less pronounced (lesser increases and decreases) than those corresponding to the other adhesive (with hydraulic binders) where the variations in the WA deeply affect the shear strenght values,

It is far harder to find an obvious explanation for the tendencies shown by the porous bodies. We are referring to the ligth, though perceptible, descent of shear strength at high levels of water absorption.

For this explanation we have to look in the cement setting processes. The cementitious and other adhesives harden due to the elimination of the excess mixing water; this however, is a necessary process for their correct hydration and in order to make tile installation easier.

Various authors (10) (21) (22), state the importance of the amount of mixing water. It is not good for the adhesive to become dry too soon -this would prevent the dispersion and dissolution of the cement particles as well as their posterior crystallization- nor should there be an excess of water in the adhesive, since when all the water that is not necessary for the hydration of the cement is eliminated, it leaves behind cavities which will be filled by air. And not only do these air-filled cavities have zero strength, they also act as stress-concentrating elements, and form actual crack starters.

PLATE 1: VARIATION OF THE TYPE OF FAILURE ACCORDING TO THE WATER ABSORPTION OF THE TILE



TILE: POROUS (RED BODY) - SUBSTRATE: CEMENT MORTAR - TEST: SHEAR

To keep the adhesives from «drying» too fast due to adverse atmospheric or physical conditions, the manufacturers add water-retaining agents. To avoid having an excess of water in the adhesive, it is best to keep strictly to the proportions indicated by the manufacturers.

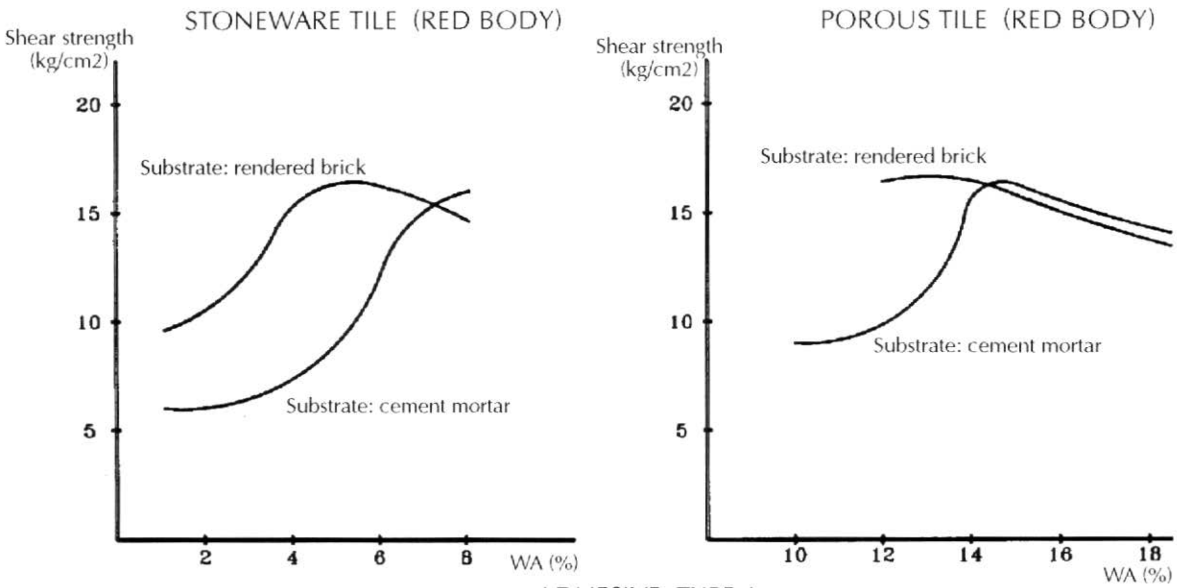
The water left over from the hydration or setting is eliminated by evaporation and through absorption by the tile and substrate. If we rule out the evaporation phenomena (equal in all the tests, with constant humidity and temperature conditions) the differences shown by the curves must be basically due to the different variations in the WA of the tile and substrate.

In the porous bodies, at low levels of WA (the same occurs in the stoneware tile bodies, for the same ranges), water suction by the tile is minimum, a fact that ends up causing its elimination to slow down. This elimination will be almost exclusively due to suction by the cement mortar background. The more we increase the WA of the tile, the more it will contribute to the extraction of superfluous water, bringing about more adequate settling and a diminishing in the creation of cavities (the adhesive is still able to adapt to the possible material faults at those points where the evacuation of the water has created pores). Finally, in the porous bodies (this does not occur with the stoneware tiles, seeing that such levels of WA are not reached), when the WA of the biscuit surpasses certain values, the suction by the tile and substrate becomes excessive, drying out the adhesive in a short space of time, and thus provoking inferior quality hydration.

In **plate 1** we can observe the variation in the type of failure that occurs when porous tiles (red body) debond, at different degrees of WA and with the two adhesives in question. By «type of failure» we refer to the kind of debonding that occurs in each case, that is, whether the fracture plane begins at the tile-adhesive interface (AF-T, adhesion failure tile), in the adhesive itself (CF-A, cohesion failure adhesive) or in the adhesive-substrate interface (AF-S, adhesion failure substrate).

We can see how the type of failure varies according to the type of adhesive and with the WA of the tile. Type B adhesive is far more adherent than type A, and leaves the surface much dirtier. On the other hand, the more we increase WA, the larger the amount of adhesive that adheres to the back of the tile after debonding. The fracture, which at first occurred at the tile-adhesive interface, gradually turns into a fracture in the adhesive itself. This variation is more pronounced in the «type A» adhesive. In «type B» there is a greater homogeneity to be found in the type of failure, a tendency which is also shown by the Shear strength-WA curve (far flatter).

