## Characterization of the Influence of Fly Ash on the Durability of Cementitious Matrix Materials

Serigne DIOP<sup>1</sup>, Oustasse Abdoulaye SALL<sup>1</sup>, Diogoye DIOUF<sup>1</sup>, Makhaly BA<sup>2</sup>

<sup>1</sup>Department of Civil Engineering, UFR SI-University of Thiès, Thiès, Senegal <sup>2</sup>Department of Geotechnics, UFR SI-University of Thiès, Thiès, Senegal

Corresponding Author: Serigne DIOP

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### ABSTRACT

The aim of this work is, on the one hand, to study the influence of fly ash on the durability of cementitious matrices through measurements of the coefficient of water absorption by capillarity and the porosity accessible to water on standardized mortar specimens in which Lafarge CEM II/32.5R cement has been substituted by fly ash (0%), 5%, 10% and 20%). And secondly, to characterize the influence of certain concrete parameters such as true cement class, E/C ratio, average compressive strength, relative humidity, granular coefficient and exposure coefficient on the kinetics of carbonation depth using the Oxand model, which is essentially based on Fick's law in porous media. The results obtained showed, on the one hand, a decrease in the water absorption coefficient and in the porosity accessible to water when the ash content increases and, on the other hand, a decrease in the carbonation depth when the cement's true class, average strength and granular coefficient increase. And a decrease in carbonation depth with decreasing W/C ratio and exposure coefficient. The results also show that carbonation depth is greatest when the relative humidity of the surrounding environment is between 40% and 60%.

*Keywords:* Durability, cementitious matrix, absorption, porosity, carbonation, fly ash

### **I. INTRODUCTION**

Studying the durability of hydraulic binderbased structures is an important step in any construction project. Indeed, if this stage is neglected, the structure will remain vulnerable to external agents and in the long term will see its performance weaken. To this end, we first studied the water behavior of hardened mortar specimens [1] in which LafargeHolcim's CEM II/B-LL 32.5 cement was substituted by fly ash at different rates (0%, 5%, 10% and 20%), by measuring the water absorption coefficient by capillarity and the water-accessible porosity of these different types of formulated mortar. Subsequently, the Oxand model, based essentially on Fick's law in porous media [2], was used in the study of carbonation to characterize the influence of certain concrete parameters such as true cement class, E/C ratio, average strength, relative humidity, granular coefficient and gamma exposure coefficient on the kinetics of the carbonation depth of cementitious matrix materials such as hydraulic concrete.

### **II. MATERIALS AND METHODS**

### II.1 DURABILITY OF CEMENTITIOUS MATRICES

### **II.1.1 MORTAR FORMULATION**

Table 1 shows the mortar formulations in which Lafarge's CEM II 32.5 cement has been substituted by fly ash at different contents (0%, 5%, 10% and 20%). The mortars are made from CEM II 32.5 cement,

standardized sand and fly ash from the bargny-senegal coal-fired power plant, the characteristics of which are given in [3]. The

mixing water used meets the requirements of standard [1].

 Table 1 : Formulation of mortars in which cement has been substituted by fly ash at different contents (0%, 5%, 10% and 20%)

Materials	Substitution rate (%)					
	MCEMIICV0	MCEMIICV5	MCEMIICV10	MCEMIICV20		
Cement (g)	900	855	810	720		
Sand (g)	2700	2700	2700	2700		
Water (g)	450	450	450	450		
Ash (g)	0	45	90	180		

### II.1.2 WATER ABSORPTION BY CAPILLARY ACTION

The measurement of water absorption by capillarity is a technique that consists in measuring the mass of water absorbed by a test specimen through a test surface in contact with the fluid. According to [4], the test consists first of all in preparing test bodies, which are 4x4x16 cm<sup>3</sup> molds made of standardized mortar with CEM I cement. which has been substituted by fly ash at different contents (0%, 5%, 10% and 20%). The specimens thus prepared are well sealed (except for the part in contact with water) and then immersed in a container to a maximum height of three (03) mm using wedges (Figure 1). In addition, the container is fitted with a lid to prevent water evaporation, and to allow the upper surface of the test tube to breathe. At each expiry date, the test tubes are removed from the container, wiped clean with a damp sponge, weighed and returned to the container. For each of the time periods (0.25, 0.5, 1, 2, 4, 8 and 24 hours), the capillary absorption coefficient (in  $kg/m^2$ ) is given by equation 1 below:

$$C_a = \frac{Mx - Mo}{A}$$
(1)

With:

 $M_x$  is the mass of the test piece at a given time (kg);

 $M_o$  is the initial mass of the specimen (kg);

A is the cross-sectional area of the specimen  $(m^2)$ .



