# CONTRIBUTION TO A RANKING PROCEDURE FOR POLYMERIC COATINGS AND HYDROPHOBIC AGENTS FOR CONCRETE

J. Aguiar[1], P. Moreira[1], P. Lukowski[2], L. Czarnecki[2], A. Camões[1] and D. Van Gemert[3]

*1: University of Minho, Department of Civil Engineering, Campus of Azurém, 4800-058 Guimarães, Portugal.*

2: Warsaw University of Technology, *Faculty of Civil Engineering,* Al. Armii Ludowej 16, 00-637 Warsaw, Poland

*3: K.U.Leuven, Department of Civil Engineering, Kasteelpark Arenberg 40, B-3001 Heverlee, Belgium.*

## ABSTRACT

One of the possible ways to protect the concrete is using coatings and hydrophobic agents that act as a barrier against the environment. When selecting the material for concrete protection, importance should be given to these properties of diffusion and permeability. The coatings and the hydrophobic agents must stop the penetration of water and delay the influence of aggressive agents, allowing the structure to breathe by a water vapour diffusion mechanism. An evaluation of the surface layer transport properties gives information on the durability of a particular concrete. In order to make the selection of coatings and hydrophobic agents for concrete protection, it is important to analyse the compound's technical and economical performances. A ranking procedure, developed by Czarnecki and Lukowski, is applied on a series of concrete protection products. The ranking procedure is applied to evaluate durability experiments, carried out on some commercially available silicone, acrylic and epoxy compounds for surface treatment of concrete. The ranking procedure transforms experimental data of properties into one numerical value, by which the products can be classified according to the way on which their properties present an optimised or even best buy combination. The paper shows the use of the ranking procedure methodology, and points at the importance of the choice of the criteria and of their relative weight factor in the evaluation. The method is a valuable tool for the ranking of similar materials, who's performance is based on the same or similar physical or chemical processes.

## INTRODUCTION

With a wide range of coatings and hydrophobic agents available in the market, it becomes extremely difficult to choose the right type of these products, since similar generic types are known to possess considerably different diffusion characteristics [1]. The performance of the available generic types under different service conditions needs to be studied. There is also a need to develop performance criteria for evaluation of concrete coatings and guidelines for the selection of appropriate products for various exposure conditions [2]. Selection of materials is an important part of the design in civil engineering. The selection needs to be made based on the knowledge of the materials' properties. The use of ranking procedures contributes to the selection of the best material available while it establishes an order between the different materials.

Concrete can be a highly durable construction material as long as care and quality control are enforced at all stages of the design, production and construction processes. However, experience has demonstrated that its potential long-term durability is not always achieved, leading to early failure of reinforced concrete structures [3]. It should be recognized that concrete is intrinsically a porous material, despite the improvements on its formulation and quality control to the best possible extent, it is not possible to prevent completely the ingress of potentially harmful agents. Micro-cracks and macro-pores will always exist on the concrete surface, providing a path for the transportation of aggressive ions into the interior of the concrete [4].

It is now accepted that the durability of reinforced concrete depends mainly on the composition and properties of the concrete surface layer [5]. This layer, sometimes with a thickness close to the cover of the reinforcement, is most of the times the only responsible for the corrosion protection of the reinforcement. Surface treatments act as a barrier between the environment and the concrete. They prevent or retard the entry of harmful substances such as water, chlorides, etc. [6]. A lot of research is made on water repellent treatment of building materials, as well as on the effect of these agents on barrier properties. Four international conferences were dedicated to the subject, of which the first took place in Delft in 1995 [7], followed by Zürich (1998), Hannover (2001), Stockholm (2005) and Brussels (2008). Selected papers from the congress in Stockholm are published in [8]. Barrier properties are discussed in [9-11]. Surface coatings with appropriate "barrier" characteristics can cut off the transportation path into concrete. The standard EN 1504-2 [12], establishes as a minimum requirement for the coated concrete ingress that the the capillary absorption and the water permeability coefficient should not exceed 0.1 $kgm^{-2}h^{-0.5}$ and the $CO_2$ permeability should at least correspond to a $s_D$ value of 50 m.

