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# **A probabilistic approach to the long term durability of concrete structures.**

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## **Abstract:**

Concrete is a heterogeneous material. A probabilistic approach appears to be more appropriate than a deterministic approach when concrete is required to have a very long lifetime, which is the case for the storage of nuclear waste.

We will start by analysing variations of concrete properties on a site through the distribution of mechanical strength. This distribution is represented approximately by a normal law for characteristics known in EC2. Experimental results respect this law.

The very long term deterioration of concrete (calcium leaching) is modelled in a simplified manner by prediction of the degraded depth after 300 years. The deterministic approach can be compared with the probabilistic approach, and it is found 1) that the average value of the distribution of degraded depths is similar to the deterministic value and 2) that it would be relevant to introduce a characteristic value (95% fractile) to take account of the width of the distribution.

## **1 FOR A PROBABILISTIC APPROACH**

Concrete is a heterogeneous material made on site under variable conditions with variable materials. Therefore, it is inevitable that there will be a fluctuation in its characteristics such as the compression strength. This aspect is always taken into consideration in construction codes through the concept of characteristic strength.

This is also true for other properties, for example related to durability, such as diffusivity and permeability. As far as durability is concerned, fluctuation related to stress is additional to fluctuation related to the material.

Therefore when a very long life is required (typically 100 years for bridges, 300 years for shallow land storage sites for nuclear waste and several thousand years for deep storage), it appears logical that this probabilistic aspect should be included in the prediction of the life of these structures. Several recent articles use such an approach ([1], [2], [3], [4], [5], [6], [7]).

The purpose of this article is to present a summary of compression strength, and then to show how taking account of the variability of diffusivity influences the very long term durability of concrete and to describe points for which more research is necessary.

## 2 COMPRESSION STRENGTH AND PROBABILITY

### 2.1 What do the regulations say?

Codes such as the BAEL (French code for reinforced concrete) or EC2 take account of the variability of concrete strength through the concept of characteristic strength. The characteristic strength is a 5% fractile, in other words 95% of samples made from this concrete will have a higher strength. EC2 adds a relation between the average strength and the characteristic strength:  $f_{cm} = f_{ck} + 8$  MPa. This equation had already been proposed in CEB-FIP Model Code 1990 and CEB-FIP Model Code 1978.

If it is assumed that the strength distribution is defined by a normal law (although this assumption is not physically accurate since a normal law corresponds to values varying from  $-\infty$  to  $+\infty$ ), we will have  $f_{ck} = f_{cm} - \lambda \sigma$  where  $\sigma$  is the standard deviation of the distribution. For a 5% fractile,  $\lambda = 1.645$ . Therefore, we have a normal law with average  $f_{cm}$  and standard deviation  $\sigma = (f_{cm} - f_{ck})/\lambda = 8/1.645 = 4.86$  MPa. Note that the standard deviation is independent of the strength. Therefore, all distribution curves can be represented through a single curve taking account of the change of variable that gives a narrow centered normal law, in other words with zero average and standard deviation equal to 1.

### 2.2 Comparison with site results

Figure 1 shows two examples of experimental strength distributions. The average strength, the 5% fractile and the standard deviation can be calculated from these distributions. The normality of distributions can also be tested using the Shapiro-Wilk test.