GRAPH 3
SHEAR STRENGTH - WATER ABSORPTION



ADHESIVE: TYPE A

Due to the interaction which exists between suction (surface water absorption) by the tile and by the substrate, we thought it convenient to find some of the curves already obtained (where we used cement mortar substrates) for a different substrate. We decided upon a rendered brick background, which has a degree of surface water absorption 2 or 3 times superior to that of the cement mortar.

In **graph 3** we can see the curves obtained for this type of background, compared to those already discussed for cement mortar beds.

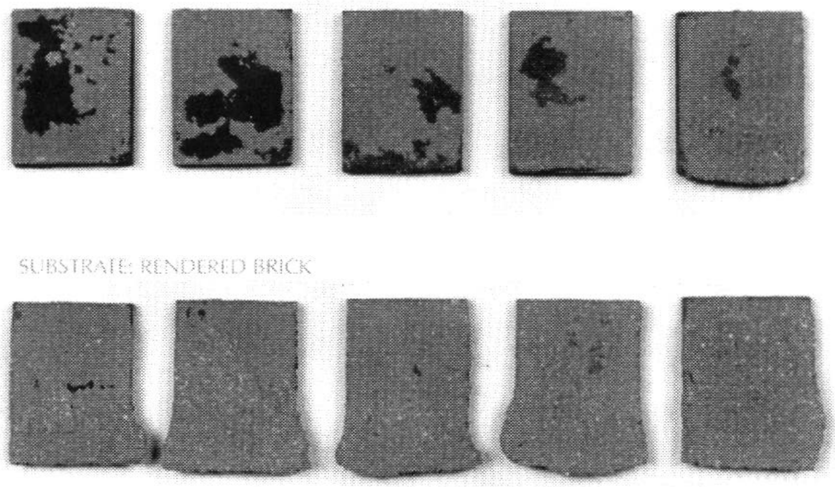
The general tendency we are able to observe is that of a «sliding» in the curves towards lower WA levels. This is so as much for the stoneware as for the porous tile (both red body).

The explanation follows the same line of reasoning as before. With a more absorbent substrate, even though the tile may not be (low WA), the excess water is eliminated by the former and setting takes place correctly. All depends upon the joint suction of the tile-and-substrate. On the other hand, we evidently cannot continue to increase indefinitely the suction capacity of the substrate (in an effort to compensate the very low levels of WA in the tile) as this would lead to hydric imbalances within the adhesive itself, which would not yield high shear strength values. The most adequate seems to be a balance between the

PLATE 2: VARIATION OF THE TYPE OF FAILURE WITH THE KIND OF SUBSTRATE USED (at different values of WA)

SUBSTRATE: CEMENT MORTAR

SUBSTRATE: RENDERED BRICK

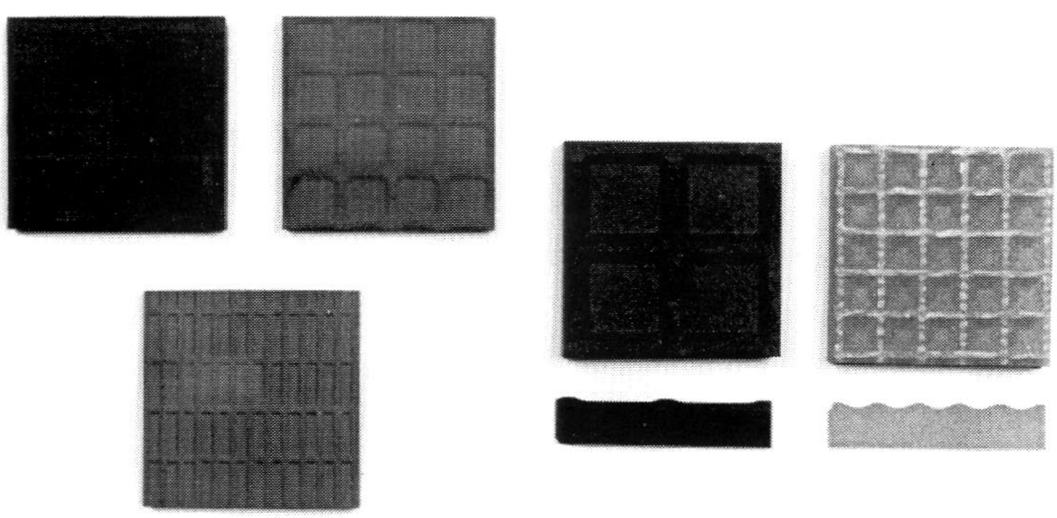


TILE: POROUS (RED BODY) - ADHESIVE: TYPE A (CEMENTITIOUS ADHESIVE) - TEST: SHEAR

two.