Swamy and Tanikawa [13] evaluated the effect of concrete coatings to preserve concrete durability and concluded that the application of an impervious surface coating to concrete is a very attractive solution to protect new and existing concrete structures. Water is the most critical agent because it lies on the root of many important degradation processes: it is related to freeze-thaw durability; it provides the transport path for chloride ions and establishes electrolytic continuity inside concrete. Besides, in order that the carbonation reaction can take place, the presence of a certain amount of water is required [14]. The effect of organic coatings on water and chloride transport in reinforced concrete was studied by Fluckiger *et al* [15]. They concluded that the concrete coatings strongly reduced the water and chloride uptake in concrete. Concrete coatings can be applied to protect either the existing or the new structures. Czarnecki and Clifton [16] have proposed a way of evaluating the usability of polymer composites for a given application. The method uses a ranking procedure based on the performance function.

the concrete hardened mass. One of the possible ways to protect the concrete is using coatings and hydrophobic agents that act as a barrier against the environment. When selecting the material for concrete protection, importance should be given to these properties of diffusion and permeability. The coatings and the hydrophobic agents must stop the penetration of water and delay the influence of aggressive agents, allowing the structure to breathe by a water vapour diffusion mechanism. An evaluation of the surface layer transport properties gives information on the durability of a particular concrete. Three different materials were tested: silicone, acrylic and epoxy. The results showed that, in general, all coatings contribute to the increasing of the durability of the concrete, in particular the epoxy resins which showed the best performance.

## RANKING PROCEDURE

Czarnecki and Lukowski [17] proposed the following ranking procedure. For each performance property $y$, two values must be selected, $y_{better}$ and $y_{worse}$, in such a way that the properties of the material should be considered good or satisfactory between these two values. The function $d(y)$ converts the values of $y$ into a performance scale [17]:

In order to make the selection of coatings and hydrophobic agents for concrete protection, it is important to analyse the compound's technical and economical performances. In the ranking procedure used, all the properties will be taken into account at the same time. The performance of a compound was evaluated by one function of general performance and was compared with the cost of the material, in order to obtain a cost/benefit ratio. A low porosity, permeability and concrete penetration to moisture and gases are the first lines of defence against several deterioration mechanisms. The durability of concrete depends largely on how hard or easy fluids (water, carbon dioxide, oxygen) in liquid or gas form can migrate through

$$d(y) = \exp\left[-\exp\left(-\frac{y - y_{worse}}{y_{better} - y_{worse}}\right)\right] \qquad (1)$$

where:

$d(y)$: function of individual performance;

$y$: performance property;

$y_{worse}, y_{better}$: worse and better values of performance properties.

The functions of individual performance for each property are combined to a complex criterion by one function of general performance:

$$D = \sum_{i=1}^{n} w_i d_i \qquad (2)$$

where:

$D$: function of general performance;

$w_i$: weight given to the performance property $y_i$;

$d_i$: function of individual performance.

Czarnecki et al [17] state that the good values of the individual performance $d_i$ are between [0.37, 0.69]. The performance values near 1 are related with a high performance of the material and the performance values near 0 are related with low performance (Figure 1).

In figure 1 the following symbols are used:

$d_i$ : performance of the property (1 = maximum value in exponential scale);

$y$ : value of the property.

In our study, four performance properties are considered: water absorption by immersion and by capillarity, oxygen and water permeability. In order to use the general function of performance in paintings, each property must be formulated quantitatively, establishing the values of $y_{better}$, $y_{worse}$ and of the weight $w$. This was made taking into account the experimental results and the performance function proposed in [17].

