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# Parametric study for the creation of the interface between concrete and repair products

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## ABSTRACT

An analysis as large as possible presents factors acting when a repair system comes into contact with a concrete support. The appetency of the first one for the second is defined from the properties of the support and the new layer – essentially in its liquid phase – as well as from the environmental conditions. These properties are cited or explained for each materials : roughness, porosity, superficial cohesion and interstitial water into concrete, nature and concentration of the binder, rigidity modulus, capillary succion for repair systems.

The thermodynamic properties of the materials as well as transport mechanisms – diffusion, capillary succion – at the interface and roughness of the concrete support are particularly developed. A sequential flow sheet related to the parameters influencing the creation of the interface is proposed.

## RÉSUMÉ

*Une analyse la plus exhaustive possible présente l'ensemble des facteurs qui peuvent interagir au moment où le produit de réparation est mis en contact avec le béton. L'affinité du premier pour le second est définie à partir des propriétés du support et de la nouvelle couche – essentiellement dans sa phase liquide – ainsi que de l'environnement dans lequel le contact est créé. Ces propriétés sont évoquées ou développées pour chacun des matériaux mis en présence : rugosité, porosité, cohésion superficielle et eau interstitielle pour le béton : nature et concentration du liant, modules de rigidité, absorption capillaire pour les produits de réparation.*

*L'aspect lié aux propriétés thermodynamiques des matériaux, ainsi que les phénomènes d'échange – diffusion, absorption par capillarité – à l'interface et l'évolution de la rugosité du support sont évoqués en particulier. Un organigramme séquentiel et représentatif de la création de l'interface est proposé.*

## 1. INTRODUCTION

If two bodies are able to associate in order to form an assembly or a composite material, the reason is the creation of the interface between these two materials of similar nature or not: at a thermodynamic point of view, we can affirm that the work of adhesion is greater than the work of cohesion. If there is creation of an interface, that means that there is a potential and mutual interaction between the two bodies. A physiological transposition of the situation would let us say that it is a case of partiality (from latin word "appetentia"): this term means the instinctive desire to all what is able to satisfy a need or something instinctive. Its application to the interface between concrete and a new layer summaries all the parameters – physical, chemical and mechanical properties – of the support, the new layer and the environment that will influence the creation and the stability of this interface. Finally, that will lead to the macroscopical effect and sign of the efficiency of the bonds: the adherence.

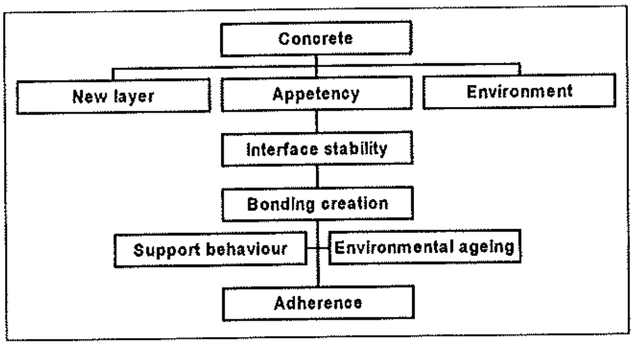


Fig. 1 – From the creation of the interface to adherence.

There is indeed a relation from cause to effect. But in order to find the link between appetency and adherence, we have to define and measure exactly the electrical, molecular and atomic forces existing between the materials. These "microscopic" phenomenon define exactly adhesion : the adhesion is a quantitative interpretation of the force or the energy necessary to separate the bodies [2].

Without appetency, there is no adhesion; without adhesion there is no adherence. Appetency, that will be here described, is not an intellectual and immaterial view of things: it may be microscopically observable and macroscopically quantified. It is a basic phenomenon in the explanation of adhesion and cohesion for concrete.

## 2. BASIC CONSIDERATIONS

Many authors [3-5] studied the causes of non-adherence of a repairing mortar or bonding layer on a concrete support. They pointed out the interest of using polymeric binders in order to modify cement mortars and to promote and/or increase adherence.

Pareek [5] proposed a report of the causes and cures in the case of repairing systems.

