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Effects of the presence of free lime nodules into concrete: Experimentation and modelling

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ABSTRACT

When nodules of lime are embedded into concrete, the expansion accompanying the transformation of CaO into $Ca(OH)_2$ induces stresses and strains in both the lime nodule and in the concrete matrix. The concrete cover thickness, the diameter and the shape of the lime nodule as well as the mechanical characteristics of concrete and lime are the key parameters influencing the development of internal pressure and hence controlling the risk of cracking or pop-out. In order to study the effect of lime into cementitious concretes, laboratory investigations and modelling have been performed and show that the minimum cover thickness necessary to avoid the development of the pop-out phenomenon is estimated of the order of half the diameter of the inclusion. This is coming from the observation that expansion happens inside the porosity of the hydrated lime $Ca(OH)_2$: ESEM and DRX analyses confirm the effect of confinement in the development of crystals.

1. Introduction

Lime has been used for a very long time in construction and buildings: Roman cement was already made of a part of lime while it remained the only binder used until modern cement was designed during XIXth century [1]. Lime is an industrial product obtained by calcination of limestone in a lime kiln [2]. This is described as a *bright lime* (Table 1), because of its high reactivity with water. The bulk density of the limestones industrially used for the manufacture of lime usually offers a lower density than calcite used for ornamental stones: porosity maybe up to 30% [3]. Quick lime is very reactive with water and hydrates are quickly formed [4]. Hydration process is accompanied by a significant proliferation (Table 1). The formation of $Ca(OH)_2$ yields in larger volume (expansive reaction). The ratio of volume change from CaO particle to $Ca(OH)_2$ is $33.1/16.8 \approx 2$.

The doubling of the molar volume (from 16.8 to 33.1 cm^3/mol) is responsible for expansion during hydration [4]. The intensity and speed of hydration are governed by lime purity, particle size, surface area, …etc. [5]. Burning temperature and kiln technology are also two important discriminant factors in the case of industrial lime production [3].

An interesting parameter used to quantify the reactivity of lime is the so-called T60, which is measured in accordance with standardized method EN 459-2:2001. It gives the speed of lime extinction, or the time needed to attempt a temperature of 60 °C: the smaller it is, the more reactive the lime is. In some cases, the lime can be dead burned, leading to high density CaO grains [4]. This dead burn lime hydrates very slowly because of a reduced porosity [6]. When lime is incorporated into concrete, problems due to expansion may occur (Fig. 1): this phenomenon is well known as *pop-out* [7–11].

In many cases, quick lime is present in steel or iron slags [8,9]. That means that it is rarely in the form of millimetre-sized aggregate in a confined environment. In the case of steel slags, Deng et al. [10] observed that expansion rates are depending on the type of cement and the percentage of lime: for lime contents of 2 and 5% (by weight of cement), the maximum observed rate of expansion is 0.12 and 0.7%, respectively, for cement type CEM I. The expansion force is estimated at 11.87 MPa in 3 days. A “dead” lime was used for experimentation and required alkali activation: the concentration of OH-ions in the pore solution of cement paste controls the expansion by affecting the positions occupied by the crystals of $Ca(OH)_2$ and the pressure of crystallization. Analyses of the behaviour of LD steel slags containing lime nodules [11] were also conducted as a result of damage observed. An expansion rate of 0.16% (measured by immersion according to the Korean standard KS F 2580) was considered. The finite element calculations show that the depth of the pop-out increases as concrete strength decreases and the diameter of the slag increases (Fig. 2).

Other authors [12,13] made investigations on fine lime particle coming from shrinkage preventing agents or wrong cement manufacturing.

Useful information may be found through the study of other expanding processes [14]: Alkali Aggregate Reaction (AAR) should induce similar stresses inside concrete. A difference is however coming

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Table 1
Hydration of quick to hydrated lime [2,3].

Property	CaO	$+H_2O$	$\rightarrow Ca(OH)_2$
Molecular weight	56.08	18.01	74.09
Bulk density (g/cm^3)	1.40–1.90		0.45–0.65
Specific density (g/cm^3)	3.33	1	2.24
Molar volume (cm^3/mol)	56.08/3.33 = 16.8		74.09/2.24 = 33.1

from the easier fulfilling of aggregate cracks by the silica gel which progressively replaces a part of the initial products present along the edge of stone material.

With regard to the very poor information coming from literature reviewing, it clearly appears a lack of knowledge on the behaviour of quick lime aggregates (up to 20 mm diameter) when mixed into concrete. A risk evaluation analysis is needed: it will be based on an experimental programme and modelling that will help in understanding free lime behaviour in confined situation.

2. Stresses calculation and modelling: theoretical background

2.1. Simplified approach

As a first simplified preliminary approach, it is considered that the swelling pressure is unable to induce cracking in the concrete as a nodule of lime can merely be considered as an air bubble, whose effect is increasing the porosity and, consequently, decreasing the compressive strength of concrete. Bolomey and Feret theories can be used to quantify this phenomenon [15].

