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Impact of reinforcement-concrete interfaces and cracking on gas transfer in concrete

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HIGHLIGHTS

- Permeability were measured on reinforced samples for different saturation degrees.
- Steel bars embedded in concrete lead to an increase in the sample permeability.
- For high saturation degrees, the steel-concrete interface is the main transfer path.
- Cracking induced by the restrained shrinkage participate to transfer.
- Equivalent defect opening can quantify the impact of the interface on air transfer.

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ABSTRACT

The durability of reinforced concrete structures is largely impacted by their transfer properties, which can be evaluated through, for example, permeability measurement. Usually, concrete permeability is studied on plain specimens and the effect of the presence of steel bars on permeability in reinforced concrete has been little studied in the literature. The steel-concrete interface presents a larger porosity than plain concrete, which can be the cause of preferential percolation paths for fluids. Such percolation paths could create a lower resistance to fluid transfer and modify transfer kinetics. For reinforced and prestressed structures with large reinforcement contents, such as found in nuclear power plants, the impact of the reinforcement on gas transfer should be identified to obtain a better assessment of the flow within the structure. The aim of this experimental study is to characterize the effect of the presence of reinforcement on such flows by measuring leakage rates, permeability, and time to reach the steady state. Measurements were performed with a Cembureau constant head permeameter on cylindrical concrete specimens with or without steel bars. Since gas transfer into concrete depends on the rate of saturation of the material, the specimens were tested at different degrees of saturation: 0%, 6%, 30%, 60%, 80%, 90% and 100%. The analysis quantifies the impact of the defects created by the steel bar for each state. The results show that material composed of concrete and reinforcement can be divided into two distinct permeability zones: the plain concrete and the steel-concrete interface with or without cracking. These two zones can be associated in series and/or in parallel according to the configuration. The consequences on permeability measurement in reinforced structures are discussed.

1. Introduction

The penetration of aggressive agents, water, chloride and other ionic species into concrete is responsible for most of its deterioration [1–3]. The viability of many structures depends on their concrete transport properties [4–6]. The permeability of a reinforced concrete and the extent to which it permits diffusion are considered as major indicators of its durability [3,5,7]. Fluid transport in a porous material is possible because of the presence of paths of connected porosity. In concrete, the pathways are mainly: the capillary pores of the cement paste [7–9]; the interfacial transition zone between cement paste and aggregate [8,10–12]; and micro cracks in aggregates and cement matrix [8,13]. Most of the research on the subject has dealt with plain concrete and mortar without reinforcement, so the effect of the presence of steel bars on the permeability of reinforced concrete has been little studied. Reinforcements lead to obtain smaller cracks opening for concrete under mechanical loading and thus to decrease permeability in damaged concrete [14–17]. This impact of reinforcement has to

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be taken into account for leakage prediction in real structures [18]. The inclusion of fibres decreases permeability properties in concrete with [19,20] or without [21] cracks due to mechanical loading. Previous experimental works analysed the mechanical role of reinforcement on the permeability of loaded concrete. In this case, several mechanisms impact concrete permeability: the modification of porosity due to mechanical loading, the cracks occurrence and the impact of the steel-concrete interface. Small stresses lead to compaction and thus to the decrease of permeability [25] and permeability increases when cracks connectivity occurs [25,26]. In reinforced concrete samples, steels densify the cracking and reduce the crack width due to loading. Reinforcement leads to a reduction of the flow through cracks and thus of the permeability.

However, reinforcement bars are also responsible for concrete cracking due to restrained shrinkage, even without external loading. The induced cracks and also the voids at the interface with the concrete [22–24] disturb the transfers in concrete, particularly close to the skin, where transfer has a preponderant effect on durability. For reinforced concrete submitted to loading, the different mechanisms acting on permeability are concomitant. To obtain precise modelling, it is necessary to distinguish the part of each mechanism: the impacts of the mechanical loading, of the induced cracks and of the steel-concrete interface. As a consequence, transfers in plain and reinforced specimens without mechanical loading have to be analysed to assess the capacity of steel-concrete interfaces to provide gas transfer paths.