Table 1 - Factors affecting adhesion and repair of finish materials and their adhesion improvment techniques [5]

| Type of Repair and Finish Material | Type of Substrate | Reason for Poor Adhesion to Substrate | Type of Damage | Adhesion Improvement Technique |
|---|---|---|---|---|
| Ordinary Cement Mortar | • Cement Concrete or Mortar<br>• Reinforcing Bar | • Dry-out<br>• Formation of Voids at the Interface<br>• Drying Shrinkage Stresses at Interface | | • Application of Polymer Dispersion, Polymer-Modified Paste as Bonding Agent to Substrate |
| Polymer-Modified Mortar | • Cement Concrete or Mortar<br>• Reinforcing Bar | • Mischoosing of Type of Polymer Dispersion and Polymer-Cement Ratio | • Loss of Adhesion<br>• Cracking<br>• Delamination | • Selection of Suitable Surface Treatment for Substrate, and of Appropriate Type of Polymer Dispersion and Polymer-Cement Ratio |
| Polymer Mortar | • Cement Concrete or Mortar | • Wetness of Substrate<br>• Setting Shrinkage of Polymer Mortar | | • Application of Coupling Agent as Primer to Substrate, and Use of Shrinkage-Reduced Polymer Mortar |

A first classification may be physically evident : on one hand, there are the factors related to the support and, on the other hand, related to the new layer. If this operation is relatively easy for a certain number of them, it is no so clear for factors like thermodynamic properties or kinetics of contact where interactions between support and new layer are continuously ageing. Consequently, if our analysis is of sequential type, it is important to keep in mind that the system is constituted – at a thermodynamic point of view – of two bodies of "different" nature but affecting continuously each other.

Moreover we must never forget another family of factors, less definite and quantifiable but however fundamental for the quality of the work: environmental factors and particularly human influence.

It is scientifically illusive to try to quantify them because they are often random and imprecise but it is important to take then into account.

## 3. SUPPORT PARAMETERS

The approach followed hereafter distinguishes the next factors:
- roughness;
- porosity;
- superficial cohesion;
- composition of interstitial water.

### 3.1 Roughness

Roughness is a global word that may give different informations according to the level of investigation : in civil engineering area, the millimetric scale usually permits to distinguish surface treatments like hammering, sandblasting or hydrojetting for example.

Mechanical interlocking and contact angle modification are two fundamental effects of surface "roughness".

The effect of the roughness profile is more in relation with the thermodynamic properties of the support and particularly by modifying the value of the contact angle, according to the Wenzel relation [2].

The evaluation of the roughness factor can be realised from surfometric and profilometric analysis [1].

A lot of authors tried to characterise the surface roughness by the ratio between the surface occupied by aggregate and the cement paste [7], by the maximal depth or roughness [8], adherence-traction tests [6] or the calculation of surface parameters determined by image analysis and microscopical observations [9]. The determination of Surface Rough Index [10] should also permit to differentiate the surface treatment but gives only a "global" view of the roughness.

The analysis of the profile obtained by profilometry or surfometry let us to observe and quantify the shape regularity and the isotropic effect of sandblasting and polishing treatments, for example [11], after filtering the total profile into long waves and short waves profiles. It is therefore possible to calculate amplitude and profile parameters in order to discriminate different surface treatments.

One conclusion of these analysis is that the discrimination is more significant for the waviness than for the roughness, that means for interlocking effect. In order to

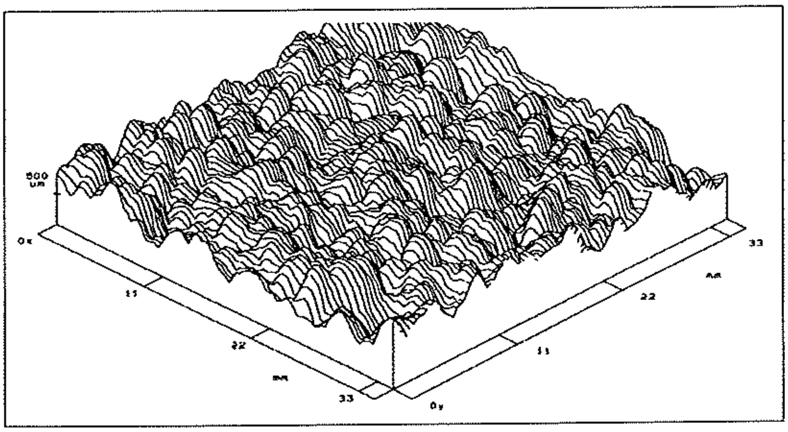

Fig. 2a - 3D visualisation of sandlasted concrete profile.