Figure 1: Device for measuring the capillary absorption coefficient of mortar specimens

# II.1.3 POROSITY ACCESSIBLE TO WATER

Measuring the water-accessible open porosity of hardened mortar test bodies, after storage, conditioning and vacuum setting as shown in Fig. 2, involves determining following quantities by weighing in accordance with [5]:

- Apparent mass in water after immersion (hydrostatic weighing) of a mortar test body previously impregnated with water under vacuum (another liquid may be used for measurement, provided its viscosity is comparable),
- Mass in air of the same soaked test body;
- Dry mass after drying at (105±5)°C and successive weighing until a constant mass is obtained (masses do not differ by more than 0.05% between two successive weighings carried out 24 h apart).

Open porosity and bulk density are calculated from equations 2 and 3 below.

$$\varepsilon = \frac{M_{air} - M_{sec}}{M_{air} - M_{eau}} \times 100$$
 (2)

$$\rho_d = \frac{M_{sec}}{M_{air} - M_{eau}} \rho_{eau} \tag{3}$$
With:

 $\rho_d$ : Apparent density in kg/m<sup>3</sup>;

 $\rho_{water}$ : Density of water in kg/m<sup>3</sup>, used for hydrostatic weighing;

 $\varepsilon$  Water-accessible porosity or pore volume in %;

 $M_{air}$  Mass obtained by weighing the same soaked test body in open air;

 $M_{eau}$  Mass obtained by hydrostatic weighing of the test body after saturation in water;

 $M_{sec}$  Mass obtained by weighing the test pieces after drying.



Figure 2: Empty device for measuring the wateraccessible porosity of mortar specimens

### **II.2 CARBONATION MODELS**

Concrete is generally in contact with the surrounding air. When it comes into contact with atmospheric carbon dioxide, it is subjected to the action of this gas. Carbon dioxide, whose concentration in air is around 0.03 to 0.05%, dissolves easily in water to form a low-concentration solution of carbonic acid ( $H_2CO_3$ ). The carbonate ions of this acid react with the majority of cement

hydrates, resulting in the formation of a solid phase composed of calcium carbonate or calcite (CaCO3). All these chemical reactions are known as carbonation [6]. They only occur if carbon dioxide balanced by an aqueous phase enters the pores of the concrete. When the carbonates come into contact with the steel, the carbonation process eliminates the steel's alkalinity reserve. As the pH of the cement matrix decreases. the reinforcement becomes depassivated, and the corrosion process begins. This is due to the fact that the quantity of calcite formed is greater than that of the reacting hydrates in the cement matrix (mainly portlandite) [6]. The presence of carbonation leads to clogging of the cement matrix. The depth to which carbonation occurs in concrete is influenced by its microscopic composition. As a result, the ability of CO<sub>2</sub> to penetrate concrete is influenced by its formulation parameters, as the properties of the cement matrix are closely linked to the type of cement used. In the literature, models for characterizing carbonation are essentially based on Fick's law in porous media.

### **II.2.1 OXAND MODEL**

The model used is that of the Oxand company, which considers that the penetration of atmospheric carbon dioxide and its reaction with the hydrates in the paste divide the concrete into two zones (a non-carbonated zone and a carbonated zone). The depth of the carbonated zone,  $X_c$  (m), evolves as a function of time t (year) and exposure coefficient $\gamma$  according to equation 4 and Table 2.

$$X_{C} = \gamma. f(HR) . k . \sqrt{t}$$
(4)

Parameter	Definition	Determination of parameter	Interest of the parameter
k	Concrete transport coefficient (m $/\sqrt{an}$ )	$\begin{array}{llllllllllllllllllllllllllllllllllll$	Concrete class and cement type taken into account. Interesting because $f_{cm,28}$ is always a known known

