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Simulation of expansion in cement based materials subjected to external sulfate attack

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Abstract The standard test for length change in hydraulic-cement mortars exposed to sulfate solution, ASTM C1012-95, has been widely used by researchers to study the sulfate resistance of cement based materials. However, there are deficiencies in this test method including lengthy measuring period, insensitivity of the measurement tool to sulfate attack, effect of curing and pH change. So, in this study, a model will be built by artificial neural networks (ANNs) to simulate this test and overcome these defects. This model will deal with different types of cement in the presence of blast-furnace slag (GGBFS) or fly ash (PFA). From the results of simulations, it is possible to understand the impact of cement chemistry and these two types of additions on resistance of sulfate attack more readily, faster, and accurately. Such an understanding improves the decision making process in every stage of construction and maintenance and will help in better administration of resources.

1. Introduction

The first approaches to characterizing sulfate attack were undertaken back in the 1920s by Thorvaldson, wherein the chemical interactions of Portland cement components in water and solutions of alkali salts were studied. He proposed simple approaches and practical methods for carrying out these tests and formulated remedies as a direct result of his investigations. Thorvaldson recognized that a cure might be affected through a modification of the chemical composition of Portland cement. He also stipulated that calcium trisulphoaluminate, better known as ettringite, is a typical product of the reaction between hydrated C_3A and Na_2SO_4 solutions at all concentrations and $MgSO_4$ solutions at low concentrations [1].

As early as 1890, Candlot had associated the formation of ettringite crystals with concrete expansion. It was then known as the "cement bacillus" [2]. Nearly forty years later, Thorvaldson explored this phenomenon as the basis for developing the mortar bar expansion test in order to correlate the chemical and microstructure changes with the behavior of concrete exposed to sulfate solutions. The findings from Thorvaldson's works provided new beneficial outlooks in the cement industry widened the understandings of cement chemistry and improved the notion of concrete durability [3].

Alumina-bearing phases and calcium hydroxide (CH) are more vulnerable to sulfate attack than other elements present

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in hydrated Portland cement. The sulfate ions react with CH and calcium aluminates hydrate (CAH). The products of reactions are gypsum and calcium sulphoaluminate (ettringite) has a considerably greater volume than the compounds that replace. Thus, the reactions with sulfate lead to expansion cause internal stresses lead to disruption of the concrete. The mechanism of expansion can be considered as, increase in solid volume, expansion in a topochemical reaction, oriented crystal growth, crystallization pressure, swelling phenomena, osmotic pressure, and reversal of local desiccation. Also, the primary manifestations of sulfate attack in cementitious materials visible to the naked eye include spalling, delamination, macrocracking, and possibly loss of cohesion [4,5].

On the other hand, the available performance tests for evaluating sulfate resistance are the rapid mortar bar test, ASTM C 452 "standard test method for potential expansion of Portland cement mortars exposed to sulfate" and ASTM C1012-95 "standard test method for length change in hydraulic-cement mortars exposed to sulfate solution" [6–8]. The first test, ASTM C 452, was originally published and approved by American society for testing and materials (ASTM C01.29), the subcommittee for sulfate resistance, in 1960. The test method involves the measurement of expansion of mortar bars made from a combination of Portland cement and gypsum. The gypsum increases the amount of ettringite produced in the fresh and hardened concrete and accelerates the reactions typical of sulfate attack. ASTM C01.29 recommends limits of 0.06% expansion at 14 days for moderate sulfate-resistant Type II cement and 0.04% expansion at 14 days for severe sulfate-resistant Type V cements.

The major advantage of ASTM C 452 is the short duration of test. The major disadvantage of the test is that it has shown to be inaccurate when used for testing mortar made with blends of cement and a mineral admixture. The first problem is that the blended cement does not develop enough maturity in the 14 day measured expansion period. Secondly, the test does not represent field conditions because the gypsum incorporated into the mix exposes the mortar to sulfate attack in its fresh state before hydration has even occurred. These flaws in the test have led researchers to limit the scope of ASTM C452.