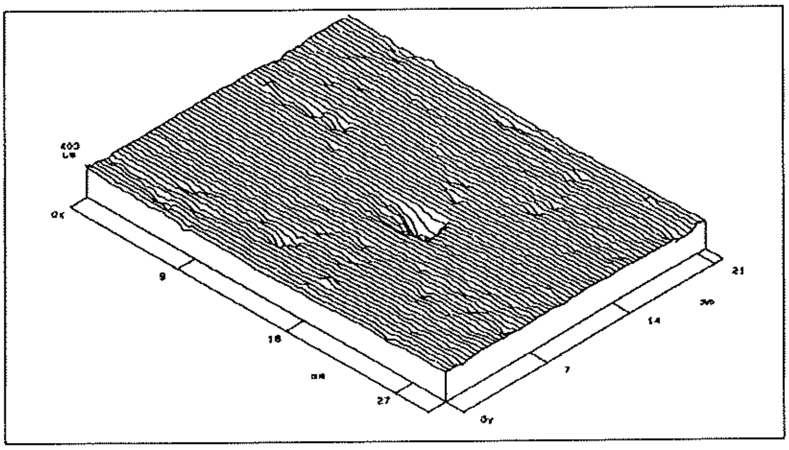

Fig. 2a - 3D visualisation of polished concrete profile.

develop this mechanical effect, it will be necessary to use materials able to penetrate into the waviness profile of the concrete support (viscosity, inert material content, ...). The minimum quantity of slurry, binder or mortar necessary to fulfil the empty waviness profile may be also evaluated from the calculation of the bearing ratio and curve of Abbott [1, 11].

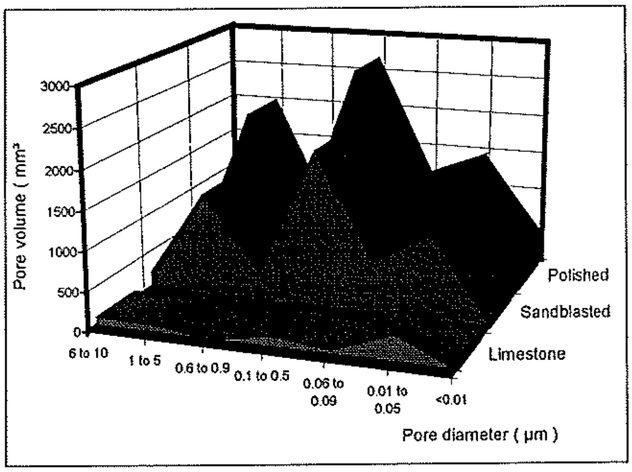


Fig. 3 - Evolution of porous volume versus diameter of the pores - concrete.

## 3.2 Porosity of the concrete

The physical properties are fundamentals for the explanation of the exchanges at the interface. A lot of notions may be defined such as opened and closed porosity, relative impregnation ratio or water absorption. Capillary absorption seems to be more accurate to describe the behaviour of the concrete "skin" in contact with the newlayer.

However, the definition of the concrete skeleton can be evaluated by means of Hg porosimetry that will estimate the specific surface, the porous volume and the mean radius.

But the most interesting information is the porous volume as a function of the diameter; it will be so possible to evaluate theoretically the maximum quantity of liquid each type of pore will be able to absorb. Based on the law of Washburn [1, 2] the calculation imposes to take into account the presence of the Interfacial Transition Zone (I.T.Z.) in order to be able to correlate theory and experimental observations [1].

The microscopical observations may be useful to determine ITZ values.

It will permit to calculate a coefficient of capillarity, that will take into account properties like connectivity, accessibility of

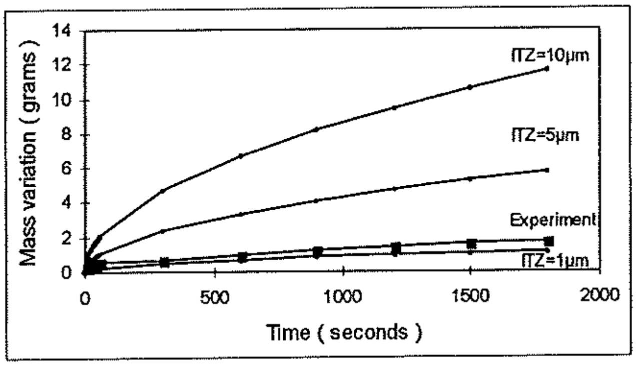


Fig. 4 - Theoretical and experimental capillary absorption of the interstitial solution of a cement slurry modified with melamine admixture [1].

the pores, tortuosity, ... [1]. It can be evaluated by comparison between theory and experiments and is a characteristic of the material.

## 3.3 Superficial cohesion

The concrete support is mechanically characterised by its superficial cohesion that will greatly influence the quality of repairing works.