Table 2: Oxand model input parameters

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f(HR)	Factor expressing relative humidity assumed to be in equilibrium with the concrete, over the depth of carbonation	Calculated on the basis of literature data literature (equation 6[7]	Taking into account outdoor conditions (relative humidity)
γ	Exposure coefficient (Table 3)	Value obtained by inverse analysis of in-situ data, for example such as carbonation depth measurements using spraying of phenolphthalein	Taking into account external conditions (CO2 content, relative humidity)

In this Oxand model, the concrete transport coefficient k is calculated using equation 5 below:

$$k = \sqrt{365} \cdot \left(\frac{1}{2, 1 \cdot \sqrt{f_{cm.28}}} - 0, 06\right)$$
 (5)  
With

With

 $f_{cm.28}$  Average compressive strength of concrete at 28 days given by the following relationship according to Bolomey:

$$f_{cm,28} = \frac{\sigma'_{28}}{1,15}$$
(6)  
$$\sigma'_{28} = G' \cdot \sigma'_c \left(\frac{E}{c} - 0.5\right)$$
(7)

 $\sigma'_{28}$  Characteristic strength of target concrete at 28 days (in MPa)

*G'*: Granular coefficient, a function of the quality and maximum size of the aggregates.  $\sigma'_c$  The true class of cement

$$\frac{E}{C} = \frac{Dosage \ en \ ciment}{Dosage \ en \ eau}$$
(8)

The influence of relative humidity H.R. is expressed and given by equation 9:

f (H.R.)= -3.5833 HR<sup>2</sup> + 3.4833 HR + 0.2(9)

Table 3: Some values for the exposure coefficient $\gamma$						
Type of work	Exposure coefficient					
Structures subject to CO <sub>2</sub> concentrations	1.5					
Structures particularly exposed to rain	0.9					

1.2

When carbon dioxide content is high, its diffusion is accelerated. This results in an increase in the exposure coefficient  $\gamma$ . As a guide, Table 4 gives the ranges of variation in CO<sub>2</sub> concentration for some characteristic locations.

Sheltered structures

Table 4:	Typical	$CO_2$	levels	in	selected

Locations	CO <sub>2</sub> content (cm <sup>3</sup> /m <sup>3</sup> )
Schools	between 500 and 1,700
Housing	between 250 and 6,000
Offices	between 450 and 1,200
Swimming pools	between 300 and 1,100
Parking lots	between 400 and 1,200
Metro	between 300 and 500
Outdoor ambient air	between 300 and 400

### II.2.2 CHARACTERIZATION OF PARAMETERS INFLUENCING CARBONATION

Parameters influencing the carbonation depth of cementitious matrices were modeled, including: true cement class, water-to-cement ratio (W/C), average compressive

strength (fcm,28), relative humidity (RH), granular coefficient (G') and gamma exposure coefficient ( $\gamma$ ). Using the Oxand model and taking into account Bolemey's relationship (equation 5.7), which highlights the dependence of the compressive strength of the target concrete at 28 days on the true class of cement  $(\sigma'_{c})$ ), the E/C ratio and the granular coefficient(G'), we were able to study the influence of concrete formulation parameters. According to this model, the depth of carbonation is closely linked to the concrete's transport coefficient (k) (equation 4) and the latter is inversely proportional to the average compressive strength fcm,28 (equation 5) and therefore to the cement's true class  $\sigma'_{c}$ . Consequently, equation 4 leads to the following relationship 10, which allows us to predict the influence of certain parameters (Figure 6).

$$X_{C} = \gamma. f(HR). \sqrt{365} \cdot \left(\frac{1}{1.96\sqrt{G'.\sigma_{C}'(\frac{E}{C}-0.5)}} - 0.06\right) \cdot \sqrt{t}$$
(10)

The influence of  $f_{cm,28}$  was studied using the Oxand model, which translates the inverse dependence of carbonation depth on the average compressive strength of concrete at 28 days into equation 11 (Figure 7).

$$X_{C} = \gamma. f(HR). \sqrt{365} \cdot \left(\frac{1}{2.1\sqrt{f_{cm,28}}} - 0,06\right) \cdot \sqrt{t}$$
(11)

Replacing equation 4 of Oxand's model with equation 9 yields equation 12, which

expresses the dependence of carbonation depth on relative humidity, allowing for external conditions. Figure 8 shows the influence of relative humidity on the kinetics of carbonation depth.

$$X_{\rm C} = \gamma. (-3,5833.\,{\rm HR}^2 + 3,4833.\,{\rm HR} + 0,2).\,{\rm k}.\,\sqrt{{\rm t}}$$
(12)

#### **III. RESULTS AND DISCUSSION**

Table 5 and Figure 3 show the capillary water absorption coefficients of mortar specimens with ash substituted for cement at various levels (0%, 5%, 10% and 20%) after 28 days curing and as a function of time.