Based on the equation p (aggregates) + s (sand) + c (cement) + w (water) + v (voids) = 1, which expresses the sum of the volume fractions for 1 m^3 of concrete, we have, with $\lambda = (c/(c+w+v))$, the Feret formula which expresses the relationship between the compressive strength of concrete and the voids (v):

$$f_{c,cube} = K_0\lambda^2 = K_0\left[\frac{c}{c+w+v}\right]^2 \text{ with } K_0 = K \cdot R_c \quad (1)$$

where $f_{c,cube}$ is the compressive strength (MPa), K is a granular coefficient and R_c = the compressive strength of cement measured on standardized mortar (EN 196-1).

This clearly indicates that the compressive strength decreases when the w/c ratio increases. If we express this equation as a function of W and C (mass ratio) for a cement relative density of 3.15, the expression can be written:

$$f_{c,cube} = K_0 \cdot \frac{1}{\left(1+3.15\frac{W}{C(+V)}\right)^2}. \quad (2)$$

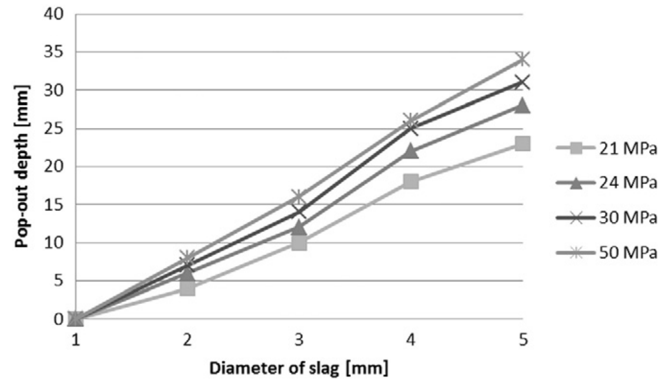

Fig. 2. Concrete cover versus diameter of the slag for different concrete types (from [11]).

It is experimentally observed that K is about 4.9 for ordinary concrete [16]. Bolomey formula also suggests a linear relationship between the compressive strength and the ratio C/W.

$$f_{c,cube} = k\left(\frac{C}{W} - h_1\right)$$

where k (26–36) and h_1 (0.45 to 0.87) depend on the quality of the cement, the age of the concrete, the shape and dimensions of the test pieces, the curing conditions and the sieving curve of aggregates and sand.

The volume occupied by the nodules can be considered as an additional volume of water in the sense of increasing W/C ratio; that will partially produce an additional volume of air after curing and evaporation. If we consider for example a W/C = 0.5 and a bulk density of lime 1.56 [3], the volume occupied by the nodules, for a percentage of 0.3% of the mass of aggregates into concrete (1300 kg/m^3 of concrete), would be: $0.003 \times 1300/1560 = 0.0025\ m^3 = 2.5$ l. This means that we can consider a fictitious increase of the amount of water for a 350 kg concrete cement of about 2.5 l, which means a total of 175 + 2.5 = 177.5 l. The W/C ratio increases thus from 0.50 to 0.507. Feret formula allows estimating the resulting loss of strength [16]:

$$\frac{1}{(1+3.15\times 0.50)^2} \bigg/ \frac{1}{(1+3.15\times 0.51)^2} = 1.017.$$

This corresponds to a loss of strength of about 1.7%.

This evaluation clearly shows that the influence of nodules inside the concrete has a very marginal impact on the major structural characteristic of concrete: compressive strength is only lightly affected by a reasonable level of pollution by lime nodules.

However, if these nodules are close to the surface, they are likely to induce pop-out and cracking, which is detrimental for concrete

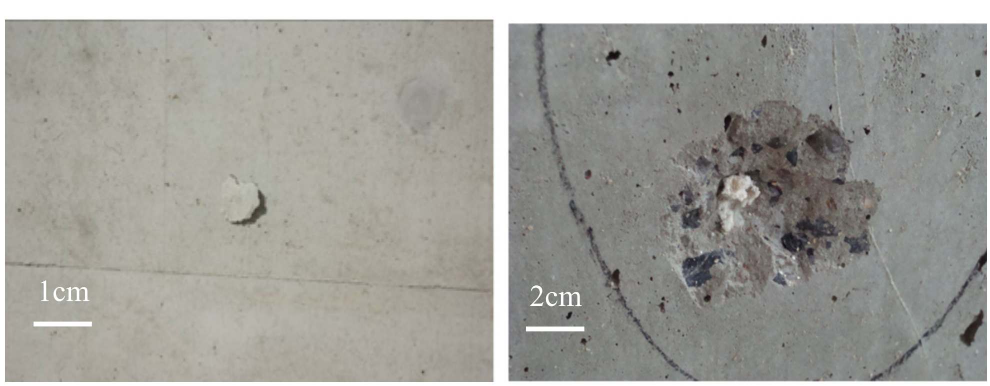

Fig. 1. Degradations induced by pop-out in concrete.