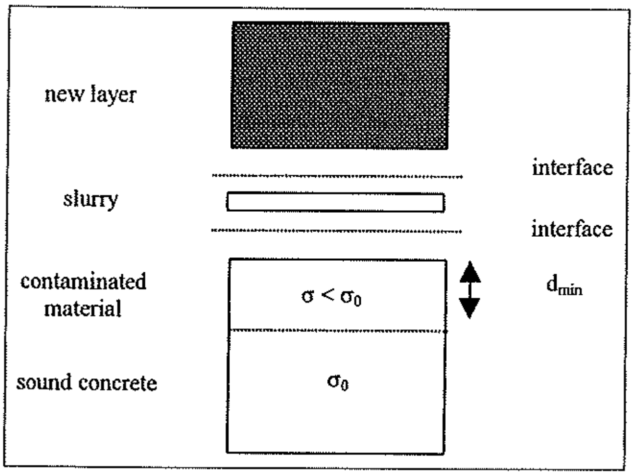


Fig. 5 – Superficial cohesion and interface.

The quality of the repairing mortar has to be chosen in such a way that $\sigma > \sigma_0$ but it is also necessary to prepare the support in order to remove low resistant or contaminated material and to reach sound concrete. The technical preparation will be also of the prime importance: for example, hammering may produce micro-cracking of the superficial layer of the concrete support and decrease the quality of the repairing works [6]. The measurement of superficial cohesion by means of adherence test [12] may be a good solution : the draft of European standard prEN 1766 imposes a characteristic value for cohesion of 3.5 $N/mm^2$ (type MC 0,4 concrete).

### 3.4 Composition of interstitial water

This property is often forgotten when a new layer is applied on a concrete support: due to its porous structure and assuming it is water saturated, diffusion of ions may be observed from the interstitial solution of the cement slurry or the PCC and CC mortar to the water present into the porous skeleton of the concrete and inversely. The analysis of the ionic composition of the solutions permits to compare the concentrations of different ions.

**Table 2 – Ionic composition of city water (Liege, Belgium), interstitial water of concrete and centrifugated solution of a cement CEM I 52.5 slurry (mg/l)**

| Ions | Ionic Composition of Water (mg/l) | | | |
|---|---|---|---|---|
| | Cement Slurry | Concrete Support | City Water Hesbaye | City Water Eupen |
| Cl⁻ | 1390 | 317 | 55.64 | 13.7 |
| Ca | 1210 | 1100 | 145.73 | 33.1 |
| Mg | < 0.05 | 19.4 | 14.24 | 1.1 |
| Na | 1500 | 220 | 16.49 | 6.2 |
| K | 7360 | 1108 | 2.98 | 0.5 |
| pH | 13.1 | 12.7 | 7.35 | 8.4 |

The interstitial solution of water may be obtain from high pressure destruction of concrete [13] or by pushing water out of concrete and gathering the quantity of liquid corresponding to the open porosity of the concrete [1]. We used this way in our research and the analysis of the results gave following observations:

– $[Ca^{2+}]$ concentration is higher in concrete than in cement slurry, probably due to the fact that the $Ca(OH)_2$ has had no time to be produced by cement hydration. The slurry is centrifugated only 20 minutes after mix;

– $[Na^+]$ and $[K^+]$ concentration indicates they are the first to go through water solution due to a higher degree of solubility of $K_2O$ and $Na_2O$ than $Ca(OH)_2$.

In any case, ionic movements may occur and participate the creation of chemicals bonds or, at least, to chemical interactions between the support and the new layer, adding a "classical" component to the classical adhesion theory.

## 4. NEW LAYER PARAMETERS

The new layer applied on the concrete support is not an inert material; its behaviour will influence again the quality of the bond. The nature and the concentration of the binder as well as the conditions of hardening reaction are important; the dimensional stability and the relative values of E modulus of the two materials which are assembled will also promote or not the durability of the bond [3].

But we would like here more analyse the very beginning conditions of the creation of the interface: the first phenomenon observed when the new layer is laid down on the concrete support is the wetting of the solid surface by the liquid. The wetting is depending on two main aspects : thermodynamic (there is wetting) and kinetic (wetting has to happen as quick as possible). The kinetic aspect is fundamental for porous surface where capillary absorption will happen and increase the contact surface between the two bodies.

The liquid spread out on the concrete surface will be partially absorbed by the support. The theoretical phenomenon is described by the laws of Laplace and Jurin:

$$H = \frac{2\gamma_L \cos\theta}{\rho \cdot g \cdot r}$$

The combination with the law of Poiseuille which describes the flow of liquid through an horizontal capillary lead to the determination of the variation of penetration height as a function of the time (law of Washburn):

$$\ell_p^2 = \frac{r \cdot \gamma_L \cdot \cos\theta}{2\eta} \cdot t$$

where $\eta$ is the viscosity of the liquid ($N/m^2.s$)
r is the radius of the pore (m)
$\gamma_L$ is the superficial tension of the liquid (N/m)
$\theta$ is the contact angle
t is the time (s).

The measurements realised on different liquids [1] show a behaviour similar to the general shape of this law.