In **plate 2** we can see the variation of the type of failure with the kind of substrate and the WA of the tile (porous, red body). There are two facts to be noted: first, the fractures on rendered brick leave a larger amount of adhesive on the back of the tile than those carried out on cement mortar, with the same WA; second, in the rendered brick series there

PLATE 3: TYPES OF RIB ON THE BACK OF THE TILE "SQUARE" RIB

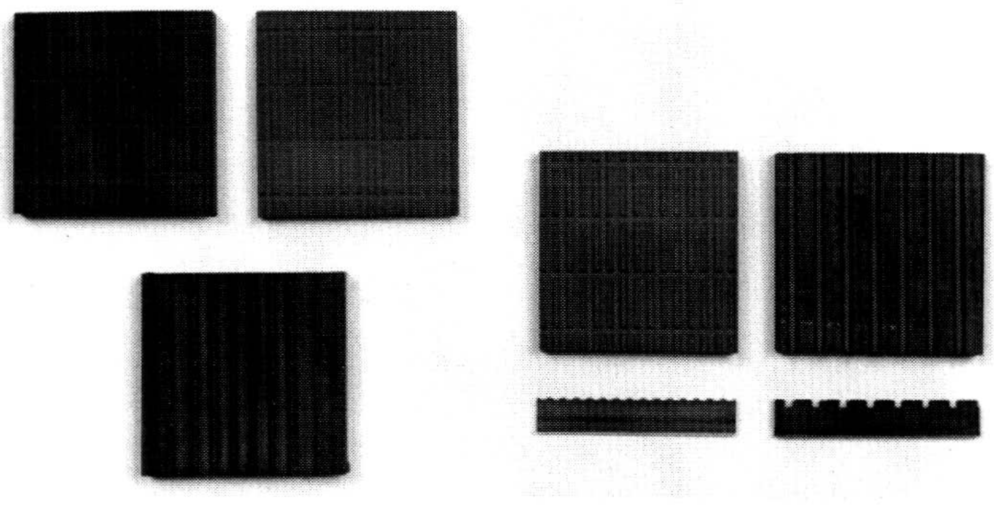


is practically no variation in the type of failure, a homogeneity that also appears in the Shear strength-WA curve for this substrate and kind of body.

4.3 SHAPE AND DISTRIBUTION OF THE RIBS. INCREASE OF THE CONTACT AREA

In this case we refer to different characteristics which have in common a geometric element: raised patterns on the back of the tile, usually known as *ribs*.

PLATE 4: TYPES OF RIB ON THE BACK OF THE TILE "ELONGATED" RIB

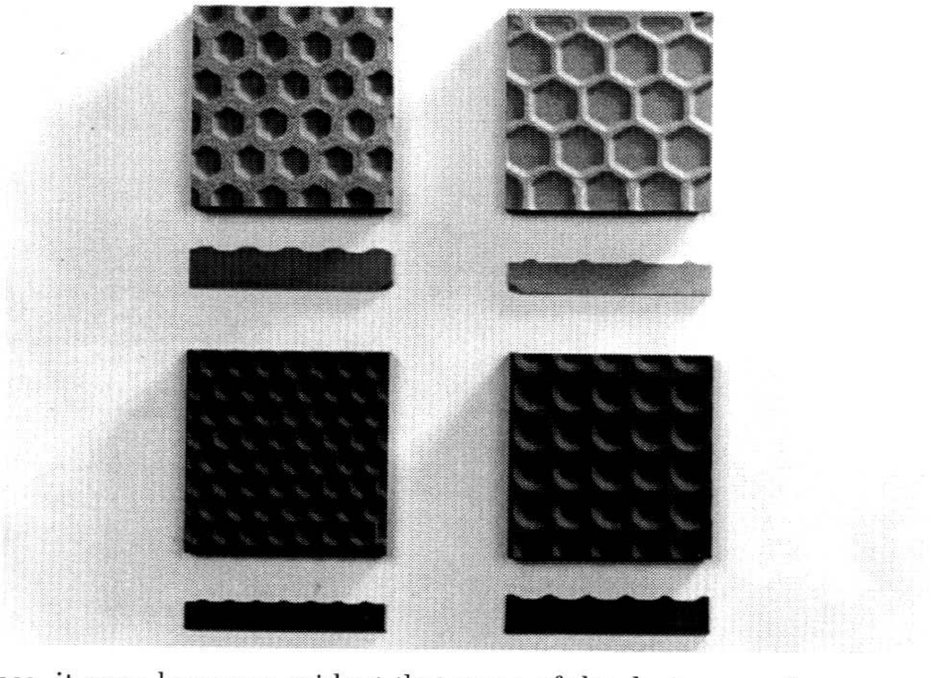


The ribs introduce, in our opinion, three aspects which although different, are at the same time closely related:

4.3.1. Rib patterns (top view and side view)

A simple market survey will reveal the existence of numerous different patterns.

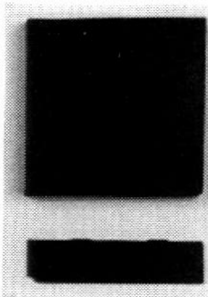
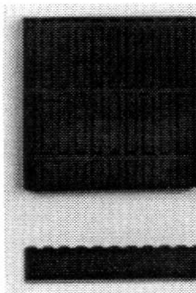
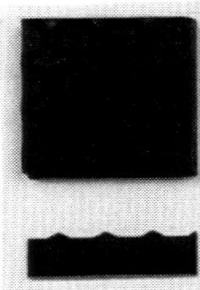
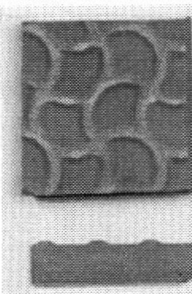
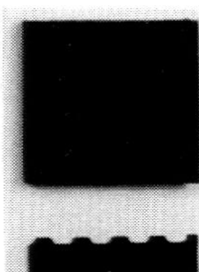
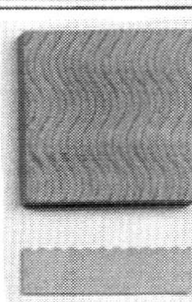
PLATE 5: TYPES OF RIB ON THE BACK OF THE TILE "BEEHIVE" AND "CIRCULAR" RIBS



Nevertheless, it soon becomes evident that some of the designs are far more widespread than others.