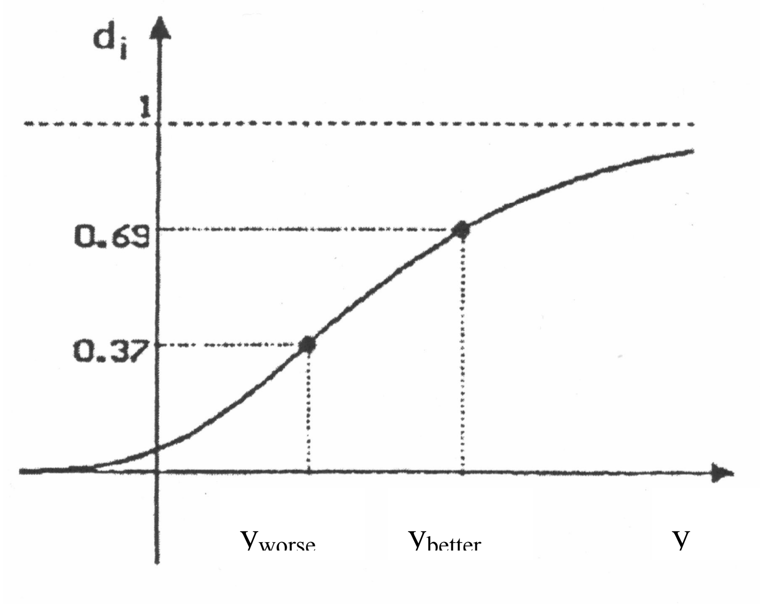


*Figure 1: Function of performance.*

## EXPERIMENTAL PROGRAM

To evaluate the influence of cement, two types of cement were used: CEM I 42.5R (CONV) and CEM IV/A 32.5R (IV) according to EN 197-1 [18]. Crushed granite with a density of 2566 kg/m$^3$, water absorption of 2.1%, fineness modulus of 5.89 and a maximum size of 9.53 mm was used as coarse aggregate, while crushed sand with a density of 2477 kg/m$^3$, water absorption of 1.36 %, fineness modulus of 3.16 and a maximum size of 4.76 mm was used as fine aggregate in the preparation of concrete specimens.

Concrete coatings and hydrophobic agents were selected to represent the following three generic types:

i. Silicone agents (S);

ii. Acrylic coatings (A);

iii. Epoxy resin coatings (E).

Each generic type was represented by two materials from different producers and commercially available in Portugal. The three types were selected between the more used concrete coatings and hydrophobic agents. Table 1 shows the application properties of the selected concrete coatings and hydrophobic agents. All materials were applied on the substrate by brush following the recommendations of the manufacturers and after drying of the specimens under laboratory conditions for at least 7 days.Concrete mixes were proportioned according to Faury method for an effective water-cement ratio of 0.60 and cement content of 320 kg/m$^3$. The composition of the concretes is presented in Table 2. The slump test results achieved a value of about 60 mm and the average compressive strength of the control concrete mix (CONV) attained 27.5 MPa at 28 days of age and the concrete mix named IV achieved 20.8 MPa. The experimental campaign was designed in order to test concrete specimens without any type of coating or hydrophobic agent (concrete CONV and IV) and treated concrete specimens (concrete CONV with the referred products).

Cylindrical concrete specimens of 110 mm in diameter and 230 mm in height (ø110 x 230) were cast to evaluate the absorption of water by capillarity of the selected concrete coatings and hydrophobic agents. Cubic concrete specimens 100x100x100 mm$^3$ were cast to evaluate the water absorption by immersion of the selected concrete coatings and hydrophobic agents. Cylindrical concrete specimens with 50 mm in diameter and 40 mm height were cast to evaluate the permeability to oxygen and the permeability to water of the selected concrete coatings and hydrophobic agents.

| | Silicone, SA | Silicone, SB | Acrylic, AA | Acrylic, AB | Epoxy, EA | Epoxy, EB |
|---|---|---|---|---|---|---|
| Generic type | siloxane resin in solvent base | siloxane resin in solvent base | acrylic resin aqueous based | acrylic resin aqueous based | two component epoxy resin | two component epoxy resin |
| Consistency | liquid | liquid | dense liquid | dense liquid | dense liquid | dense liquid |
| Coverage rate (m$^2$/dm$^3$) | 4.0 | 2.8 | 5.0 | 3.5 | 2.2 | 4.0 |
| Density at 20 ºC (kg/dm$^3$) | 0.80 | 0.83 | 1.30 | 1.40 | 1.60 | 1.30 |
| Brookfield viscosity at 20 ºC (mPa.s) | 2 | 11 | 9000 | 6000 | 1000 | 1500 |
| Surface drying time (min) | 300 | 60 | 30 | 40 | 360 | 300 |
| Interval between coats (h) | wet on wet | 2 | 6 | 24 | 24 | 24 |