If concrete may be represented by a porous material with parallel capillaries of different radius, perpendicular

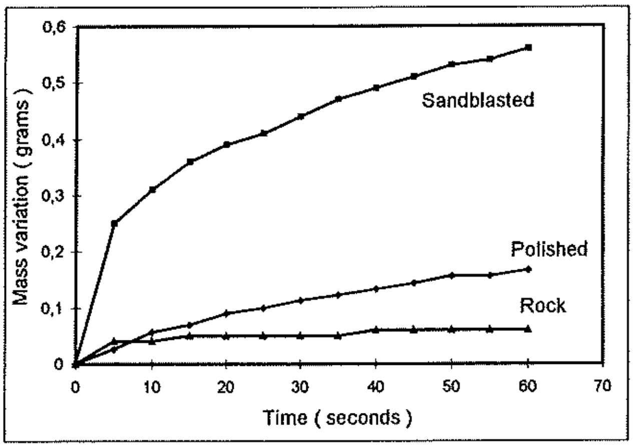


Fig. 6 – Capillary absorption of water on concrete slab between 0 and 60 sec. - variation in mass (g).

to the liquid surface, the liquid will be absorbed with a higher force (Laplace) for fine capillaries but at a higher speed and in higher quantity (Washburn) for big capillaries. The Washburn relation shows also that the penetration height increases when:

- the viscosity of the liquid decreases;
- the contact angle increases;
- the superficial tension of liquid increases.

These two last conditions are in contradiction and will need the reach to an equilibrium.

Many remarks may be formulated about the use of Washburn law:

- the shape of the pore will influence the results [1] (circular or bottle-ink for example);
- the contact angle value is not a constant and will depend on time and temperature (Table 3);
- the pollution of the concrete surface may modify the kinetics of contact;
- the viscosity is also depending on time. An example is given hereafter about the variation of W/C ratio into a cement slurry applied on a concrete support.

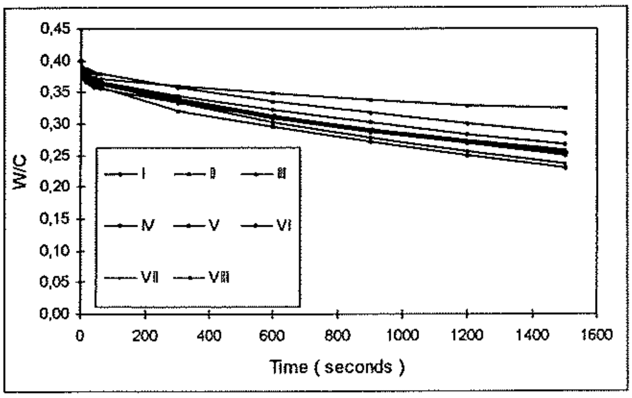


Fig. 7 – Evolution of W/C versus time for a cement slurry modified with admixtures applied on a concrete support [1].

It seems to be fundamental to define clearly the conditions of application in order to be able to modelise the behaviour of the liquid applied on the concrete support. The continuous interaction between the two bodies shows also that it is illusory to choose one without the other.

## 5. THERMODYNAMIC APPROACH

The superficial tension of a liquid determines its ability for wetting a solid surface: an efficient spreading of the liquid on the solid increases the effective surface of contact and promotes adhesion.

The second law of thermodynamics indicates that a system of two phases is stable if local energy is minimum. For the creation and the stability of the interface between concrete and new layer, we make the hypothesis that this minimisation of the interfacial energy corresponds to a maximum of resistance and durability of the joint.

It is not our scope to present here in details developments on thermodynamic considerations [1]. However, we want to point out some important conclusions.

### 5.1 Fundamental laws and spreading conditions

The relation between contact angle and free energies of liquid and solid is defined according to the law of Young-Dupre.

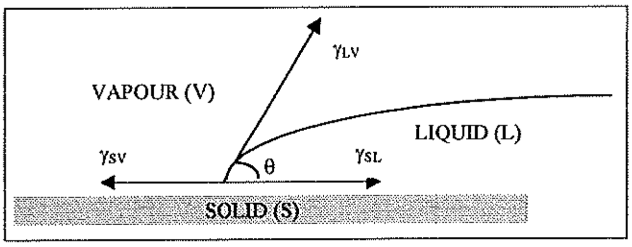


Fig. 8 – Wetting of a solid surface by a liquid.

$$\gamma_S = \gamma_{SL} + \gamma_L \cos\theta$$

where $\gamma_S$ is the surface free energy of solid;
$\gamma_L$ is the surface free energy of liquid;
$\gamma_{SL}$ is the surface free energy liquid/solid.