If the steel-concrete interfaces are actually preferential paths of transfer and become accessible to fluids from the surface through cracking, the reinforcement cover would become unable to assume its protective role against aggression and so the steel bars could be directly exposed. The degradation kinetics of reinforced concrete becomes greatly accelerated if other phenomena do not occur (healing, precipitation). Similarly, as these steel-concrete interfaces act on the kinetics of the fluid flow, they can change the time necessary to reach the steady state of flow due to their low resistance to transfer [27], according to the design of the reinforcement in the structure. In heavily reinforced structures, the steel-concrete interfaces are numerous, have considerable area and are highly connected. Therefore, they form significant pathways for transfers, which should be considered when predicting the durability, and particularly the air tightness of such structures. This study analyses the contribution of steel-concrete interfaces to gas transfer within reinforced concrete.

The degree of saturation of concrete on site is usually very high close to water supply and in locations submitted to rainfall and is usually over 80% at 50 mm depth [28], which prevents most of the transfer in plain concrete. However, the Kelvin Laplace equation indicates that cracks with an opening greater than one micrometre are drained even at high relative humidity (99.99%). So, in the presence of skin cracking, the steel-concrete interface can easily be drained even if the saturation level of the rest of the concrete is high. Since the permeability of concrete is affected by its water saturation [5,29–32], it is important to perform this study on material at different states of water saturation.

2. Objectives

The objective of this paper is to analyse the impact of the steel-concrete interfaces on reinforced concrete permeability, by inducing pathways for gas transport into concrete. They can change the transfer kinetics and the time to reach steady state during a measurement of gas leak rate and can thus constitute weak zones regarding the air tightness of reinforced concrete structures. Three specific points are particularly highlighted:

- Impact of the steel-concrete interface on permeability,
- Impact of the steel-concrete interface on flow kinetics,
- Impact of induced cracking close to the steel-concrete interface on permeability.

The first two points will lead us to identify the different zones of permeability in reinforced concrete, including the steel-concrete interface and induced cracking. The third point concerns an analysis of the impact of the crack opening on the transfer. To obtain a more relevant identification and characterization of the variation of permeability with the length of the steel-concrete interfaces in site conditions, all three studies were performed for various states of saturation.

3. Theoretical background

Permeability is defined as the ability of a material to allow fluids to pass through it under a pressure gradient. This property governs the flow rate of a fluid through a porous medium.

For the sake of simplicity, the "coefficient of permeability" is referred to simply as "permeability" in this article unless otherwise noted. The gas permeability of a porous solid is calculated using the Hagen-Poiseuille relationship for laminar flow of a compressible fluid through a porous medium with small capillaries under steady-state conditions. The relationship solved for the apparent permeability k_a can be written as in Eq. (1) [33].

$$k_a = \frac{2\mu L Q_O}{S}\frac{P_O}{P_I^2 - P_O^2} \tag{1}$$

where Q_O is the volume flow rate of the fluid (m^3/s), S is the cross-sectional area of the specimen (m^2), L is the thickness of the specimen in the direction of flow (m), μ is the dynamic viscosity of the fluid at the test temperature (Pa·s), P_I is the absolute inlet pressure (Pa), and P_O is the outlet pressure (the pressure at which the volume flow rate is determined, assumed in this test to be equal to atmospheric pressure – Pa).

For dried air at a temperature of 20 °C, the dynamic viscosity μ may be taken as 1.83×10^{-5} Pa·s.

4. Materials and methodology

4.1. Experimental setup

The permeability of porous materials can be evaluated through a gas flow measurement using a permeameter with constant head (the difference in pressure is fixed during the measurement) or variable head. In this study, a constant head permeameter was used. The apparatus is known as a Cembureau permeameter. The permeating medium was dried air. Fig. 1 gives an overview of the apparatus. The main elements are: an air supply cylinder fitted with a pressure reducing valve, a precision pressure regulator, a pressure gauge, the permeability cell, a flow meter and a computer to record the air flow.

In order to reach a precision of 1% in the determination of permeability, Kollek's specifications [33] were followed: the inlet pressure, P_I, to the cell was controlled over a range of absolute pressure from 2 to 5 bars (2×10^5–5×10^5 Pa) by the pressure regulator and the set pressure level was maintained within 1% of the selected pressure during the whole time of air flow measurement. The graduations on the pressure gauge were 5×10^{-2} bars (5×10^3 Pa). The permeability cells were sealed by a tightly fitting polyurethane rubber joint under a pressure of 8 bars (1.5 times the maximum inlet pressure) against the curved surface. So a pressure difference of up to 4 bars (4×10^5 Pa) could be applied to the specimens in the permeability cells.