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Moisture transport and drying shrinkage properties of steel–fibre-reinforced-concrete

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HIGHLIGHTS

- Moisture transport and shrinkage properties are obtained for CC, RCC and SFRC.
- Nonlinear moisture diffusivity is determined by experiments and FE inverse analysis.
- Hygral contraction coefficient, or free shrinkage versus moisture loss, is derived.
- These values can be used to numerically predict shrinkage distress in ground slabs.
- Moisture diffusivity of RCC is higher than CC, RCC shrinks at a more uniform rate.

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ABSTRACT

Drying shrinkage has a serious impact on the structural and durability performance of concrete pavements. Shrinkage strain development and distress can only be fully understood by knowing the moisture transport and free shrinkage properties of concrete. This paper uses experiments and FE inverse analysis to determine these properties for conventional concrete (CC) and RCC reinforced with recycled-steel–fibres from tyres. Moisture diffusivity versus moisture content and a relationship between free shrinkage and moisture loss are derived. These values can be used to predict shrinkage strains and stresses in road pavements and other ground restrained slabs.

1. Introduction

In studying drying shrinkage, it is important to understand and quantify moisture movement in concrete during drying [1–3]. When concrete dries, the pore water moves towards the surface through the pore network and this results in variable moisture content in space and time. Moisture transport in concrete is more complex than in other porous media, as it has a wide variety of pore structures and the pore structures themselves change with time [4].

Drying shrinkage is critical for concrete pavements due to their large surface area. In particular, it significantly affects the performance and life time of concrete roads [5]. It has been demonstrated numerically by the authors [6] that shrinkage induced internal strains and cracking can reduce the effective design stress used in pavements by up to 50%. For jointless SFRC pavements, shrinkage is the main limiting factor that determines the size of the slab. The same applies to RCC which can be used as an alternative to asphalt roads, or SFR-RCC in which the roller-compaction construction technique is used for placing SFRC. Early shrinkage behaviour of RCC is reported to be quite different to that of CC [7]. The few published investigations report that drying shrinkage of RCC is relatively low compared to CC [8,9]. This is attributed to its lower moisture content or lower paste content. Whilst less paste in RCC can help to reduce the volumetric changes induced by drying, more voids and pores due to the nature of RCC may also change the moisture transport and shrinkage properties. Fibres can also change the

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Abbreviations: CC, conventional concrete; FE, finite element; RCC, roller-compacted-concrete; RTSF, recycled-tyre-steel–fibres; SFRC, steel–fibre-reinforced-concrete; SFR-CC, steel–fibre-reinforced conventional-concrete; SFR-RCC, steel–fibre-reinforced roller-compacted-concrete.

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pore structure of the concrete and affect the moisture transport and drying shrinkage [10]. Published research work on RCC and SFR-RCC does not deal with moisture transport and shrinkage properties.

Using fibres in concrete leads to increased strain capacity and energy absorption by controlling crack propagation. Many different types of fibres have been used in concrete, but steel fibre is the most common. Steel fibres are produced in different shapes and lengths. The ability of fibres to bond with the concrete depends on the aspect ratio of the fibres and the surface characteristics. Thinner steel fibres could bridge microcracks more effectively and influence positively the early-age shrinkage of concrete. Such fibres can be obtained from recycling post-consumer tyres and can contribute to making SFRC more economical and environmentally friendly [11]. Recycled-tyre-steel–fibres (RTSF) have been developed at the University of Sheffield and examined extensively during the EU collaborative research project, Ecolanes [6,12–16]. The work reported in this paper was part of Ecolanes and contributed to the development of numerical models for the analysis of road pavements. The objective of this work was to determine the moisture transport and shrinkage properties of CC and RCC reinforced with a practical content of steel fibres recycled from post-consumer tyres (2.5% by weight) for FE modelling and comparison and design purposes. The material properties which are directly involved in the drying procedure of concrete are moisture diffusivity, convective moisture transport coefficient (also called film factor or surface factor) and hygral contraction coefficient (also called shrinkage coefficient) [17,18]. These properties cannot be determined from the simple ring tests and in this paper special experimental procedures are adopted and modified to determine them. The approach followed in this paper is based on a combination of experimental studies and inverse analysis techniques. During the inverse analysis (or back-calculation), the properties are changed in a FE model so as to achieve iteratively the same moisture profiles or shrinkage history as obtained from experiments.