The best spreading of liquid on the solid surface may be expressed by many criteria:

- minimisation of contact angle: the lower the contact angle, the better the spreading. The measurements of contact angle can be performed with goniometer [1, 5]. Some additives may modify the interactions into the interstitial solution of the cement slurry, binder layer or mortar.

The effects of the use of admixtures are a low decreasing of viscosity and a more large decreasing of contact angle values.

- free energies criteria : it is possible, from the Young-Dupre equation to conclude that, for a fixed value of gL, an increase of the difference $\gamma_S$ - $\gamma_{SL}$ is favourable for the wettability of the surface. This criteria is however low attractive due to the difficulty to determine $\gamma_S$ and $\gamma_{SL}$. Another criteria is to say that $\gamma_L$ has to be the highest as possible to obtain the lowest value of the contact angle $\theta$. As already mentioned in 4, this criterion is in contradic-

Table 3 – Evolution of contact angle on a cement paste and calcereous rock for centrifugated solutions of cement slurries modified with different admixtures versus time

| Liquid | Supports | | | | | |
|---|---|---|---|---|---|---|
| | Cement paste | | Cement paste + hydrophobic treatment | | Rock | |
| | 20 sec. | 2 min. | 20 sec. | 2 min. | 20 sec. | 2 min. |
| I | 12 | 9 | 115 | 113 | 16 | 11 |
| II | 17 | 14 | 126 | 123 | 19 | 13 |
| III | 19 | 15 | 130 | 129 | 23 | 17 |
| IV | 21 | 18 | 122 | 120 | 21 | 16 |
| V | 32 | 29 | 111 | 110 | 23 | 18 |
| VI | 23 | 21 | 127 | 125 | 29 | 20 |
| VII | 34 | 31 | 124 | 120 | 21 | 26 |
| VIII | 8 | 5 | 103 | 98 | 16 | 8 |
| *Water* | 58 | 50 | 120 | 116 | 43 | 35 |

tion with the capillary laws and an equilibrium has to be reached;

$\gamma_S$ minimisation of interfacial energy or maximisation of the work of adhesion. The work of adhesion represents the work necessary to separate the two bodies.

$$W_A = \gamma_S + \gamma_L - g\gamma_{SL}$$

These criteria are not really applicable to the situation of the creation of an interface, when liquid is spread on solid. It is more related to the resistance of the interface solid/solid, after hardening or polymerisation of the liquid phase.

## 5.2. Relation between thermodynamic parameters and adherence

Some relations were found [1, 15, 16] between the shear strength of metallic plates or glass fibres with resin and thermodynamic parameters :

$$\tau = f_1(\gamma_{SL} / \gamma^C_L) \text{ or } \tau = f_2(\gamma_S / \gamma^C_L)$$

where $\gamma^C_L$ is the superficial tension of the liquid phase after hardening.

However, it is very difficult to establish such as relation between concrete and repair products due to several reasons:

– test devices used to measure adherence are generally not able to make distinction between the contribution of adhesion forces and loss of viscoelastic or plastic energy into concrete or the new layer;

– thermodynamic considerations on the stability of the interface solid/solid may be correlated with adherence only if rupture happens at the interface;

– the measurement of the contact angle θ with goniometer is very imprecise due to the unhomogeneity and porosity of the support. This measurement is the base for the calculation of $\gamma_S$, $\gamma_{SL}$ and $W_A$. More precision could be eventually obtain by working on powders.

For the analysis of the creation of the interface, it seems that the more representative criterion is the contact angle because it is a direct representation of the wettability of the surface. It is a necessary but not a sufficient condition to guarantee the efficiency of the bond.

## 6. ENVIRONMENTAL FACTORS

The influence of temperature or relative humidity of the ambient atmosphere before the application and during the curing of the new layer are relatively well-known. The degree of saturation of the support has also a great importance and we showed [14] that the adherence strength was changing in a clock-shape as a function of it : the characteristic adherence is relatively low for low saturation level (≤ 50%). It reaches classical values for saturation levels between 55 and 75% and decreases after that.

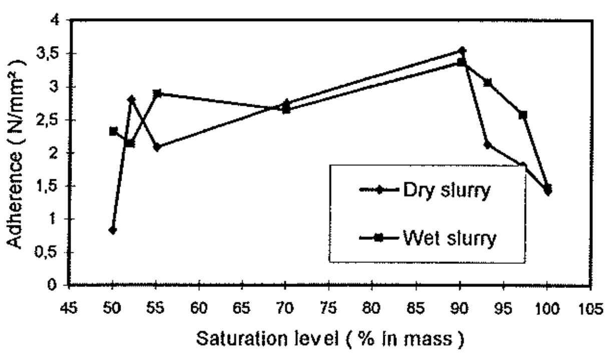


Fig. 9 – Adherence strength of PCC mortar on concrete with wet and dry slurries.