In floor tile, the most usual designs are the grid patterns, with square or rectangular designs. The depths used generally do not exceed 1mm: on the other hand, the increase in the surface area that this entails varies from 1% to 8%, while the side views present different angles of inclination. In **plate 3** we are able to see various models which can be classified within this group.

TABLE ONE: COMPARISON OF DIFFERENT TYPES OF RIB

TYPE ANALYZED	INITIAL DATA AND RESULTS	TYPE ANALYZED	INITIAL DATA AND RESULTS
	STONEWARE TILE (Red Body) WA = 4.5% IA = 2% D = 0.3% SSPI = 14%		POROUS TILE (Red Body) WA = 16% IA = 10% D = 0.5% SSPI = 5%
	STONEWARE TILE (Red Body) WA = 4.5% IA = 10% D = 1.2% SSPI = 25%		POROUS TILE (Red Body) WA = 16% IA = 22% D = 0.75% SSPI = 20%
	STONEWARE TILE (Red Body) WA = 5.5% IA = 25% D = 0.65% SSPI = 25%		STONEWARE TILE (White Body) WA = 3.3% IA = ? D = 0.6% SSPI = 15%
	STONEWARE TILE (Red Body) WA = 6.5% IA = 25% D = 1.15% SSPI = 14%		POROUS TILE (White Body) WA = 17.7% IA = ? D = 0.4% SSPI = 20%

TESTING CONDITIONS: TYPE A ADHESIVE, SHEAR TEST (NB: In the non-symmetrical models, the results are averages of the values obtained in two perpendicular directions).
WA: WATER ABSORPTION OF THE BISCUIT; IA: INCREASE IN SURFACE AREA; D: DEPTH OF RIB; SSPI: SHEAR STREGTH PERCENTAGE
INCREASE COMPARED TO BACKS WITHOUT RIBS (WITH THE SAME CHARACTERISTICS).

In wall tiling, although the type of rib we have described is also widespread, it shares the top spot with a type of geometry that better fits the label «rib». We refer to patterns that consist of small, longish, raised shapes set out in rows and columns. These raised shapes are usually 10-12 mm long, 1.5-2 mm wide and 0.5-1 mm high, with rather sharp-angled chamfers). With this pattern, the increases in the surface area reach values of up to 20%, although they do not usually exceed 12-15%. In **plate 4** we can see several of these patterns, as well as another, similar model, which consists of narrow ribs set out lengthwise, crossing the whole of the back of the tile (one design obtained by pressing and the other by extrusion). In the latter, the profiles have right angles.

Apart from these patterns -which are, I must insist, very common- there are many others (**plates 5** and **6**). We could name (if we look at the top view) the circular ribs (with raised or sunken patterns), the «beehives», «the swallow-tails», (obtained by extrusion) and various more elaborate designs. In the «beehive» and «circular» designs the pattern is not greatly raised. The «swallow-tail» ribs are a different matter; here the amount of surface area that is gained can reach important dimensions, attaining values of 45-50% gain for this type of rib that has depths of up to 3 mm.

Table 1 details the results obtained for several of the described patterns. A description is provided of the principal characteristics of the biscuit, the most significant details regarding the geometry, and the approximate percentage of the increase in shear strength (abbreviated as SSPI) that can occur on a surface and in material with the same characteristics but without any type of «macro-relief» (ribs).

4.3.2. Distribution of the ribs

This variable is significant in those ribs that, seen from the top, do not show complete symmetry, that is, do not have as many symmetry axes as sides (e.g. the raised ribs described as the most usual in wall tiling). The experiments carried out by shear testing seem to indicate that the distribution of this type of rib (or a similar one) perpendicular to the direction of the applied force yields slight increases in adhesive strength (approximately 5%).

4.3.3. Increase of the contact area (IA)

We have already mentioned in previous sections the increase in the area of contact usually gained with patterns to be found in the market. There are several techniques for gaining increases in the surface area. They are all based upon the search for important areas in the chamfers that join the parallel horizontal areas to the fair face of the tile. We therefore have:

a) Once a pattern has been chosen, by providing greater depths in the designs, even though maintaining the inclination angles of the chamfers.

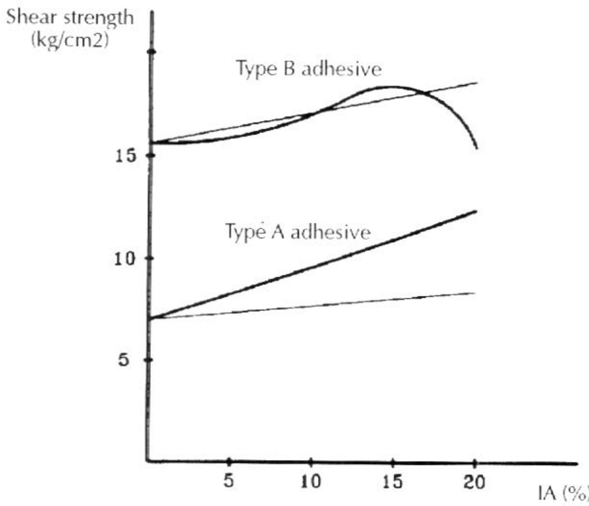
b) Generating angles of close to 90º for the chamfers.

c) Looking for widely separated geometries. That is, for the same shape, a smaller design generates a larger total surface area.

d) Looking for great compaction in the designs (as in the «beehive» pattern or in circular patterns set out in a staggered arrangement).

e) Through special designs as in the «swallow-tail» pattern.

