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# Construction and Building Materials

journal homepage: [www.elsevier.com/locate/conbuildmat](http://www.elsevier.com/locate/conbuildmat)

## Rate of carbonation in cement modified base course material

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### HIGHLIGHTS

- An analytical model displays a high potential for the estimations of carbonation rate in soil cement.
- Carbonation progress is measurable for soil cement materials either analytically or experimentally.
- Nanosilica assists in mitigation of deleterious reactions.

### ARTICLE INFO

#### Article history:

Received 1 October 2016

Received in revised form 10 May 2017

Accepted 22 May 2017

Available online 14 June 2017

#### Keywords:

Carbonation rate

Soil cement

Analytical model

Pavement and nanosilica

### ABSTRACT

In the absence of a carbonation model for soil cement, this research aims to assess the compatibility and applicability of an analytical model initially developed for concrete. Carbonation can be observed in any pavement layer which includes cement or lime. For instance, carbonation damages the cement-modified crushed rocks as a typical material for base course layer due to poor curing of material or cracking of asphalt. Experimental laboratory tests are utilised here in accelerated carbonation conditions to evaluate the analytical model. Cylindrical specimens are subjected to one-dimensional carbonation condition. Weight and ratio of constituents of mixes, as well as environmental factors, such as CO<sub>2</sub> concentration and relative humidity are recorded for analytical estimation of failure progresses. Nanosilica is also introduced in mixes to explore its effects during carbonation reactions. Results show linear correlations between experimental records and analytical model calculations. Thus, it can be concluded that carbonation rate can be predicted in soil cement also. In addition, the inclusion of nanosilica has a positive influence by slowing of the carbonation progress.

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## 1. Introduction

Carbonation of hydrated cement involves the reaction of carbon dioxide CO<sub>2</sub> with the hydration products. Calcium hydroxide Ca(OH)<sub>2</sub> and calcium silicate hydrate (C-S-H) are attacked by CO<sub>2</sub> in the hydrous voids which exist in cementitious mixtures. Hence, strength developments are stopped or reversed through the production of calcium carbonate CaCO<sub>3</sub>. These deleterious reactions act to destroy the cementitious bonds of aggregates or soil particles which lead to rutting, spalling and cracking of bituminous layers in pavements [23]. These reactions also reduce the strength, density and elasticity of the material alongside increasing porosity and permeability of stabilised material. In this process, cement treated soils can lose their strength up to 70% which is a significant decrease with respect to load bearing layers in pavements [21].

These reactions can also develop internal expansive forces beyond tensile strength, which weaken or disintegrate soil cements [20]. As such, carbonation is labelled as an unfavourable chemical reaction in stabilised soils. Typically in Western Australia, this type of failure has been reported in trial sections of the Kwinana Freeway, Reid highway and taxiway D at the Broome Airport [7,8,30].

Along this line, the carbonation reaction can be initiated even when cement paste is exposed to air during mixing, so it should be limited as far as possible. To date, the latest suggested methods of its control in soil cement are the use of high cement content, early compaction and immediate surface sealing or protection by means of different prime coats including bituminous solutions [22].

Indeed, depth of carbonation in concrete is around 0.5–2 mm after several years [11,15], which is much lower than soil cement. In soil cement, limited observed records indicate that the rates are about 3–50 mm/year in South Africa [17]. This range is high for a base layer with nearly 200 mm thickness that should last for

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20–40 years. It has therefore been inferred that carbonation would be important for service-life assessments in pavements [34].

To date, the majority of investigations or models of carbonation relate to concrete material. The first model was developed by Uchida and Hamada in the 1930s cited by Richardson [32] using the following empirical relationship:

$$x = \frac{w_0 - 0.3}{\sqrt{0.3(1 + 3w_0)}} \sqrt{t} \quad (1)$$

where  $w_0$  is water/cement ratio,  $x$  is the carbonation depth (mm) and  $t$  is the time (year). Since then, other empirical relations have been developed which consider various environmental classes (urban, coastal), exposures of structures (external and internal) and water/cement ratios [18,32]. However, these empirical models are not applicable for soil cement materials in pavements as these types of exposures do not exist or the range of water/cement ratio differ significantly.

For example, the cement content for coarse soils is in the range of 1% to 6% [27], which is much lower than corresponding ranges in ordinary concrete materials (10–15%). Similarly, the water content of stabilised soils can vary typically from 5 to 15% which is much higher than typically 3–6% (by dry weight of aggregates) in concrete. Overall these points imply that empirical correlations in concrete may not be suitable for soil cement investigations.

