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Crack control in concrete walls through novel mixture design, full-scale testing, and finite element analysis

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HIGHLIGHTS

- Novel mixtures including crystalline PRA showed excellent strength performance.
- Use of fibers showed acceptable workability during field placement.
- The mixture containing the PRA showed the lowest hydraulic conductivity.
- The novel mixtures resulted in a significant reduction in the heat of hydration.
- Greatest thermal strains will occur in the lower third of the wall.
- HoH has the greatest effect on cracking potential of cast-in-place walls.

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ABSTRACT

The research evaluates novel concrete mixtures, including crystalline admixtures, coarse ground calcium carbonate, and macro/micro-fibers, for use in basement walls that satisfy the International Residential Code with a reduction in reinforcement. The experimental investigation proved the mixture exceeds the 28-day design strength within 7 days of age with excellent long-term strength gain. Addition of the crystalline permeability-reducing admixture was found to reduce the rapid chloride permeability and hydraulic conductivity. To validate the applicability of the respective mixtures, a nonlinear finite element analysis was developed to estimate thermal stresses and cracking at the basement walls when subjected to environmental loads and thermal gain from the heat of hydration. It is concluded through the experimental and numerical efforts that the novel mixtures are capable of mitigating thermal and early-age shrinkage cracks.

1. Introduction

It is expected that the U.S. housing market will grow 7% in total households during the next five years [1]. With this potential economic opportunity, it is advantageous to develop innovative methods of constructing more economical homes. As a result, it is beneficial to evaluate concrete mixtures for basement walls that can provide equivalent water-tightness to that of current installation methods and have the potential to decrease the required area of temperature and shrinkage steel. Thus, this research seeks to establish the behavioral characteristics of novel concrete mixtures through modeling and analysis of basement walls using the finite element method.

Section 406 – Foundation Waterproofing and Damp-proofing of the 2015 International Residential Code (IRC) requires foundation walls that retain earth and enclose interior spaces and floors below grade to be damp-proofed from the higher of (a) the top of the footing or (b) 6 in (15 cm) below the top of the basement floor up to the finished grade [2]. Parging is generally applied to the exterior of the wall to provide this waterproof membrane. Per IRC406.1 and IRC406.2, the parging must be damp-proofed or waterproofed in accordance to one of the approved methods within the standard that typically include products such as bituminous coatings, surface-bonding cements, polyvinyl chloride, polymer-modified asphalt, among others. Further, there are requirements for lapping and sealing the waterproof membrane across joints.

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Tables IRC 404.1.2(1), (2), (3), and (4) provide minimum horizontal and vertical reinforcement for walls of varying thicknesses and unsupported heights. The horizontal bars and spacing are specified based on the overall height of the wall and falls within two conditions. Additionally, the tables prescribe the bar sizes and spacing for vertical reinforcement based on wall height, backfill, and soil classifications with patterns confined as #6 reinforcing bars spaced at 15 in. (38 cm) on-center (o.c.) to a more open pattern of #5 bars at 48 in. (121 cm) o.c.

This paper is aimed at utilizing novel concrete mixtures including crystalline permeability reducing admixtures (PRAs) and coarse ground calcium carbonate (GCC), and macro/micro-fibers that improve the overall performance of conventional residential concrete basement walls. The incorporation of crystalline PRAs, GCC, and fibers are shown to result in mixtures with a reduced heat of hydration that produce little-to-no early age cracking as a result of the thermal load and improved strength characteristics. Through the utilization of experimental concrete batching, large-scale field testing, and a coupled thermal-mechanical non-linear finite element analyses, experimental design mixtures are shown to effectively reduce water intrusion to indoor spaces and decrease reinforcing steel. The delivered final solution is holistic in that it considers each critical aspect of basement wall design to prevent thermal and early-age cracking.

2. Background

The IRC provides design and construction guide specifications for essential structural, mechanical, and electrical components of residential homes. Chapter 4 of the IRC details the minimum requirements for residential foundation and wall design and the influential variables that control design outcomes: compressive strength of structural concrete, load-bearing pressure of soil, and unbalanced backfill. In addition to the geometries of footings and wall systems based on unbalanced backfill, the code concurrently specifies the needed ratio and maximal spacing of reinforcing steel and general waterproofing practices. The design assumptions for concrete walls and footings, found in Section 404.1.4.2 of the code, is essential to assessing the applicability of the provided design for a particular installation. For example, the code requires that the limits of design applicability include a maximal backfill height of 4ft (1.2 m) but walls systems often are subjected to higher active soil pressure and significant hydrostatic pressure depending on the drainage of the soil, questioning their global applicability [2]. Section 406 details the requirements associated with damp-proofing and waterproofing of masonry and concrete foundations and singularly lists topical solutions to prevent water intrusion into interior spaces, when previous research suggests that imbedded waterproofing agents provide a more effective solution to reducing the cause of water migration into homes.