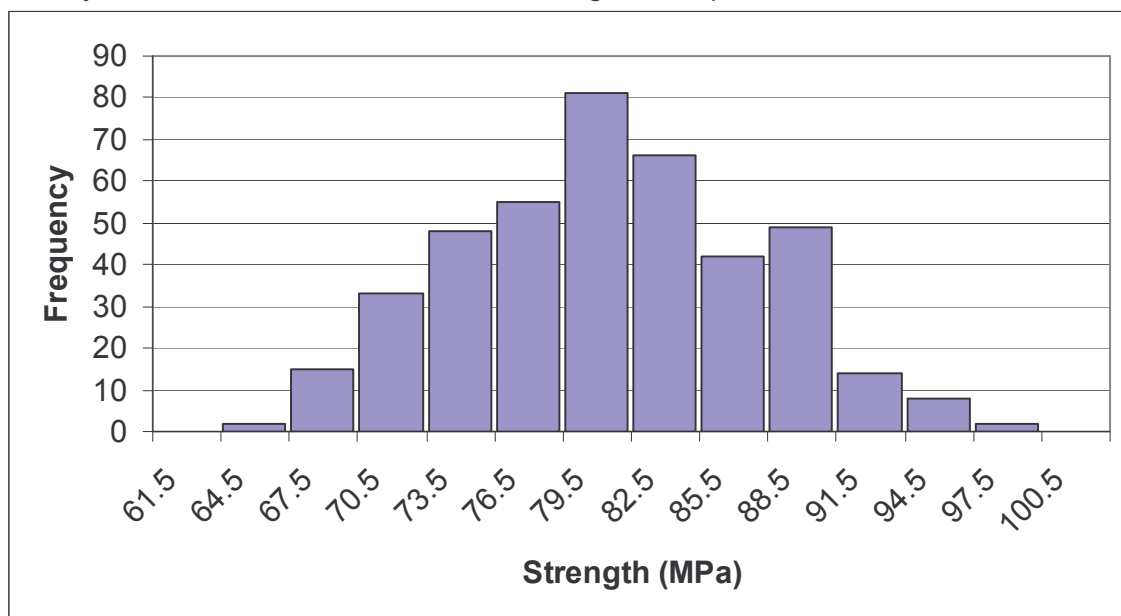


Figure 1.a) histogram of measured strengths on concrete in piers on Millau viaduct (415 samples) [8]

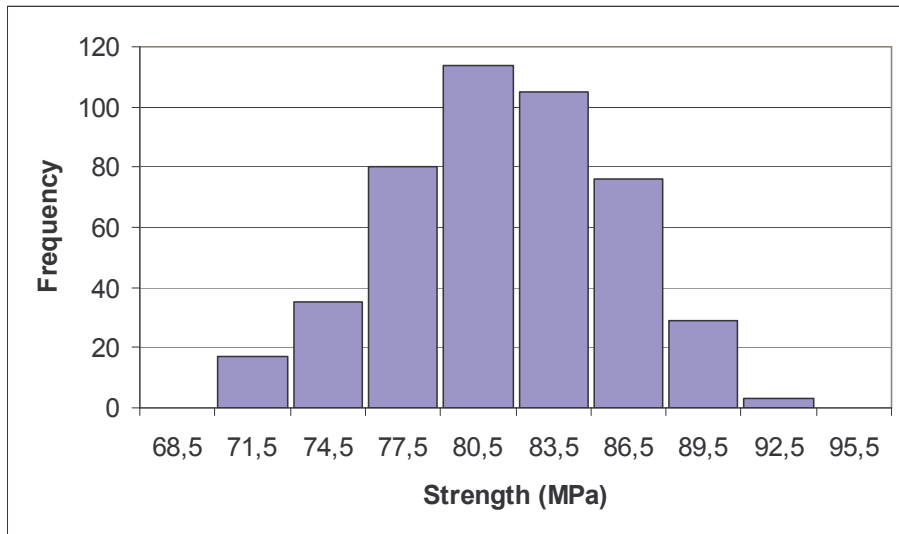


Figure 1.b) histogram of measured strengths on concrete in north access viaduct to Normandy Bridge (459 samples) [9]

Figure 1: example of experimental strength distributions.

Table 1 shows results obtained on several sites. An analysis of experimental results shows that the difference between the average strength and the 5% fractile of the experimental distribution is not very much different from the value proposed by EC2. Furthermore, experimental distributions may be similar to the normal distribution, but are usually not normal according to the meaning of the Shapiro-Wilk normality test.

	average	standard deviation	fck (5% fractile)	fcm - fck	number of samples	normality / Shapiro-Wilk test
Normandy bridge	81.6	4.5	73	8.6	459	no
Sylans viaduct	68.5	6.3	-	-	141	-
grande arche de la Défense	66.5	5	-	-	66	-
Ré island bridge	67.7	6.3	-	-	798	-
Millau viaduct B60	80.1	6.5	68.5	11.6	415	no
Millau viaduct B35	49.3	3.9	41.5	7.8	87	yes
Concrete batching plant B35	44.4	4.8	36	8.4	410	no
Tancarville bridge	46	5	36	10	147	no
Offshore drilling platform	55	3.26	48	7	493	no
EC2	-	4.9	-	8	-	-

Table 1: analysis of experimental results on different sites.

Figure 2 shows experimental distributions for 3 sites compared with the normal distribution according to EC2 assumptions, confirming these results. Consequently, it will always be advantageous to use experimental results when they are available, but the normal law with EC2 assumptions could be used for predictive calculations as a first approach.