However, mathematical models might have potential to validate or develop for other cementitious materials. For example, an analytical method has been developed by Papadakis et al. [24] for ordinary concrete which considers a broad set of mixture constituents. This model takes into account the concepts of chemical reaction engineering, mix design details and physicochemical processes. A similar model has been developed for high-volume fly ash concrete which considers the degree of hydration as well [10]. Therefore, it is valuable to examine Papadakis et al. model for soil cement materials. In this way, effects of mixture constituent may be better studied and in more detail. Hereafter, further details of this model are discussed including the full explanation of laboratory works.

## 2. Details of analytical model

Papadakis et al. [26] assumed the mass conservation of carbon dioxide whilst it diffuses into cementitious material and reacts with cement hydration products. Accordingly, Fick's first law is applicable for this purpose as shown in Fig. 1.

$$dn = DA \frac{(r_x - r)}{x} dt \quad (2)$$

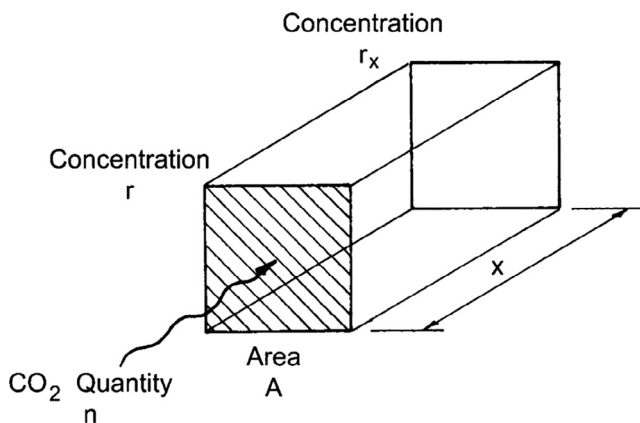


Fig. 1. dimensional diffusion of CO<sub>2</sub>. [32].

The chemical process can be represented as:

$$dn = c.A.dx \quad (3)$$

$n$  is the quantity of CO<sub>2</sub> diffusing through the element (kg),  $D$  is the diffusion rate (m<sup>2</sup>/s),  $A$  is area (m<sup>2</sup>),  $t$  is time (s),  $r$  and  $r_x$  are the concentration of CO<sub>2</sub> (kg/m<sup>3</sup>) at the surface and a depth of  $x$  and  $c$  is the amount of alkaline material in a unit volume of material (kg/m<sup>3</sup>). Hence, equating the carbon differentials from Eqs. (2) and (3) yields:

$$x.dx = D \frac{(r_x - r)}{c} dt \quad (4)$$

Assuming zero CO<sub>2</sub> concentration at the depth of sample, the integration will result in:

$$x = \sqrt{\frac{2Drt}{c}} \quad (5)$$

Accordingly, Eq. (5) can be rewritten in terms of molar concentration as illustrated in Eqs. (6) and (7). The underlying assumptions for this transformation are porosity reduction (due to higher molar volumes of carbonation products rather than hydration products) and mass conservation of CO<sub>2</sub>, Ca(OH)<sub>2</sub> and C-S-H [26].

$$x = K_c \sqrt{t} \quad (6)$$

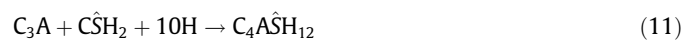
$$K_c = \left( \sqrt{\frac{2[CO_2].D_{e,CO_2}}{[Ca(OH)_2] + 3[C \cdot S \cdot H]}} \right) \quad (7)$$

where  $[CO_2]$  is the molar concentration of carbon dioxide (mol/m<sup>3</sup>),  $[Ca(OH)_2]$  is the molar concentration of calcium hydroxide (mol/m<sup>3</sup>),  $[C-S-H]$  is the molar concentration of calcium silicate hydrate (mol/m<sup>3</sup>),  $D_{e,CO_2}$  is the effective diffusivity of carbon dioxide (m<sup>2</sup>/s) and  $K_c$  is the carbonation coefficient (m/s<sup>0.5</sup>).

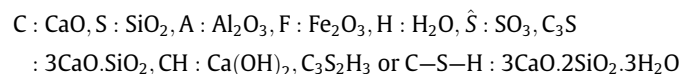
The main assumption of above relationships is direct interaction of calcium hydroxide in solution and carbon dioxide in air. Lilkov et al. [14] verified this assumption during X-ray Diffraction (XRD) observations of cement hydration in different time intervals. They found out that carbonation is a process between the calcium ions and the carbon dioxide without formation of Portlandite and Ettringite.

## 3. Effect of hydration products

As indicated in Eq. (7), quantitative evaluations of carbonation reactions depend upon the concentrations of calcium hydroxide (CH) and calcium silicate hydrate (C-S-H). These concentrations can be obtained from below expressions, assuming an excess of gypsum and thus having no Ettringite formation and complete cement hydration and pozzolanic activities [24]:



where notations stand for following:



The reaction of the oxides (their phases) of a pozzolan with Ca(OH)<sub>2</sub> and/or pozzolanic activity are proposed as follows:

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