Table 5: Capillary absorption coefficient values as a function of time for mortars in kg/m<sup>2</sup>

Mortars	1/4h	1/2h	1h	2h	4h	19h	24h
MCV0	2,87	4,03	5,89	8,56	11,98	19,20	20,67
MCV5	2,80	3,98	5,81	8,35	11,83	20,03	21,66
MCV10	2,05	2,50	3,66	5,49	8,04	16,97	18,20
MCV20	2,29	2,83	3,96	5,81	8,70	16,38	17,29

Analysis of Figure 3 initially shows an increasing trend in the absorption coefficient of all mortars over a 24-hour period. On the other hand, the coefficient virtually decreases with increasing ash content. Subsequently, at 5% ash, a slight decrease in the coefficient is observed compared with the control mortar (0% ash), and the coefficient remains higher towards the end of the 24h.

However, this decrease in the absorption coefficient at higher ash contents could be explained by the fact that the use of ash results in fewer connected pores in the

material, accessible to water. The results for porosity open to water are given in Table 5 and Figure 4 below.



Figure 3: Evolution over time of the capillary absorption coefficient with the rate of substitution of cement by fly ash

Test tubes mortar	M <sub>water</sub> (kg)	M <sub>air</sub> (kg)	M <sub>dry</sub> (kg)	ρ <sub>d</sub> (kg/m <sup>3</sup> )	ρ <sub>water</sub> (kg/m <sup>3</sup> )	(%)
MCV0	0,164	0,291	0.265	2088	998.6	20
MCV5	0,166	0,297	0,272	2080	998.6	19
MCV10	0,160	0,284	0,260	2094	998.6	19
MCV20	0,139	0,279	0,254	1865	998.6	18

Table 6: Water open porosity values for mortar-based proofing bodies



Figure 4: Evolution of water-accessible porosity with the rate of cement substitution by fly ash

Analysis of Table 5 and Figure 4 shows that the substitution of CEM II 32.5 R cement by fly ash results in a reduction in the porosity accessible to water, and this reduction is more marked when the ash content remains high, up to 20%. In fact, this is perfectly in line with the evolution of the capillary absorption coefficient, since low material porosity can lead to a drop in the absorption coefficient. Together, these pores form the capillary network, which is highly connected in the early stages of concrete formation [2]. Over time, this network becomes less and less connected as the volume of hydrates formed increases. Capillary porosity, characterized by its volume and connectivity, plays a crucial role in concrete strength. Results relating to the characterization of the influence of certain parameters such as E/C,  $f_{cm,28}$ , HR, G',  $\gamma$  are given in the following Figures 5 to 10.



Figure 5: Influence of true cement class on carbonation depth kinetics



Figure 6: Influence of W/C ratio on carbonation depth kinetics



Figure 7: Influence of average 28-day strength on carbonation depth kinetics



Figure 8: Influence of relative humidity (RH) on carbonation depth kinetics



Figure 9: Influence of granular coefficient on carbonation depth kinetics



Figure 10: Influence of gamma exposure  $coefficient(\gamma)$  on carbonation depth kinetics

