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Analysis of sulfate resistance in concrete based on artificial neural networks and USBR4908-modeling

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Abstract One of the available tests that can be used to evaluate concrete sulfate resistance is USBR4908. However, there are deficiencies in this test method. This study focuses on the ANN as an alternative approach to evaluate the sulfate expansion. Three types of cement combined with FA or SF, along with variable W/B were study by USBR4908. ANN model were developed by five input parameters, W/B, cement content, FA or SF, C_3A, and exposure duration; output parameter is determined as expansion. Back propagation algorithm was employed for the ANN training; a Tansig function was used as the nonlinear transfer function. It was clear that the ANN models give high prediction accuracy. In addition, The engineer can avoid the use of the borderline 2.5–5% C_3A content in severe sulfate environments and borderline 6–8% C_3A content in moderate sulfate environments, specially with W/B ratio greater than 0.45.

1. Introduction

The obvious benefits of mineral admixtures are the reduction in concrete permeability and the replacement of the Portland cement. Lowering the permeability slows the penetration of sulfate ions into hardened concrete while replacing the Portland cement with mineral admixture reduces the presence of compounds such as C_3A that cause ettringite formation. The mineral admixtures most frequently examined for use in sulfate environments include FA, SF, and blast furnace slag (GGBFS). The five chemical and mineralogical components of FA which affect sulfate resistance are calcium, alumina, iron oxide, silica, and sulfate. The calcium content is the most important of these five components. Low calcium, pozzolanic FA (Class F) is described as pozzolanic because they primarily hydrate by reacting with the calcium hydroxide (CH) formed from the hydration of Portland cement. High calcium, pozzolanic and cementitious FA (Class C) is cementitious because they can provide their own source of calcium and thus hydrate independent of the Portland cement [1,2].

As the industry of concrete repair grows it has become critical that engineers emphasize durability and long-term performance in all new construction. Specifications need to be developed to ensure new materials, technologies, and construc-

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tion practices can be utilized to produce high quality, long-lasting concrete structures. Currently, engineers are limited by the same parameters and guidelines that were developed several years ago. Under today's specifications, if an engineer needed a low permeability concrete to ensure durability in a severe environment, this need would be addressed by keeping the mix design water-to-cementitious material ratio below a specified maximum value [3].

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", ASTM C1012-95 "standard test method for length change of hydraulic-cement mortars exposed to sulfate solution" and USBR 4908 "procedure for length change of hardened concrete exposed to alkali sulfates" [4–8].

ASTM C 452 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 subcommittee C01.29 recommends limits of 0.06% expansion at 14 day 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 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.

Both tests, ASTM C 452 and ASTM C 1012-95, are evaluating the resistance of mortar to sulfate attack and not the actual concrete. The United States Bureau of Reclamation (USBR) has provided the standardized test, USBR4908, procedure for length change of hardened concrete cylinder, instead of mortar bar, exposed to alkali sulfate.

The USBR4908 test procedures provide three methods in which the type of soaking is varied for each method. Method A involves continuous curing of cylinders in a 2.1% Na_2SO_4 solution, method B involves continuous immersing in a 10% Na_2SO_4 solution, and method C is a wetting/drying test where the cylinders are alternately soaked for 16 h in a 2.1% solution and then dried for 8 h under a forced air draft of 54 °C. Method B and the wetting/drying method C are equally rigorous test while method A requires more time to show deterioration. Method B was found to be a true accelerated test with no apparent irregularities in the mechanisms of sulfate attack. Even for the more rigorous methods, the USBR4908 test requires at least 1–2 years before any significant results can be obtained. There are currently no widely accepted expansion limits or mass change limits that go along with this procedures. The main advantage of the USBR4908 test is its flexibility. It can be used to evaluate effects of permeability, mineral and chemical admixtures, and other mix design alternatives as well as various curing procedures on the sulfate resistance of concrete.

However, there are deficiencies in this test method including lengthy measuring period (usually more than 1 or 2 year), 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 the pH change during the time in the solution [9,10]. Moreover, it is difficult to obtain expansion from experiments due to time and cost limitations.

Recently, some researches on the neural network in data processing are introduced in the field of durability and they are very efficient compared with simple regression method from experimental data. This is because, the ANN technique use nonlinear transfer function, in addition the testing process is included in the optimization of ANN. In area of research on concrete, a neural network technique is mainly applied to concrete properties evaluation [11], mixture design [12,13], strength evaluation [14,15], reaction of hydration [16,17], and estimation of sulfate expansion [18]. In this study, the artificial neural network approach, which is mainly utilized in mixture design and strength evaluation, is applied for estimation the expansion in USBR4908, concrete cylinders test, considering various parameters in mixture design.

2. Experimental program

2.1. Materials and mix proportions

Three commercially available Portland cements were evaluated in this testing program as Type I, Types II, and Type V cement. Chemical and mineralogical composition has been determined by ASTM C 114 "Standard Test Methods for Chemical Analysis of Hydraulic Cement" and XRD-determined compositions, respectively. Chemical and mineralogical composition for the three cements is provided in Table 1. The Type I cement has no ASTM C150 limit for C_3A content; thus, the high 12% value is acceptable. The Type II cement has a C_3A content of 7%. This value is considerably lower than the ASTM C150 maximum limit of 8% for Type II cement and is above the 5% limit required for Type V cements. Finally, the Type V cement meets the C_3A content limit of 5% for sulfate-resistant cement because the cement contains zero C_3A.

The fine aggregate used for concrete cylinders was a graded sand meeting the requirements of ASTM C778-97 [19]. The sand has a specific gravity of 2.65 and an absorption capacity of 0.5%. Natural gravel coarse aggregates with maximum aggregate size of 19 mm were considered. The characteristics of the used coarse aggregates are presented in Table 2. Clean tap water with a variable W/B ratio of 0.35, 0.45, and 0.55 was used in concrete mixing. Two different types of mineral admixture were chosen in mixes. FA to replace 20% and 30% and SF to replace 10% and 20% of the cement were used. The blain fineness as the product specific was 420 m^2/kg and 15,000 m^2/kg, respectively. The chemical analyses of the mineral admixtures are shown in Table 3.

All mixes have a slump value in the range of 102–204 mm (4–8 in.). This is difficult for the 0.35 water to cement ratio