GRAPH 4
SHEAR STRENGTH - INCREASE OF THE BACK SURFACE AREA



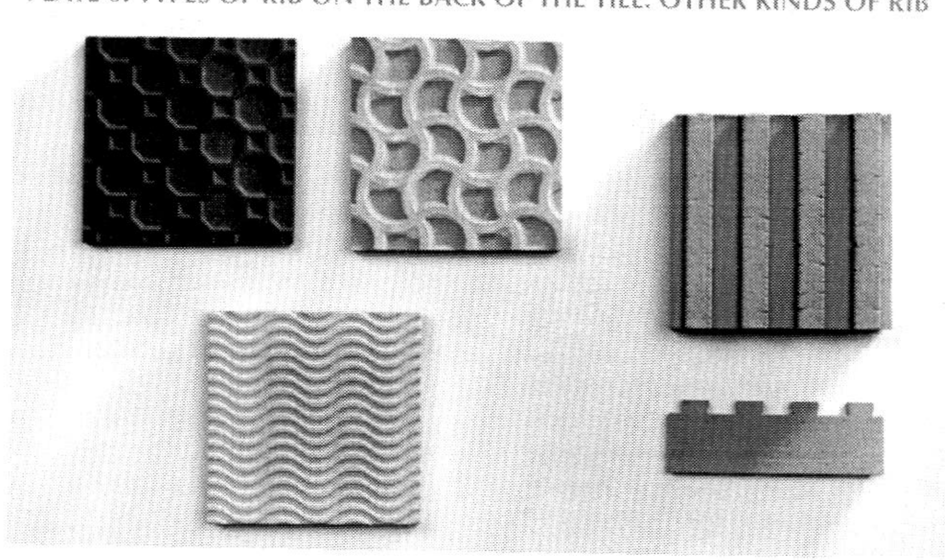
TESTING CONDITIONS
STONEWARE TILE (RED BODY) WA = 2.5 - 3 %
CEMENT MORTAR SUBSTRATE

NB: The broken lines represent the theoretical curves for Shear strengt-IA that would be obtained by the simple increase of the contact area

The increase in the adhesive strength, obtained by a given increase in the area of contact, will depend to a high degree on the geometry to which this IA is associated. It will be the «quality» of these motifs that will yield greater increases. In order to study the effect of the IA we had to decide upon a pattern. We chose a grid design, similar to that most employed in floor tiling. We obtained the variation in the contact area by the methods listed in sections a), b) and c), that is, increasing the depth of the designs and the chamfer angles, and using a widely separated geometry.

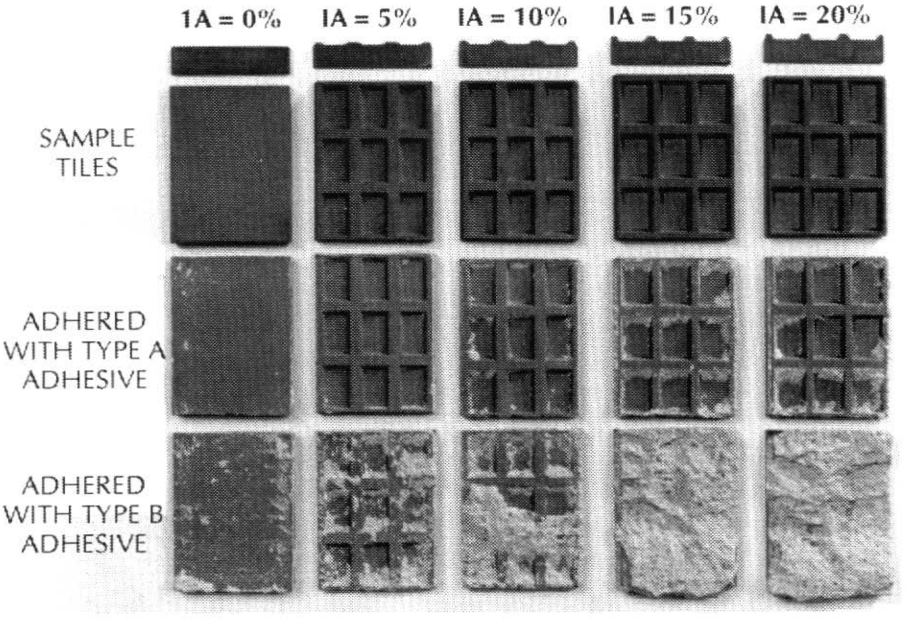
We tested stoneware tiles (red body) with a WA level of 2.5 - 3 %, fixed to cement mortar substrates with the already described adhesives. The results are plotted by a Shear strength - IA (%) graph, **graph 4.**

PLATE 6: TYPES OF RIB ON THE BACK OF THE TILE. OTHER KINDS OF RIB



The broken lines represent the curves that theoretically should be formed when the increase in shear strength is due to a simple increase of the contact area (i.e. a given percentage of IA corresponds to a given percentage of increase in the adhesive strength). Theoretically, these curves should follow each other if the adhesion were purely chemical, and a greater contact area meant a proportional increase in adhesive strength. In mechanical adhesion, the appearance of «physical anchorings» would invalidate this hypothesis.