Analysis of Figure 5 shows that the depth of carbonation decreases as the cement's true class increases. This shows that the higher the cement's strength, the better the material's resistance to carbonation. Therefore, true cement class has a positive influence on carbonation. This could also be explained by the fact that, the more a concrete or mortar is made with high-performance cement, the greater its compactness and the smaller the volume of pores accessible to external agents such as CO<sub>2</sub>. Cement dosage is also a factor influencing concrete carbonation. Indeed, an increase in cement dosage reduces the porosity of the material and, consequently, the diffusion of  $CO_2$  is slowed down [7] and [8]. Furthermore, according to the work of [9], the rate of carbonation varies inversely with cement dosage, between 300 and 420  $kg/m^3$ . If cement dosage is reduced below 300 kg/m<sup>3</sup>, carbonation rate increases more rapidly. Higher cement dosages tend to slow down the rate of carbon dioxide penetration, provided sufficient curing is carried out [10]. Analysis of figure 6 shows a very significant carbonation depth decrease in with increasing E/C ratio. In fact, according to the work of [11], any increase in this ratio leads to a drop in concrete strength, and therefore a higher carbonation depth. However, a higher E/C ratio results in an excess of water in relation to the cement, i.e. there will be more evaporable water in the mix, resulting in a porous concrete that favors  $CO_2$ penetration and, in turn, accelerates the rate of carbonation. Furthermore, work by [12] and [13] shows that concrete permeability depends on the structure of its capillary network. To reduce the permeability of concrete, it is therefore advisable to reduce the value of the W/C ratio (water to cement) and to take care with the curing process. On the other hand, studies by [14] on the influence of W/C ratio and cement content have led to the conclusion that the most important parameter is the W/C ratio, and that the effect of cement content is comparatively insignificant. [15] have also shown the influence of alkali content on the increase in W/C ratio and therefore on carbonation.

Analysis of figure 7 shows that the depth of carbonation decreases as the average 28-day compressive strength increases. This could be explained by the simple fact that, according to the Bolomey formula [11] for the formulation of ordinary concrete, this average compressive strength is a function of the granular coefficient, the true class of the cement and possibly the E/C ratio, and according to the results derived from the analysis of figures 5 and 6, this granular coefficient and true class of cement all have beneficial effect on resistance a to carbonation. These results are also in line with the work of [16]. Numerous studies indicate that the depth of carbonation is less in high-strength concretes, as in [17]. And [18] shows that the compressive and flexural

strengths of CEM I-based carbonated concretes can increase by up to 30%. Indeed, it is often mentioned in the scientific literature that mechanical strength and modulus of elasticity increase after carbonation in the case of common formulations [19] and [20]. Unlike materials based on CEM I or even CEM II, [6] notes that concretes containing blast furnace slag cements see their mechanical properties deteriorate after carbonation.

Figure 8 shows that carbonation depth is at its maximum when relative humidity is between 40% and 60%. However, this carbonation depth takes smaller values when humidity is lower than 40% or higher than 60%, and is more noticeable when humidity reaches 100%. This confirms the findings of [21] that "carbonation does not occur in totally or totally water-saturated dry concrete. It is greatest in traditional concrete when relative humidity is between 40% and 60%". [22], based on measurements by, maintains that the highest carbonation rate at 20°C is obtained at a relative humidity of between 50 and 70%. These relative humidity limits are in perfect agreement with the work of [7].

An analysis of Figure 9 shows that an increase in the granular coefficient is a factor that adversely affects carbonation, as the depth of carbonation decreases considerably. Furthermore, we know that the granular coefficient increases with aggregate diameter, which in turn increases the average compressive strength at 28 days. This confirms the results obtained from the study of the influence of true cement class on carbonation depth.

Figure 10 shows that carbonation depth decreases with decreasing environmental aggressiveness. In other words, with a higher gamma coefficient, the depth of carbonation becomes greater. In fact, this gamma coefficient is inversely proportional to the design compressive strength, and any effort to increase this coefficient will decrease the strength and therefore increase the penetration rate of carbon dioxide  $(CO_2)$  - in other words, increase the carbonation depth

of the concrete. The study of this coefficient is particularly important when assessing the durability of concrete in a highly aggressive environment (high  $CO_2$  and sufficient H.R. content).

### **IV. CONCLUSION**

The durability of cementitious matrices has been studied, as they are easily attacked by external agents if this study has been neglected or omitted. For this reason, in this manuscript, durability studies have been carried out on standardized mortar specimens in which cement has been substituted by fly ash. This involved measuring the coefficient of water absorption by capillarity and the porosity accessible to water. The results showed that the use of fly ash resulted in fewer connected pores accessible to water in the material, since low material porosity can lead to a drop in the water absorption coefficient. Subsequently, carbonation models were presented to characterize the cementitious influence of materials formulation parameters on the evolution of concrete carbonation depth, which follows a square-root law of time  $(x = K\sqrt{t})$ . The results show a decrease in carbonation depth when the true cement class, the average strength and the granular coefficient increase in value, and similarly when the E/C ratio and the  $\gamma$  coefficient decrease. The results also show that carbonation depth becomes maximum for relative humidity values between 40% and 60%.