Optimal humidification of the substrate will be obtained by storage at 100%, which can be easily reached in the laboratory.

Human factors will also induce difference in the results, depending on the tools, the cleverly of the worker and the way he will follow to do the repairing work. Photo's 1 and 2 show microscopical views of interface between a concrete slab and a PCC mortar applied in the same environmental conditions and from the same bag; the first worker (A) choose the technic of pressure and smoothing while the second (B) only pressed the mortar without any post-manipulation.

The first view shows a lot of cracks parallel to the interface, at the interface or in the mortar, while the second is representative of a good continuity at the interface with a good spreading of air bubbles.

## 7. PARAMETERS AND PROPERTIES CLASSIFICATION

The discussion herebefore let us to point out some fundamental parameters able to describe the phenomenons happening at the interface. These paramaters can be defined from the properties of the materials as given in Table 4. These parameters are of course not independent from each other:

– stress release will depend on binder type and concentration, ...

– thermal dilatation coefficient or capillary absorption coefficient will be related to the physical properties of the support and the new layer;

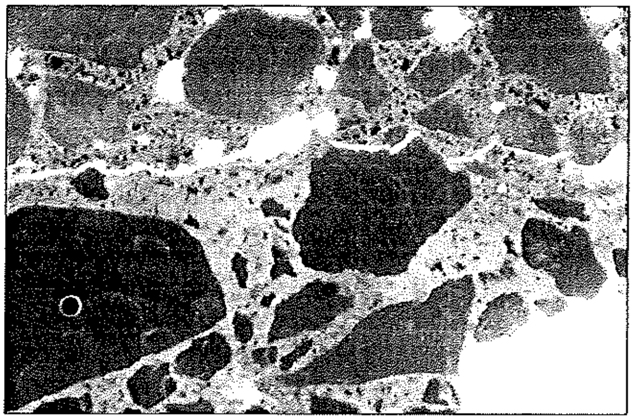

Photo 1

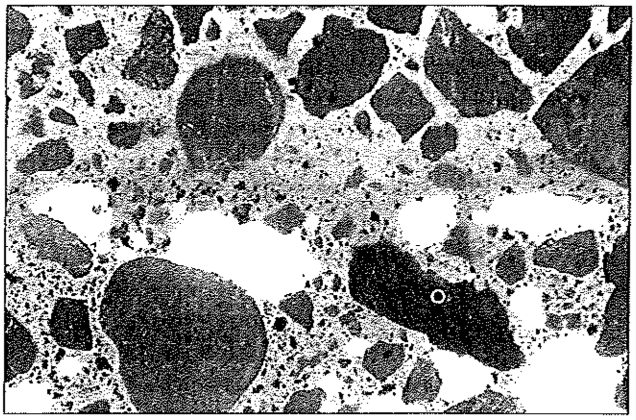

Photo 2

**Table 4 – Parameters and properties influencing the creation and the stability of the interface**

| | | |
|---|---|---|
| <u>Support</u> : | | |
| surface energy | superficial tension | $\gamma_S$ |
| roughness | effective surface waviness | $r_f$ |
| porosity | water absorption | A |
| capillarity | capillary absorption coefficient | $A_{CA}$ |
| saturation level | water content | [e] |
| mechanical characteristics | superficial cohesion, | $\sigma$, |
| | E modulus | $E_S$ |
| interstitial water | chemical analysis | I |
| <u>New layer</u> : | | |
| surface energy | superficial tension | $\gamma_L$ |
| | interfacial tension | $\gamma_{SL}$ |
| | contact angle | $\theta$ |
| | work of adhesion | $W_A$ |
| | effective binding factor | $\phi_0$ |
| binder hardening | hardening | $t_p$ |
| kinetics of contact | viscosity | $\eta$ |
| | binder content | E/C |
| | time | t |
| | temperature | T |
| thermal dilatations | thermal dilatation coefficient | $\alpha$ |
| shrinkage | water content | E/C |
| | moisture | T, R.H. |
| | geometrical characteristics | x |
| porosity, capillarity | water absorption | A |
| | capillary absorption coefficient | $A_{CA}$ |
| | water vapour diffusion coefficient | $\mu$ |
| mechanical characteristics | cohesion | $\sigma_A$ |
| | E modulus | $E_A$ |
| | stress release | $R_A$ |
| <u>Environnement</u> : | | |
| hygrothermal | temperature | T |
| conditions of support and air | relative moisture | R.H. |
| curing conditions | temperature, moisture, protection | M |
| application human factors | pressure | P |
| | - | $F_H$ |

– a lot of parameters are depending on time, temperature, relative humidity, …

A classification more according to the distinction between what happens at the moment of the contact – creation of the interface – and during the curing of the products – stability of the interface – needs to find an answer to the next three questions:

– what are the parameters conditioning the contact between the concrete support and the new layer?