PLATE 7: VARIATION OF THE TYPE OF FAILURE WITH THE INCREASE IN THE SURFACE AREA OF THE BACK OF THE TILE



TILE: STONEWARE (RED BODY) WITH WA = 2.5 - 3%
SUBSTRATE: CEMENT MORTAR; TEST: SHEAR

Observing the tendencies shown by the curves, we can see how, for the «type A» adhesive, the increase obtained is practically linear and certainly exceeds the one traced by the broken line. In the case of the «type B» adhesive, the results follow fairly closely the corresponding unbroken line to a certain point (with the IA at approx. 15%) at which an important descent occurs. These results confirm the theoretical hypothesis we have already stated. **Plate 7** shows the variation of the type of failure that resulted from the above experiments. We have included «sample tiles» to show the patterns of the ribs used.

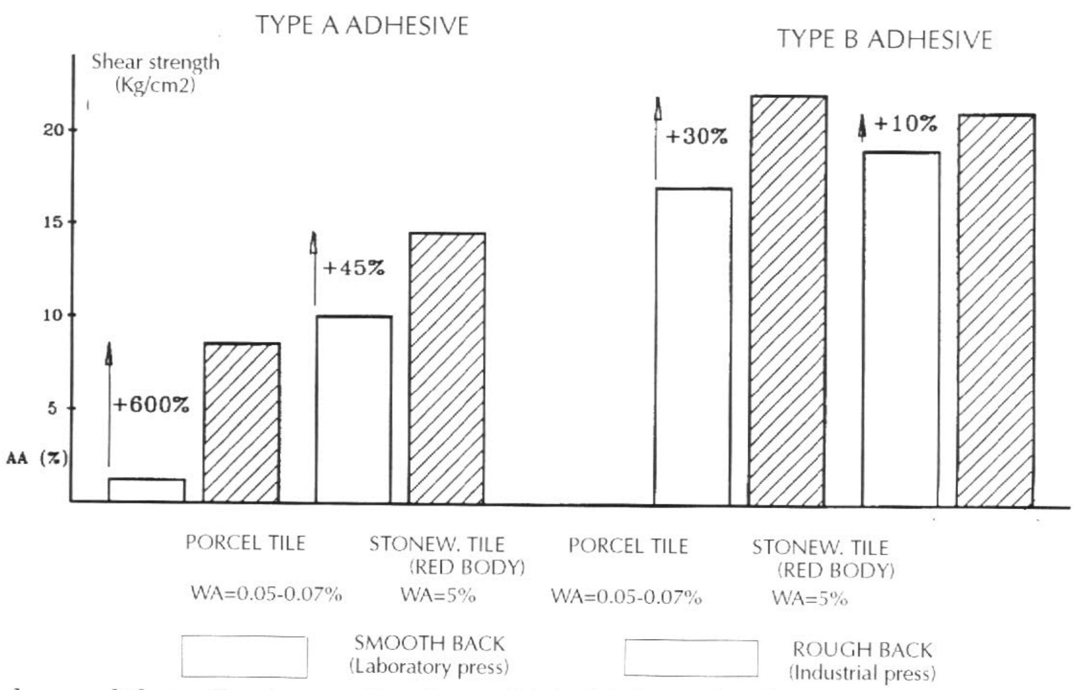
The fall that occurred in the shear strength value in the case of the «type B» adhesive, with IA's exceeding 15%, may possibly be due to factors we shall now discuss.

In principle we may assume that it is the more «aggressive» patterns (with greater anchoring capacity) which should provide greater adhesive strength, especially in shear testing. The experiments we carried out show that this is not always the case. There are several reasons we can give to explain this fact:

- The «aggressive» patterns (which can be defined as those consisting of chamfer angles close to 90º and pronounced rib depths, between 1.5 to 3 mm) can foster concentrated points of stress, real originators of the consequent crack which, in turn, will cause the failure. The non-existence of points of conflict will retard the appearance of the crack, and at the same time favour more «resistant» types of fracture, such as the AF-T fractures (Adhesion failure tile) (with certain set conditions for the rest of the variables that affect adhesion).

- The new adhesives in the market should be employed using the thin set method (or proven alternatives), which means that the thickness of the adhesive will be between 2 and 3 mm (as recommended by international regulations). This aspect has been verified by different tests, which show an important fall in the adhesive strength (between approx. 30 and 45%, depending on the adhesive employed) when we exceed the thicknesses recommended for layers of adhesive and go to layers of between 6 and 8 mm thick. It has

GRAPH 5
EFFECT OF THE SURFACE ROUGHNES OF THE BACK OF THE TILE



been observed that adhesive applications of this thickness lead to faulty installation (with a large number of cavities and small cracks in the setting). These facts counsel against the use of «aggressive» ribs with these adhesives, installed with the thin-set method, especially if we take into account the difficulty involved in achieving the proper application of adhesive on the back of a tile with excessive relief.

Considering all the above-mentioned facts, we advise the use of symmetrical designs which are softer (with chamfer angles not exceeding 45º), with widely separated geometries, high degrees of compaction and rib depths not exceeding 1-1.3 mm.

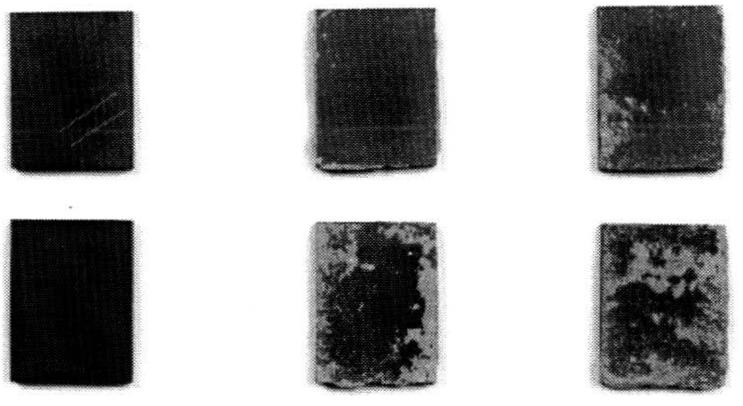
4.4 SURFACE ROUGHNESS OF THE BACK OF THE TILE

This is what we might call an «unsought» variable that appears in the industrial process (as in the case of WA, or of the rib) ; it is a characteristic that arises in the process itself.