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### V. REFERENCES

- NF EN 196-1 (2016), Test methods for cements - Part 1: Determination of strengths, 35 pages;
- CRANK J., (1975), The Mathematics of Diffusion Oxford science publication 2nd edition, Clarendon Press Oxford, 421 pages;
- 3. Diop, S., Sall, O.A., Diouf, D., and BA, M. (2025), "Physicochemical and mechanical

characterization of unconventional fly ash from the bargny-sendou coal-fired power plant in Senegal", Journal of Scientific and Engineering Research, 2024, 11(12) :103-110;

- 4. NF EN 15801 (2010), Test methods -Determination of water absorption by capillarity, 9 pages;
- NF P 18-459 5 (2022), Béton Essai pour béton durci - Essai de porosité et de masse volumique, 16 pages ;
- Perlot C., Capra B., Rougeau P. (2007), Mieux maîtriser la durabilité des bétons par l'approche probabiliste, 99 pages ;
- 7. Venuat M., Alexandre J. (1968), De la carbonatation des bétons. Revue des matériaux de construction,  $n^{\circ}$  638, pp. 45 ;
- 8. Zhang, L., & Glasser, F. (2005), Investigation of the microstructure and carbonation of CSA-based concretes removed from services. Cement and Concrete Research;
- Grandet J., Thenoz B. (1972), "Evolution dans le temps des constituants d'une pâte de ciment Portland au contact d'un matériau poreux". Publication de l'institut nationale des sciences appliquées de Toulouse (France) pp94-111;
- Houst Y.F., (1992), "Diffusion de gaz, carbonatation et retrait de la pâte de ciment durcie "Thèse de Doctorat, Université de Lausanne (1992);
- Dreux, G. and Festa, J. (1998), Nouveau guide du béton et de ses constituants. Eyrolles, Paris, France. ISBN-13: 978-2212102314. 1, 3, 4, 6, 7;
- Kart, A., & Thompson, A. (1986), Quantitative predicition of permeability in porous rocks. Physical Review B, 34, 8179-8181;
- 13. Dullien, F. (1979), Porous media fluid transport and pore structure. New York Academic Press 483 pages;
- Loo Y. M., Chin M. S., Tam C. T. and Ong K. C. G. (1994), A carbonation prediction model for accelerated carbonation testing of

concrete, Magazine of Concrete Research, 46, N°168, pp.191-200;

- Kobayashi K. and Uno. Y. (1989), Influence of alkali on carbonation of concrete. Part I, Preliminary tests with mortar specimens, Cement and Concrete Research, vol. 19, N°5, pp. 821-826. (1990), Part II, Influence of alkali in cement on rate of carbonation of concrete, Cement and Concrete Research, vol. 20, N° 4, pp. 619-622, Copyright 1990;
- Saetta A.V., Schrefler B.A., Vitalini R.V (1993). The carbonation of concrete and the mechanism of moisture, heat and carbon dioxide flow through porous materials. Cement and Concrete Research, vol. 23, no. 4, pp. 761-772 ; 1993 ;
- 17. Ollivier, J.-P., & Vichot, A. (2008c), La durabilité des bétons (P. de l'école nationale des ponts et chaussées, Éd.) ;
- 18. Lea F. M. (1970), "The Chemistry of Cement and Concrete". Edward Arnol;
- Ait-Mokhtar A. (2002), "Durabilité des matériaux, Transfert d'agents agressifs dans les matériaux cimentaires". Habilitation à diriger des recherches en sciences, 2002 ;
- Hornain H (1976), "Carbonation accélérée et résistances mécaniques" In : Rilem Intarnational Symposium, Carbonation of Concrete, Cement and Concrete Association, Slough, paper5.2;
- De Ceukelaire L., Van Nieuwenburg D. (1993), "Accelerated carbonation of a blast furnace cement concrete". Cement and Concrete Research, vol. 23, 1993, p.442-452;
- 22. Venuat M. (1978), "Relation entre la carbonatation du béton et les phénomènes

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