In 1984, ASTM subcommittee Co1.29 began researching the development of a new performance test that would be applicable to blended hydraulic cement. The result of this work was the formation and standardization of the mortar bar test ASTM C 1012-95. Sulfate exposure is provided by immersing the mortar bars into a sulfate solution after the mortar has reached certain strength. The test criterion requires a maximum expansion limit of 0.1% at 180 days of sulfate solution exposure for moderate sulfate resistance and a limit of 0.05% at 180 days for sever sulfate resistance. However, there are deficiencies in this test method, including lengthy measuring period, insensitivity of the measurement tool to the progression of sulfate attack, the effect of curing especially in the case of mineral admixture, and the effect of pH change during the time in the solution. In addition to all this, there is the cost factor.

Recently, some researches on the ANN in data processing are introduced in the field of durability, and they are very efficient compared with simple regression method from experimental data. In area of research on concrete, ANN technique is mainly applied to mixture design [9,10], strength evaluation [11,12], and reaction of hydration [13,14]. Dias and Pooliyadda [15] used back propagation neural networks to predict the strength and slump of ready mixed concrete and high strength concrete (HSC), in which chemical admixtures and mineral additives were used. According to the authors, the ANN models also performed better than the multiple regression ones, especially in reducing the scatter of predictions [15].

Oztas et al. [16] studied with the ANN for developing a methodology for predicting compressive strength of HSC with suitable workability. They arranged to the data used in ANN model in a format of seven input parameters that cover the water-to-binder ratio, water content, fine aggregate ratio, fly ash content, air entraining agent content, and silica fume replacement. The proposed ANN model predicts the compressive strength and slump value of HSCs [16].

Pala et al. [17] focused on studying the effects of PFA and silica fume (SF) replacement content on the strength of concrete cured for a long-term period of time by using ANN. The model arranged was composed of eight input parameters that cover PFA replacement ratio, SF replacement ratio, total cementitious material, fine aggregate, coarse aggregate, water content, high rate water reducing agent, and age of samples, while an output parameter that is compressive strength. The authors explained that ANNs have strong potential as a feasible tool for evaluation of the effect of cementitious material on the concrete compressive strength [17].

The ultimate goal of this study is the use of ANN to create a model simulates the ASTM C1012-95 standard test and overcome his flaws. Then, it can be used in analyzing the behavior of PFA and GGBFS and their impact on the different types of cement to resistance sulfate attack. Also, use this model as a quick guide for an engineer to make a decision in the quality of the cement used in the presence of two types of mineral additions.

2. Experimental program

2.1. Materials and mix proportions

Four commercially available Portland cements were evaluated in this testing program as Type I, Types II (A and B), and Type V cement, which contain 12%, 5.1%, 7%, and 0% C_3A, respectively. Chemical and mineralogical component of cements is provided in Table 1. The fine aggregate used for making the mortar was a graded sand meeting the requirements of ASTM C778-97 [18]. The sand has a specific gravity of 2.65 and an absorption capacity of 0.5%. Two different types of mineral admixture were chosen. PFA to replace 20% and 30% and GGBFS to replace 50% of the cement were used. The chemical analyses of the mineral admixtures are shown in Table 2.

Clean tap water with a constant w/c ratio of 0.485 was used in mortar mixing, where it is recommended that the water to cementations material ratio produce a flow number within the range of 110 ± 5. But in case of mortars with mineral admixture ASTM C1012-95 stats, the water to cementations material ratio shall develop a flow within ± 5 of the flow number found for the mortars with cement only. The mix proportioning consisted of adding one part of cement to 2.75 parts of graded standard sand by weight: 265 kg/m^3 water, 532 kg/m^3 cement, and 1456.5 kg/m^3 sand. Sixteen different mixes were used in practical program, description, mix condition, and