In 1994, Day established that moisture migration through basement walls can be generally traced to three general phenomena: hydrostatic pressure, capillary action, and a water vapor pressure differential between the exterior and interior of a space [3]. In a 1997 publication on concrete floor slabs, Day further identified that without consideration of a fluctuating water table, sub-slab flooding could potentially occur and stated that there is a need for contractors to consistently implement a sub-slab drainage system of coarse gravel [4]. A decade later, Stuart Edwards [5] of Verdant Energi and Environment published a keystone article in ASCE's Fourth Forensic Engineering Congress discussing the need for holistic and first-principle based design and construction practices with respect to basement walls, foundations, and slabs. In addition to identifying root causes of common failures, Edwards also identified that homes with leaking or cracked basement walls can result in 30% reduction in a home's equity. Using case studies as a primary method of validation, Edwards details that the longevity of a basement wall and foundation are not only dependent on designing for increased hydrostatic pressure from a rising water table, mirroring Day's 1997 claim, but also construction related processes, such as grading. In short, Edwards makes a clear claim that there is soon to be a leaking-basement wall "epidemic" in the United States for homes on the range of 20–40 years of age that can result in expensive repair costs for homeowners due to implementation of old structural code and poor construction practice [5].

In 2014, Mendes et al. identified and discussed the current problems associated with bituminous or geo-membranes to waterproof concrete foundations resulting from a lack of empirical data on their use and success [6]. Any waterproofing agent or membrane must be able to withstand the punching resistance and stress cracking often found in foundations while still displaying high flexibility to conform to the geometry of the sub-structure. In addition to the complex mechanical performance required of a waterproofing coating systems, it is recognized that product quality varies from manufacturer-to-manufacturer and labor-induced perforation is known to be a main cause of failure. Often, sodium bentonite, a clay that displays high swelling, is used in accompaniment of membrane system due to its crack-filling characteristics and to reduce the uncertainty of the coating system's performance [6].

Rather than solely relying on surface alterations or treatments for water permeability through concrete, admixture suppliers have developed integrated waterproofing technologies as stock products to prevent water and other suspended particles from transiting through a hardening concrete paste matrix. There are three essential types of permeability reducing admixtures (PRAs): densifier, repellant, and crystalline. Densifier PRAs are typically supplementary cementitious materials, such as silica fume or clays, and pack the paste matrix reducing the total porosity and permeability of the concrete. Repellant PRAs utilize hydrophobic materials that force water to stay on the surface of a concrete placement. Lastly, crystalline PRAs react with water permeating a concrete placement and the remaining hydration products such as calcium hydroxide. Crystalline PRAs generate new hydration products that fill already existing micro-pores and cracks in the hardened paste matrix. Within the concrete industry, densifying and repelling PRAs are utilized in scenarios where a concrete placement is not exposed to hydrostatic head. Crystalline PRAs are generally accepted to be a long-term solution when concrete structures are subjected to pressure as a result of hydraulic head [7].

Although integrated waterproofing admixtures reduce the permeability of a concrete placement, the structural components must still be designed with engineering and construction best practices as water can enter interior spaces through construction joints or large cracks. Previous work has been carried out to increase the tensile capacity of concrete through the use of different scale fibers and to better understand the influence of early-age thermal development on cracking. The findings of many of these studies have been translated into numerical models to improve the predictive structural performance of monolithic and reinforced concrete placement.

The use of ground limestone as a partial replacement of cement has been used for many decades in Europe and more recently in Canada and the United States [8]. ASTM C 150 was modified in 2004 to allow a 5% mass fraction of limestone in ordinary portland cement. Limestone percentages up to 15% have been utilized in more recent years. Tsivilis et al. observed equal or improved strength performance when 15% calcium carbonate limestone was incorporated into the cement/limestone blend [9]. Further, Tsivillis et al. found that mixtures incorporating the ground cal-