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Experimental study of the material and bond properties of frost-damaged concrete

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ABSTRACT

In an extensive experimental investigation, several types of tests were conducted on a reference specimen and frost-damaged concrete. Two levels of internal frost damage were quantified by the relative dynamic modulus of elasticity and compressive strength. Test results showed a significant influence of freeze–thaw cycles on the compressive strength and even more influence on the modulus of elasticity and the compressive strain at peak stress. Reduced tensile strength and increased fracture energy were measured. From inverse analysis of wedge splitting test results, a significant effect of frost on the shape of the tensile stress–crack opening relationship was observed: tensile strength was reduced, while the post-peak behaviour was more ductile for the frost-damaged concrete. Pull-out tests showed the influence of freeze–thaw cycles on bond strength and slip. The pull-out test results are compared with similar tests available in the literature and the effect of frost on bond behaviour is discussed.

1. Introduction

One of the severe types of deterioration in concrete structures is associated with the volume expansion of concrete caused by freezing and thawing. When evaluating the residual load-carrying capacity of frost-damaged concrete structures by the finite element method, the effect of internal frost damage can be modelled as a change in material and bond properties [1]. Therefore the effect of frost damage needs to be quantified in terms of material and bond properties.

As the volume expansion of freezing water cannot be accommodated in the pore system of concrete, it is restrained by the surrounding concrete. Thereby, tensile stresses are initiated and micro and macro cracks are introduced into the concrete body, which leads to a type of damage known as internal frost damage. This mechanism affects the stress–strain relation in compression and tension, as well as compressive and tensile strengths, elastic modulus, fracture energy, and bond strength between the reinforcement and surrounding concrete in damaged regions [2]. Another type of frost damage, known as surface scaling, is caused by mechanisms involving the differing thermal expansion of ice and concrete [3]. This mechanism is involved when a concrete structure is subjected to cold climates in the presence of saline water. The present paper deals with the effect of internal frost damage on the material and bond properties of concrete; it does not include the effect of surface scaling.

Several research articles have been primarily concerned with the causes and mechanisms of frost deterioration, see [4–6]. However, very little attention has been given to the effect of frost damage on the material and bond properties of concrete. Zandi Hanjari [1] showed that the relations between compressive and tensile strength for undamaged concrete cannot be used directly for frost-damaged concrete. A stress–strain model relating to stiffness degradation of concrete subjected to the effect of freezing and thawing cycles has been proposed [7,8]. In their model, a freezing–thawing fracture parameter was introduced, in addition to the fracture parameter for mechanical loading, to express degradation in initial stiffness caused by micro-cracking during freezing and thawing exposure. Shih et al. [9] showed that cyclic temperature changes have a decisive influence on the maximum bond resistance of concrete subjected to monotonic and reversed cyclic loading. Experimental observation proved that the bond stress–slip relation before maximum bond stress is similar for damaged and undamaged concrete [10]. However, the bond capacity and slip at the maximum bond strength change significantly with frost damage [2]. To the authors' knowledge, there have been no tests made to experimentally investigate the stress–strain response of frost-damaged concrete in tension.

The experiments presented here were carried out to investigate the effect of frost damage on the material and bond properties of concrete. Therefore, the level of frost damage was quantified by the relative dynamic modulus of elasticity, calculated from ultrasonic measurements made on all specimens, and by the compressive strength of concrete. The change in microstructure of the concrete was visually observed by microscopic imaging; the distribution of cracks was investigated using image analysis of thin sections. The behaviour of frost-damaged concrete was evaluated in compression, by compression tests and elastic modulus tests, and in tension, by splitting tensile and wedge splitting tests. Crack propagation in wedge

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