The paper begins by reviewing the factors involved in moisture transport and drying shrinkage of concrete. The moisture measurement methods are then evaluated to plan the experimental programme. The experimental procedures are presented followed by numerical inverse analysis and results.

2. Factors involved in moisture transport and drying shrinkage of concrete

In porous media, moisture can flow partly as liquid in capillaries and partly as vapour. In soil, the water movement happens distinguishably with both mechanisms (bulk water and vapour flux). Bulk water flux is controlled by pore water suction and elevation potential (capillary action). Vapour flux is governed by vapour diffusion in unsaturated pore space [1].

In concrete, when pore relative humidity is in the range of 15–95%, moisture movement in the form of vapour flux is dominant [19]. Therefore, the flow of moisture in concrete subjected to drying is in general assumed to obey the diffusion principles [1–3,17,19–24], especially when the moisture content decreases below 70–80% of initial saturation [25].

The first application of diffusion principles in a study of moisture distribution in concrete was reported in 1937 by Carlson [20]. Pickett [21] in 1946 revealed that the diffusion equation describing moisture movement in concrete can be equivalent to the equation of heat conduction. However, the order of magnitude of the corresponding coefficients for diffusion of heat and diffusion of moisture are entirely different. Using this approach, only one material property, diffusivity, is involved in characterising the moisture movement within concrete, which makes it very convenient for analysis.

2.1. Diffusion coefficient

Assuming that the diffusion theory applies, the transport of moisture in concrete is governed by Fick's second law [17,23], details of which are given in Appendix A.

To determine the moisture diffusivity, K_C, as a material property, moisture measurements should be taken from drying specimens as a function of time and depth. Based on experimental moisture profiles, the diffusivity equation can be solved numerically or analytically to obtain the relevant moisture diffusivity. Different forms of analytically or empirically estimated closed-form functions defining the dependency of K_C on the moisture content, C, have been introduced in the literature [2,3,5,10,18,22,26].

In an approach proposed by Sakata [2] and adopted by others [1,23,24,26], by assuming one-dimensional moisture transport the diffusion equation can be solved (Eq. (1)) using Boltzman's transformation, $\tau(x,t) = x/\sqrt{t}$.

$$K_C]_{C=C1} = \left(-1/2\int_1^{C1} \tau \cdot dC\right) \Big/ \left(dC/d\tau]_{C=C1}\right) \tag{1}$$

$$\text{Initial condition}: \quad C = 1 \quad \text{for} \quad x > 0,\ t = 0$$

$$\text{Boundary condition}: \quad C = C_1 \quad \text{for } x = 0,\ t > 0$$

where x is the distance from the drying surface and t is the drying time.

Since the slope of the curve $C(\tau)$ is very sharp at the beginning of drying, small inaccuracies in estimating the function $C(\tau)$ from experimental data can make a big difference on the resulting derivative to be used in Eq. (1). This affects significantly the calculated K_C at the beginning of drying. Therefore, this method is not generally satisfactory and some scholars have suggested adopting numerical inverse analysis instead [3,4] to obtain K_C.

Vapour transfer in air occurs with a diffusion coefficient of about 218 mm^2/day at 20 °C, that is nearly 50–100 times faster than in concrete [18]. This upper limit has not been respected in values determined by some researchers (e.g. [1,23]), proposing values up to 10,000 mm^2/day for the diffusion coefficient in concrete. Based on the values proposed by other researchers [2,18,22,27], the diffusion coefficient in concrete reaches maximum values between 20 and 100 mm^2/day at 100% moisture content. In some studies a constant value has been determined for the diffusion coefficient of concrete (the constant value of 9.29 mm^2/day by Carlson [20] and the value of 23 mm^2/day by Pickett [21]), while an S-shape curve has been proposed in other Refs. [2,19] to express the variation of the moisture diffusivity with the moisture content. These differences in values proposed in the literature are large enough to change completely the drying pattern in concrete. Hence, for the particular concrete mixes studied herein the diffusion coefficient will be determined from experimental measurements combined with inverse FE analysis.

2.2. Convective moisture transfer coefficient

Convective moisture transfer coefficient, f, deals with the moisture exchange between the concrete surface and the atmosphere. It depends on the water–cement ratio, w/c [2], the moisture gradient, the surface texture and the speed of air flow. However, the overall effect of the environment on f is negligible [18]. For normal concrete, f was found by Sakata [2] to be in the range of 0.75–7.0 mm/day; a very wide range of values. To improve the accuracy of predictions, for the particular concrete mixes studied in this paper, f will be calculated by inverse FE analysis.