– what are the parameters and phenomenons affecting the creation of the interface?

– what are the parameters and phenomenons affecting the stability and the durability of the interface?

## 8. CONCLUSIONS

Appetency may be defined as a function of:

– the thermodynamic properties of the liquid and the solid that will characterise the wettability of the support;

– the roughness of the surface, affecting the wettability of the support through the contact angle and the specific surface;

– the capillary absorption, that will depend on the concrete surface porosity but also on the thermodynamic properties and the viscosity of the new layer;

– the chemical composition, affecting the interaction between solid and liquid but also into the interstitial solutions of concrete and new layer.

Scientifically speaking, the bases of the theory of adhesion are the mechanical interlocking and the specific adhesion, explained in terms of chemical bonds, electro-chemical

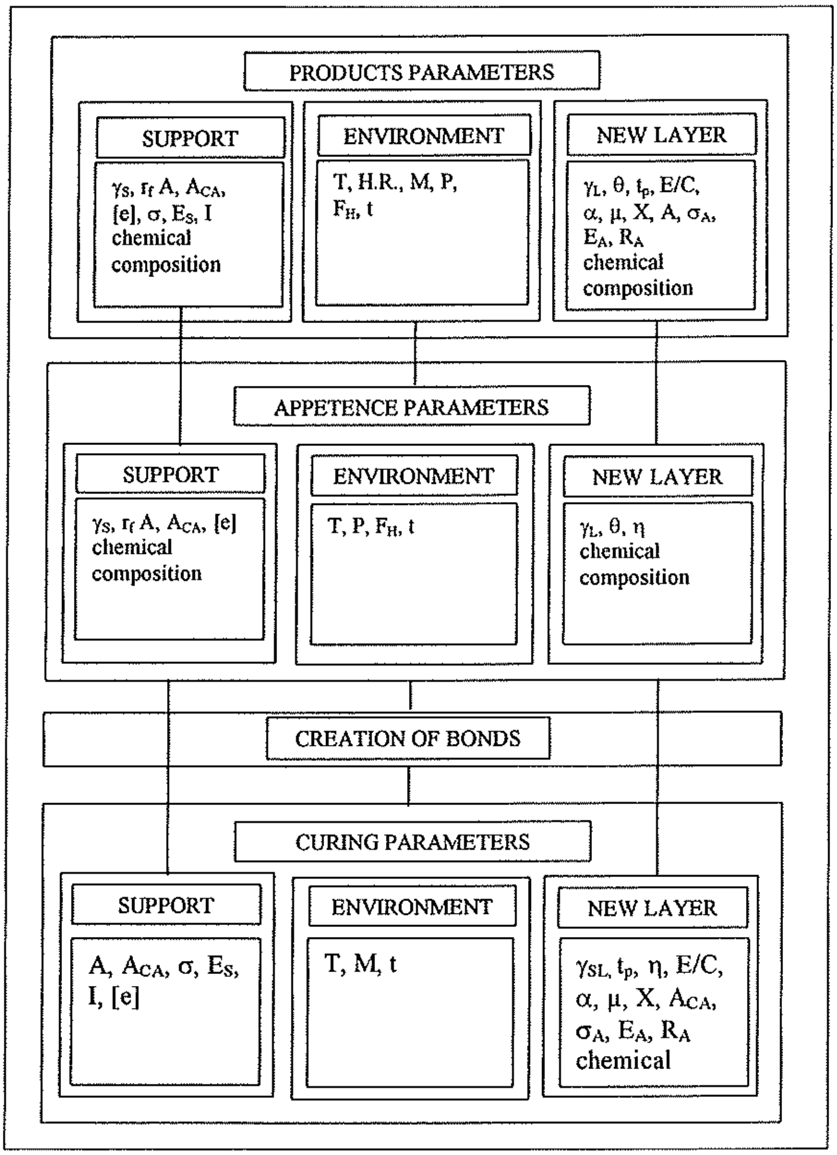


Fig. 10 – Flow sheet for the description of the interface formation.

interaction and thermodynamic properties. The transposition of these theories to the problems of repair technics and products is not as simple as it seems because many parameters will act between the cause and the effect. One condition for the success is a good knowledge of the appetency of the liquid phase of the repair product for the solid phase of the concrete support.

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