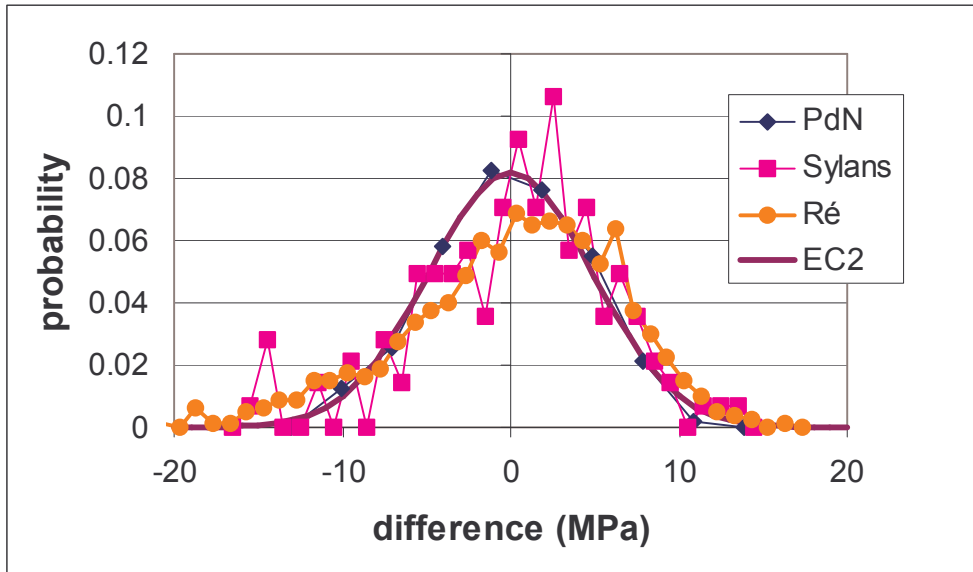


Figure 2: experimental comparison – reduced centered normal law with EC2 assumption; The experimental results are for the Normandy bridge, Sylans viaduct and Ré island bridge [21].

### 3 DURABILITY AND PROBABILITY

#### 3.1 Assumptions

In the following, we will consider the durability of concrete structures for the storage of nuclear waste, but the developed approach may also be applicable to the penetration of chlorides and corrosion of reinforcement. Concrete used for waste storage is typically affected by leaching by pure water. Since interstitial water in concrete has a very basic pH, contact with pure water is like an acid attack on concrete. However, this aggression is very slow and can often be neglected for conventional civil engineering structures<sup>1</sup> [10]. However, it becomes important for storage sites, considering the lifetime.

Experimental results show that the degraded depth  $x_d$  is proportional to  $\sqrt{t}$  ([11], [12], [13], [14], [15], [16], [17], [18], [20]). In general, predictive models for leaching are deterministic. But there is no reason why the proportionality coefficient  $k = x_d / \sqrt{t}$  should be constant. For example, it is known that the leached depth of a cement paste at a given time is a function of  $w/c$  [17]. Unfortunately, we do not have any data about the natural variability of the parameter  $k$ . Leaching tests are fairly complicated and are not done repeatedly like compression tests.

Due to the lack of experimental results, we need to make a major assumption; it is assumed that  $k$  varies with the concrete strength, in proportion to the square root of the diffusion coefficient for sound material. This assumption can be justified as follows:

- if the diffusion coefficient for degraded material is constant and equal to  $D$ , solution of the diffusion equation shows that  $k$  would be proportional to  $\sqrt{D}$ ;

<sup>1</sup> Even if there are some cases in which very pure water, such as snowmelt, has leached concretes.

- in all simplified leaching models, the diffusivity of the degraded material depends on  $D_0$  which is the diffusivity of sound material.

This assumption will no doubt be reconsidered based on experimental results, since although the diffusivity of the degraded material depends on  $D_0$ , it also depends on other factors such as the porosity or initial composition of the material [17]. And it is very unlikely that these factors will not vary at the same time on a site.

We now need to determine how the diffusivity of sound material can vary. Diffusivity tests [19] show that diffusivity can be represented by an equation of the type  $D = D_0 \exp(- a f_c)$  (figure 3), for concretes composed of the same materials. The parameters  $D_0$  and  $a$  in this equation will undoubtedly be different if materials are changed but this is reasonable for a given site.

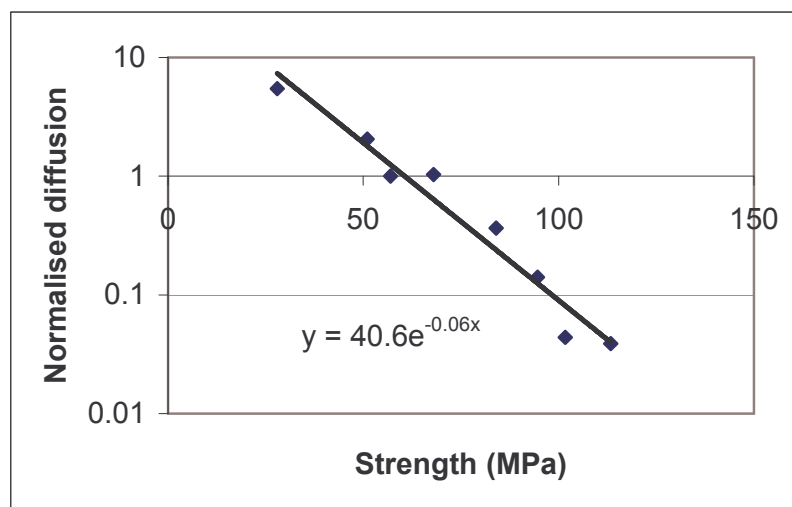


Figure 3: determination of the relation  $D = D_0 \exp(- a f_c)$  from experimental results [19]. Diffusivity is normalised at 1 for  $f_c = 57$  MPa