We have observed that the surface roughness of the back of the different tiles is not uniform, especially between the ones that come from our laboratory press and those which were obtained from industrial presses (with much rougher backs). This roughness may be due to the «dirtiness» of the industrial pressing dies or to the different grain sizes in the bodies. Logic dictates that any one of the factors or characteristics of the surface in question (which forms part of the adhesive bond) can affect decisively the ultimate adhesive strength.

PLATE 8: VARIATION OF THE TYPE OF FAILURE IN TILES WITH DIFFERENT KINDS OF SURFACE ROUGHNESS OF THE BACK

SAMPLE TEST PIECE ADHESIVE: TYPE A ADHESIVE: TYPE B



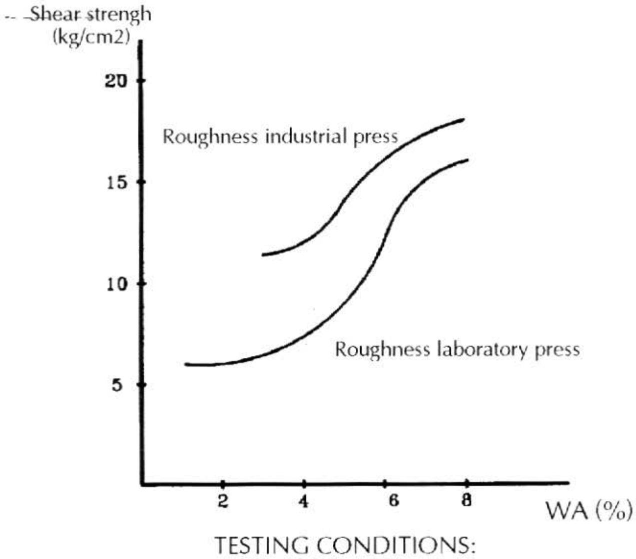
TILE: STONEWARE (RED BODY) WITH WA = 2.5 - 3%
SUBSTRATE: CEMENT MORTAR
TEST: SHEAR

Once this hypothesis was established, we decided to check its validity.

In **graph 5** we can observe the increases obtained by varying the surface roughness of the back of the tile. This information shows the growing importance of this factor in keeping with the rate at which the contribution of other variables in the mechanical anchoring -e.g. WA- becomes critical. This aspect is confirmed by the fact that in the porous tiles no outstanding differences were observed between backs with a different roughness.

Therefore, there seems to exist an important interaction between two factors, namely WA

GRAPH 6
INTERACTION BETWEEN TWO VARIABLES:
ROUGHNES AND WA



TESTING CONDITIONS:
STONEW, TILE (RED BODY)
TYPE A ADHESIVE
CEMENT MORTAR SUBSTRATE

and roughness. As proof of this, in **graph 6**, we can observe the curves corresponding to stoneware tiles (red body) fixed to cement mortar with type A adhesive. The more the WA decreases, the more the difference between the two curves increases.

In **plate 8** the differences can be observed in the types of failure obtained by varying the roughness of the back (rougher in the bottom row). The sample test pieces used in each case have also been included. In the photograph we can observe, even visually, the differences in the roughness. We can see how the rougher back leaves the surface covered with a larger amount of adhesive, resulting from the possible existence of a greater number of anchoring points.

The results obtained in this direction are encouraging and could open up a new and interesting field of action in the search for an ever greater reliability of the ceramic tile installation systems.

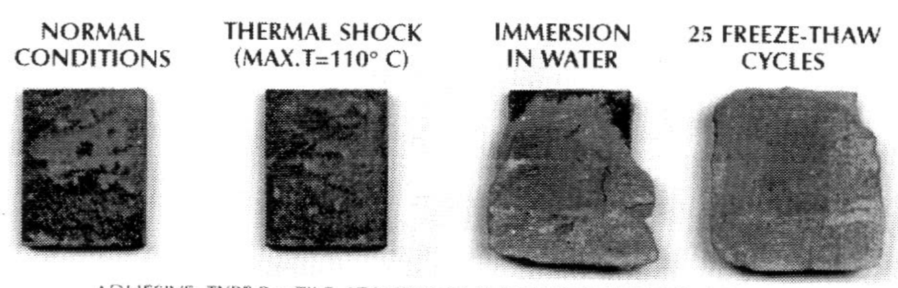
4.5 EFFECT OF OTHER CHARACTERISTICS

In this section we refer to characteristics mentioned in the literature surveyed, which have not constituted the main object of this study.

4.5.1. Coefficient of thermal expansion of the biscuit. Thermal shock and other climatic conditioning factors

As we know, the thermal expansion of a material when its temperature varies is proportional to the alteration in temperatures and to its coefficient of thermal expansion.