*Table 1: Description of the selected coatings and hydrophobic agents.*

| Materials | Quantities (kg/m$^3$) | |
|---|---|---|
| | CONV | IV |
| Cement | 320 | 320 |
| Gravel 5 - 10 | 796 | 814 |
| Sand 0 - 5 | 940 | 898 |
| Water | 181 | 180 |

*Table 2: Composition of the concretes.*

The selected concrete coatings and hydrophobic agents were applied to the concrete. The coverage rate is shown in Table 1. The purpose of the tests performed in laboratory was the evaluation of the "barrier" properties of the coatings against water and gases, by determining their absorption by capillarity and immersion, permeability to water and to oxygen. The detail of the test procedures and the obtained results was published previously [19]. In this limited test program, only some representative properties were tested. In a more elaborate study also the permeability to water damp, to $CO_2$ and others should be incorporated, as well as the effects of relative air humidity and of water in the pore system.

*RANKING OF CONCRETE COATINGS AND HYDROPHOBIC AGENTS*

The rankings of the tested concrete coatings and hydrophobic agents were established using the procedure previously presented. The three products are different. Acrylic and epoxy compounds are film forming polymer coatings. Silicon is a water repellent agent, which does not close surface near pores. In order to take into account the differences between the products, two evaluations will be made. The first one will consider water permeability as the most important property (Tables 3 to 5). The second one, will consider that water is the main responsible for the principal mechanisms of concrete degradation and it is the way how aggressive agents could penetrate, high weights were given to the performance properties directly connected with water penetrability, except water permeability (Tables 6 to 8). For some applications the water permeability under high pressures is not relevant. The performance of each compound was evaluated by one function of general performance and compared with the cost of the material, in order to obtain a cost/benefit ratio. Tables 3 and 6 present the criteria used for evaluating the materials.

| Performance properties | $y_{worse}$ | $y_{better}$ | $w$ |
|---|---|---|---|
| Water absorption by immersion, % | 15.0 | 5.0 | 0.2 |
| Water absorption by capillarity, kg/(m$^2$.min$^{0.5}$) | 0.5 | 0.4 | 0.2 |
| Oxygen permeability, 1E-16 m$^2$ | 0.2 | 0.05 | 0.2 |
| Water permeability, 1E-16 m/s | 0.1 | 0.001 | 0.4 |

*Table 3: Criteria for evaluation of products (Set 1).*

Tables 4 and 7 present the functions of general performance of the products. Taking into account the weights considered for the first evaluation the following ranking was found (Table 4):

EB → EA → AB → AA →SA, SB → CONV, IV

The cost of the material needs to be taken into account in any way in addition to the technical performance. For that a relation performance to cost had been established, using the cost of 1 m$^2$ of painting, based on information given by the furnishers of the materials. The calculations only include the cost of the used materials; the costs for substrate preparation, homogenisation and application, were not included (Table 5).

Considering this analysis another ranking was found (Table 5):

AB → EB → SA, SB → EA → AA

| $d_i$ | Immersion | Capillarity | Oxygen Permeability | Water Permeability | **D** |
|---|---|---|---|---|---|
| IV | 0.307 | 0.690 | 0.000 | 0.000 | 0.20 |
| CONV | 0.301 | 0.718 | 0.000 | 0.000 | 0.20 |
| SA | 0.331 | 0.750 | 0.000 | 0.000 | 0.22 |
| SB | 0.342 | 0.750 | 0.000 | 0.000 | 0.22 |
| AA | 0.475 | 0.747 | 0.567 | 0.207 | 0.44 |
| AB | 0.482 | 0.746 | 0.619 | 0.492 | 0.57 |
| EA | 0.668 | 0.748 | 0.600 | 0.635 | 0.66 |
| EB | 0.733 | 0.750 | 0.764 | 0.695 | 0.73 |