## 3.2 Applications

### 3.2.1 Deterministic calculation

The value of  $k$  is adjusted to match experimental observations made on a concrete with a mean strength close to 40 MPa, degraded in accelerated tests in an ammonium nitrate solution [20]. Kamali's results [17] were used to convert to a degraded depth in deionised water. The result is  $k = 0.195 (D(f_c)/D_0)^{0.5}$

The depth after 300 years is thus calculated. The deterministic calculation gives a degraded depth equal to 87.6 mm.

### 3.2.2 Probabilistic approach

A Monte Carlo type method is used for the probabilistic approach, with sampling using the latin hypercubes method, assuming that the strength is represented by an EC2 type normal law ( $f_{cm} = 40$  MPa,  $\sigma = 4.86$  MPa), all other parameters being deterministic.

The results obtained (figure 3) show firstly that the average degradation is equal to 88.6 mm, which is close to the deterministic value obtained using the average strength. However, it is observed that the distribution of degraded depths is wide. Therefore, the deterministic value only corresponds to an upper limit for 50% of concretes. A characteristic value, for example the 95% fractile, would be more relevant and obviously better than the deterministic value (in this case this fractile is equal to 111.8 mm<sup>2</sup>).

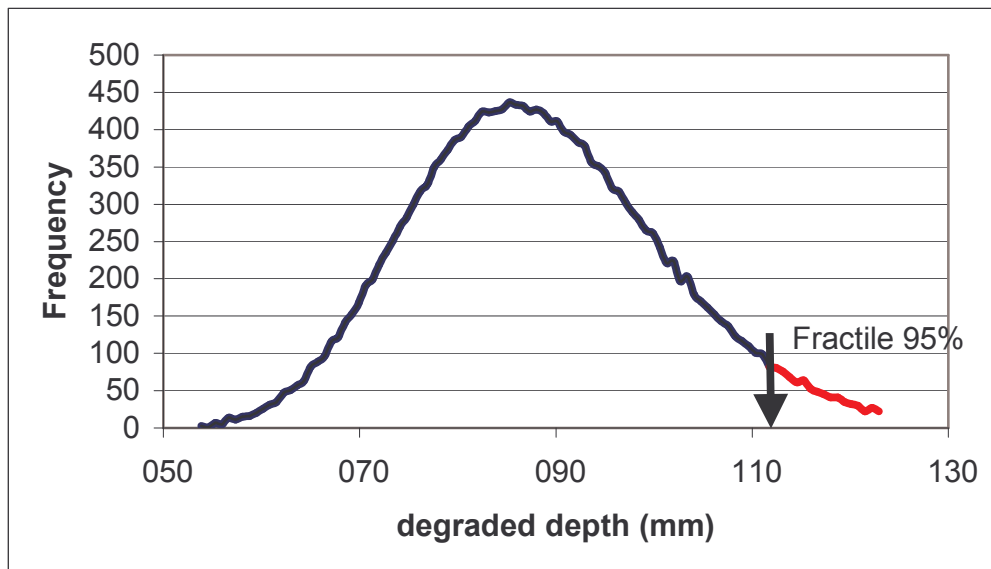


Figure 3: distribution of degraded depths after 300 years. The concrete strength follows a normal law with an average  $f_{cm} = 40$  MPa and standard deviation  $\sigma = 4.86$  MPa.

## 4 CONCLUSIONS

This article presents a probabilistic approach to durability. This approach appears necessary if it is required to predict the life of structures such as nuclear waste storage sites over very long periods. The application presented here was only qualitative, considering assumptions about the variation of diffusivity. An experimental investigation with reference to a specific site is necessary to obtain more reliable data. It would make it possible to validate or modify modelling assumptions.

The approach used showed (based on our assumptions):

- that the average value obtained by the probabilistic approach is not very different from the deterministic value;
- that it would be relevant to introduce a characteristic value of the degraded depth, for example the 95% fractile.

Finally, some points that were not discussed here should be considered in the future:

- what is the representativeness of test pieces compared with in-situ concrete? This point should be discussed as part of the experimental study required above.
- should the parameter controlling durability be related to the compression strength or to another parameter, for example such as porosity?

<sup>2</sup> Note that, with our very simple model, using the value of  $D$  corresponding to the characteristic strength we can calculate directly the characteristic value of the degraded depth.

- how can the measurement of the degradation on the structure be made systematically, so that Bayesian approaches can be integrated in the life prediction, so that it can be improved (see an example in [7]).

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