PLATE 9: VARIATION OF THE TYPE OF FAILURE IN TILES SUBJECTED TO DIFFERENT CLIMATIC CONDITIONS



ADHESIVE: TYPE B • TILE: STONEWARE (RED BODY) WITH WA=2.5-3%
SUBSTRATE: CEMENT MORTAR • TEST: SHEAR

In a multilayer system -like the ceramic tile installation system- the differences between the thermal expansion coefficients can provoke important states of stress in the strata that join the different materials. The analysis of these coefficients indicates a relative homogeneity between them in those cases where the substrate and the adhesive are both of a basically mineral nature. If the components of an organic nature are increasingly important in the adhesive, the discrepancies begin to take on importance and consequently, the states of stress which may occur. In any event, an adequate design of the expansion joints necessary in each case has proved to be essential.

On the other hand, one author (9) mentions the effect of the thermal expansion coefficient of the tile upon shear strength and to the flexural bond strength of the background/ rendering and rendering/mortar (adhesive) interfaces, when variations of temperature occur in the whole. It is evident that the obtention of an interval for these coefficients (of the tile), which would lessen the existing tensile stresses would be most beneficial in situations such as facades subjected to important cycles of thermal shock.

All the experiments described in this study, up to this point, have been carried out by subjecting the models to laboratory conditions, far less demanding than those to be found in certain circumstances (exteriors subjected to frost, important thermal shocks and/ or the effects of water). We thought it convenient to carry out some tests where the models would be subjected to different conditions. In this manner, we are able to discover new behaviour, especially of the adhesive, seeing that the characteristics of the tile in many cases are determined by other conditioning factors (for example, stoneware products should be used in exteriors when there is a possibility of frosts).

In **plate 9** we can observe the types of failure which occur in the debonding of some stoneware tiles belonging to group BI (WA< 3%), fixed with a type B adhesive and subjected to different conditions. The action of the water (both through immersion and in the frost cycles) produces a significant variation in the type of failure obtained, right through from an AF-T type of debonding (in the tile-adhesive interface) to an AF-S type (in the adhesive-substrate interface). The corresponding shear strength values are the following:

- 28 days in laboratory conditions: 16.5 kg/cm2
- subjected to 12 thermal shock cycles with a T_{max} = 110º C: 6.2 kg/cm2
- subjected to the action of water: 11.9 kg/cm2
- subjected to 25 freeze-thaw cycles: 8.3 kg/cm2

There is a significant loss in shear strength values.

A more complete study of this point would require an analysis of the possible interactions between those characteristics of the tiles that have an effect, and the indicated climatic conditions.

4.5.2. Thickness/surface area ratio of the ceramic piece

Different authors (16) state that this ratio is another variable in the common aim to improve the characteristics of the bond. The explanation is obvious: seeing that there are joins in the fixing, the tile does not adhere only at the back but also at the sides. The thicker the tile, the greater the increase in the surface area. This rise will grow with the increase in the area of the joints within the total tiled area, which in turn, will be determined by the width of the joints and of the tile sizes employed.

Thus, in small tile sizes (for example, mosaics) of a substantial thickness, the thickness/surface area ratio may have notable effects upon the whole of the adhesive strength. In this context, we should like to give a special mention to the tiling technique of the «trencadis» (small, irregular fragments, resulting from the cutting up of larger tiles) employed in the modernist architecture of the start of the century. Despite the time that has elapsed, it still persists on facades and roofs in all its beauty and splendour, thanks -in part- to the use of the facts that we have just described.

CONCLUSIONS

Throughout this article, we have stressed the importance of the effect that the different tile characteristics have upon their greater or lesser adhesion strength to cement mortar substrates.

The different behaviour has been studied of two types of adhesives (a cementitious adhesive with hydraulic binders -which we have named «type A»- and its homologue with mixed binders -»type B»), with regard to the characteristics mentioned.

We have analyzed in depth the effect of the water absorption (WA) of the biscuit, having obtained the Shear strength-WA curves for stoneware and porous tile bodies.

Regarding this point, the following conclusions should be mentioned:

- In the stoneware tile bodies, an increase in the WA of the biscuit (from 1% up to 8%) produces a significant increase in shear strength. This rise depends on the adhesive and the type of body employed. Thus we can observe how the increases obtained are greater for the «type A» adhesive than for «type B», although, on the other hand, the absolute values are always higher for the latter. Regarding the type of body, we must state that the increases in shear strength are lower in the white bodies than in the red.

- This behaviour, which corresponds to the stoneware tile bodies, is different in the case of the porous tile. For this type of body, the initial tendency is similar, that is, there is an increase in the shear strength with the degree of WA of the biscuit. Once a certain value of WA has been attained (different for each of the two adhesives) the shear strength not only stops increasing, but begins to slowly diminish as this variable rises.

- These curves, obtained for cement mortar substrates, vary on using a different type of substrate. For a rendered brick substrate, with greater surface water absorption than that of the cement mortar background, the differences in the processes of setting and elimination of the excess hydration water, provoke a «sliding» of the obtained curves toward lower WA values. In consequence, greater values of shear strength are usually obtained with rendered brick substrates than with cement mortar ones, in the industrial WA ranges of stoneware and porous tile production. This tendency has been found employing only the «type A» adhesive (cementitious adhesive with hydraulic binders).

We have shown the importance of a «good design» for the ribs on the back of a tile. Based on the research carried out, we advise the use of soft, symmetrical designs, with widely separated geometries, high degrees of compaction and rib depths no greater than 1 - 1.3 mm.

And finally, we have discussed the beneficial effect of a sufficient surface roughness on the back of the tile, and how this variable interacts with the water absorption of the biscuit. This interaction indicates that as WA decreases, surface roughness plays a more important part in adhesion.

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