*Table 4: Function of general performance of products (Set 1).*

| Reference | D | Cost (€/m$^2$) | D/cost |
|---|---|---|---|
| SA | 0.22 | 1.68 | 0.13 |
| SB | 0.22 | 1.75 | 0.13 |
| AA | 0.44 | 4.27 | 0.10 |
| AB | 0.57 | 1.13 | 0.50 |
| EA | 0.66 | 5.86 | 0.11 |
| EB | 0.73 | 2.27 | 0.32 |

*Table 5: General performance and cost of products (Set 1).*

| Performance properties | $y_{worse}$ | $y_{better}$ | $w$ |
|---|---|---|---|
| Water absorption by immersion, % | 15.0 | 5.0 | 0.4 |
| Water absorption by capillarity, kg/(m$^2$.min$^{0.5}$) | 0.5 | 0.4 | 0.4 |
| Oxygen permeability, 1E-16 m$^2$ | 0.2 | 0.05 | 0.2 |
| Water permeability, 1E-16 m/s | 0.1 | 0.001 | 0.0 |

*Table 6: Criteria for evaluation of products (Set 2).*

Taking into account the weights considered for the second evaluation the following ranking was found (Table 7):

EB → EA → AB → AA →SA, SB → CONV → IV

Considering the cost of the materials another ranking was found (Table 8):

AB → EB → SA → SB → AA → EA

After the establishment of the rankings, one can conclude that the furnisher B has the best performance/cost materials except for the silicone agents. Taking into account the performance/cost ratio, the first two classified are from furnisher B. With only a technical analysis, epoxy resins are on the first places, followed by acrylics and by silicones.

| $d_i$ | Immersion | Capillarity | Oxygen Permeability | Water Permeability | **D** |
|---|---|---|---|---|---|
| IV | 0.307 | 0.690 | 0.000 | 0.000 | 0.40 |
| CONV | 0.301 | 0.718 | 0.000 | 0.000 | 0.41 |
| SA | 0.331 | 0.750 | 0.000 | 0.000 | 0.43 |
| SB | 0.342 | 0.750 | 0.000 | 0.000 | 0.43 |
| AA | 0.475 | 0.747 | 0.567 | 0.207 | 0.60 |
| AB | 0.482 | 0.746 | 0.619 | 0.492 | 0.62 |
| EA | 0.668 | 0.748 | 0.600 | 0.635 | 0.69 |
| EB | 0.733 | 0.750 | 0.764 | 0.695 | 0.75 |

*Table 7: Function of general performance of products (Set 2).*

| Reference | D | Cost (€/m$^2$) | D/cost |
|---|---|---|---|
| SA | 0.43 | 1.68 | 0.26 |
| SB | 0.43 | 1.75 | 0.25 |
| AA | 0.60 | 4.27 | 0.14 |
| AB | 0.62 | 1.13 | 0.55 |
| EA | 0.69 | 5.86 | 0.12 |
| EB | 0.75 | 2.27 | 0.33 |

*Table 8: General performance and cost of products (Set 2).*

The concrete with cement IV shows lower performance than concrete with cement I. Taking into account the cost of the materials, the silicone of furnisher A achieved better classification than acrylic and epoxy. In the same way the acrylic of the furnisher B achieved better classification than epoxy.

## CONCLUSIONS

The use of a ranking procedure enables the selection of the best material between coatings or hydrophobic agents for concrete protection, based on a quantified ranking value. For the set of criteria used in this analysis, which is of course not universally applicable and should be adapted for each exposure case, and from the technical evaluation the best material was epoxy from the furnisher B. Taking into account at the same time the cost and the technical evaluation the best material changed to acrylic, also from the furnisher B. The used procedure showed that furnisher B had the best epoxy and acrylic. The furnisher A had the best silicone.

The selected coatings proved to be effective for protecting the concrete against the action of water and gas (oxygen). As all the materials show different effectiveness in each performance test, the proposed ranking enables to make a choice, based on technical performances, or based on technical performance-cost ratio. The quantification of the material selection criterion makes the choice more objective and independent on subjective feelings or sensations. The set of criteria can be extended, to take into account other aspects, such as durability, continuity of a film or penetration depth of a hydrophobic agent. The insertion of such criteria could drastically change the ranking of products. The method certainly presents a valuable tool for the ranking of similar materials, who's performance is based on the same physical or chemical processes.

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