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Review

A review of the impact of micro- and nanoparticles on freeze-thaw durability of hardened concrete: Mechanism perspective

Khashayar Ebrahimi, Mohammad Javad Daiezadeh, Mohammad Zakertabrizi, Farhad Zahmatkesh, Asghar Habibnejad Korayem *

School of Civil Engineering, Iran University of Science and Technology, Tehran, Iran

HIGHLIGHTS

- Additives can be used via four mechanisms to enhance concrete freeze-thaw durability.
- Despite strength reduction, air bubbles decrease water pressure within ice formation.
- Less permeability and better pore refinement is achieved by consolidation mechanism.
- Bridging effect provided by fibers and nanoparticles can control crack propagation.
- Applying hydrophobic admixtures could reduce the ice formation in internal surfaces.

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ABSTRACT

Frost resistance is an important factor that can affect the durability of structural concrete. This paper reviews previous studies on freeze-thaw resistance of concrete from the mechanism viewpoint. Observations have revealed that concrete additives can be utilized via different mechanisms to enhance concrete freeze-thaw durability. There are four mechanisms contributing frost resistance: (a) providing extra space for ice expansion in concrete using air bubbles, (b) reducing the porosity of concrete using pozzolans and fillers, (c) containing crack propagation using microfibers, nanotubes and nanosheets, and (d) decreasing water absorption using hydrophobic agents. Each mechanism has been discussed profoundly. However, future investigations are needed to provide a better insight into the grey areas, especially in nanoscale additives and hydrophobic concrete. Researchers should devote more investigations to integrate experiments and extract optimum conditions and dosages for the discussed additives.

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* Corresponding author.
E-mail address: ahkorayem@iust.ac.ir (A. Habibnejad Korayem).

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1. Introduction

In today's world, the construction industry is a considerable part of every economy. Every year, it consumes a huge proportion of available resources to construct infrastructures. The problem is that every year, old buildings that need to be maintained and repaired wastes a notable proportion of dedicated resources. In response, if we can succeed in prolonging the lifespan of structures, it will enable a revolution in resources management. Frost damage is a contributing factor in eventual rupture and erosion in concrete structures, especially in cold areas where continuous freezing and thawing causes cracks to spread and weakens the concrete to the point of failure.

Several theories have been proposed to explain the frost damage mechanism. The first theories held the expansion of freezing water into pores responsible for the surplus pressure. Collins [1] proposed another explanation in his ice lens formation theory; in this theory, ice crystals are assumed to grow in the direction of heat flow. Their growth continues until either the available water is depleted or the freezing is impossible; the latter is the cause of pressure on the surface of the voids. The repetitive process of freezing and thawing creates weak layers parallel to the cooling surface, which makes them more susceptible to the pressure created by the ice crystals. In the following years, as the positive effect of air voids was recognized, the hydraulic pressure theory [2] was developed by Powers. It mentioned the air voids as the only available space for water to freeze without damaging the structure. In order to reach this space, water must pass through the paste; a travel which is ruled by Darcy's law. According to which if the pressure required for water to travel a certain distance surpasses the tensile strength of the paste, it causes damage.

The hydraulic pressure theory was later completed into osmotic pressure theory [3]. The hydraulic pressure theory is now recognized to be invalid; as it is established that the freezing water tends to move to capillary pores, opposing to the water flowing from capillary pores assumed in the hydraulic pressure theory. The more complete osmotic pressure theory explains that with decreasing temperature, the water first begins to freeze in capillary pores, raising the concentration of dissolved chemicals, forcing water in smaller pores to travel to larger pores to reestablish the equilibrium. If the specimen is saturated, the mentioned process builds internal pressure which may damage the specimen, provided passed a certain level. Powers explained that the air voids compete with the larger pores in attracting water; since ice forms harmlessly on the walls of air voids, if they win the competition, the specimen survives through the frost damage. To address the gaps in Powers and Helmuth's theory of osmotic pressure, Litvan presented another theory [4]. He explained that the water in capillary pores did not freeze in situ; when the temperature drops below 0℃, water becomes supercooled and tends to travel to a surface to freeze which results in desiccation of the specimen. According to Litvan, damage is the result of the desorption process which happens when the concentration of water is much higher than it should be according to equilibrium. The air voids reduce the traveling distance to a freezing surface, thereby facilitating the process of desorption, permitting more water to leave the pores and protecting the specimen. To draw a conclusion from the mentioned theories, we can safely assume that pore refinement, transforming larger voids into evenly-distributed and smaller air voids can contribute to the frost resistance of the concrete.

As regards an assessment of the frost resistance, it is necessary to conduct the test by which the resistance of concrete to internal micro cracking can be calculated. This phenomenon is due to rapid freezing and thawing cycles. The test method is described in ASTM C 666 standard [5]. The C666 standard has defined three factors for durability assessment: Relative dynamic modulus of elasticity (RDME), Durability factor (DF) and Length change in percent, which have all been thoroughly introduced in the aforementioned standard. As a matter of fact, these parameters are important to understand how much additives should be used for better freeze-thaw achievement in concrete.

In the last decades, researchers have suggested various solutions for the frost damage problem; but above all, this weakness can be fixed by adding complementary additives ranging from micro sized additives to various types of nanoparticles. The effects from the mentioned additives can be categorized by their type, their scale and the mechanism by which they improve the freeze-thaw performance of concrete. Previous researchers, mainly focused on the substance: there are concentrated reviews on silica fume [6] and fly ash [7] separately focusing on each additive performance.

However, we review studies of the effect of additives on freeze-thaw resistance of hardened concrete and organize them by their mechanism. We provide a wide-range of review covering studies of the most common additives in concrete focusing on the mechanism by which they affect concrete. We categorize the additives based on their mechanism of action as (a) air entraining agents, (b) consolidation agents, (c) crack crosslinking additives, and (d) hydrophobic agents. The attributed mechanism to these additives are firstly providing extra volume for ice expansion to decrease hydraulic water pressure; secondly reducing porosity and refining concrete pores to decrease water absorption; thirdly bridging the cracks to prevent crack propagation, and finally altering concrete hydrophilicity to limit water presence in concrete. The differentiation not only means that each group is just limited to the main mechanism, but also it highlights the main approach which the concrete is improved by the additive. The paper concludes with recommendations for future research needs.

2. Providing extra space for ice expansion using air bubbles

The first approach to enhance the freeze-thaw properties of concrete is to induce small disconnected voids in the concrete matrix in order to increase the flexibility of the concrete. Development of air entrained concrete is one of the greatest advancements in concrete technology. Air entrainment involves the incorporation of small air bubbles into the concrete mix so that the concrete contains tiny air bubbles uniformly distributed throughout the cement paste. The air void system was studied by using three parameters: the bubble size, the space factor and the pore size distribution, it was established that among these parameters pore size distribution is more important [8–10]. According to Power's definition, the space factor is the maximum distance between two air void bubbles in concrete. To stabilize the air entrapped, air-entraining admixture (AEA) is used and it has been found that the chemical nature of AEAs influences its performance. The main reason for using air-entrained concrete is to develop strength of the concrete when it is exposed to alternating freezing and thawing cycles [10]. In this case, the entrained air bubbles reduce the hydraulic pres-