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FULL LENGTH ARTICLE

Simulating USBR4908 by ANN modeling to analyse the effect of mineral admixture with ordinary and pozzolanic cements on the sulfate resistance of concrete

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Abstract One of the available tests that can be used to evaluate the sulfate resistance of concrete is a procedure for length change of hardened concrete exposed to alkali sulfates (USBR4908). However, there are deficiencies in this test method including a lengthy measuring period, insensitivity of the measurement tool to the progression of sulfate attack. Moreover it is difficult to obtain experimental expansion due to time and cost limitations. A reasonable prediction for the expansion in USBR4908 is basically required. This study focuses on the artificial neural network (ANN) as an alternative approach to evaluate the sulfate resistance of concrete. A total of 273 different data for three types of Portland cement combined with fly ash (FA) or silica fume (SF) concrete mixes, along with different w/c ratios of 0.35, 0.45 and 0.55 were collected from the experimental program. ANN models were developed. The data used in the ANN model consisted of five input parameters which include W/B ratio, cement content(CC), FA or SF content, tricalcium aluminate content (C_3A), and exposure duration (D). Output parameter is determined as expansion (E). Back propagation (BP) algorithm was employed for the ANN training in which a Tansig function was used as the nonlinear transfer function. Through the comparison of the estimated results from the ANN models and experimental data, it was clear that the ANN models give high prediction accuracy. In addition, the research results demonstrate that using ANN models to predict the expansion in concrete cylinders is practical and beneficial.

Introduction

The obvious benefits of mineral admixtures are the reduction in concrete permeability and the replacement of Portland cement. Lowering the permeability slows the penetration of sulfate ions into hardened concrete while replacing Portland cement with a mineral admixture reduces the presence of

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compounds such as C_3A that causes 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) are cementitious because they can provide their own source of calcium and thus hydrate independent of 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 constructions. Specifications need to be developed to ensure new materials, technologies, and construction practices can be utilized to produce high quality, long-lasting concrete structures. Currently, engineers are imited by the same parameters and guidelines that were developed several years ago.

Under today's specifications, if an engineer needed 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 the potential expansion of Portland-cement mortars exposed to sulfate", ASTM C1012-95 "standard test method for length change of hydraulic-cement mortars exposed to the 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. 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 the 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 the test. The major disadvantage of the test is that it was 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 a 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 severe 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, USBR 4908, 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 tests 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 these 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 1/2 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].

Recently, some researches on the neural network in data processing are introduced in the field of durability and they are very efficient compared with the simple regression method from experimental data. In the area of research on concrete, a neural network technique is mainly applied to mixture design [11,12], strength evaluation [13,14] and reaction of hydration [15,16].

In this study, the artificial neural network approach, which is mainly utilized in mixture design and strength evaluation, is applied for the estimation of the expansion in USBR4908, concrete cylinders test, considering various parameters in mixture design.

Experimental program

Materials and mix proportions

Three commercially available Portland cements were evaluated in this testing program as Type I, Type II and Type V cements. Chemical analyses for the three cements are 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 [17]. The sand has a specific gravity of 2.65 and an absorption capacity

Table 1 Chemical and mineralogical components of cements, wt.%.

Cement type (ASTM C150)	Oxides											
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	LOI	IR	C_3S	C_2S	C_4AF	C_3A
I	20.6	5.07	2.9	63.9	1.53	2.53	1.58	0.16	61	14	6	12
II	20.9	4.5	3.2	61.5	1.4	3	1.3	0.15	54	25	4.5	7
V	21.86	3.18	5,66	60	0.75	1.3	0.67	0.17	54.2	22	7	0

Table 2 Characteristics of the used coarse aggregates.

Specific weight	Bulk density (t/m^3)	Water absorption (%)	Crushing value %	Coefficient of abrasion	Clay and fine dust content (% by volume)
2.9	1.82	0.69	14.3	5.4	0.55

of 0.5%. Natural coarse gravel aggregates with a maximum aggregate size of 19 mm were considered. The physical properties of the coarse aggregates are presented in Table 2. Clean tap water with a variable *w*/*c* ratio of 0.35, 0.45 and 0.55 was used in concrete mixing. Two different types of mineral admixtures were chosen in mixes. FA to replace 20% and 30% and SF to replace 10% and 20% of the cement were used. The blaine 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. This is difficult for the 0.35 water to cement ratio mixes because of the medium level cement content and low water to cement ratio, which led to low water content and an extremely dry mix. A high range water reducing HRWR admixture was used for some of the mixes in this program.

Twenty-one concrete mixes according to USBR4908, nine plain Portland cement concrete and twelve concrete mixes,

Table 3 Chemical analysis of mineral admixtures, wt%.

Mineral admixture	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	S	LOI	Specific gravity
FA	58.72	24.86	4.94	4.56	1.57	0.21	–	0.25	2.16
SF	93.5	0.15	0.1	0.8	0.15	0.5	1.3	2.5	2.22

Table 4 Outlines the mix proportions of concrete mixes.

Batch details				Aggregate moisture contents		Mix proportions (kg/m^3)					
Batch name	Cement type	Fly ash (% rep) silica fume	*W*/*B* (by weight)	C.A (%)	F.A (%)	% of HRWR as wt. of cement	Water	Portland cement	FA or SF	F. A	C.A
PC1-1	I	Non	0.35	0.34	1.53	0.9	116	335	0	855	1069
PC1-2	I	Non	0.45	1.26	3.37	0.42	127	335	0	835	1069
PC1-3	I	Non	0.55	1.26	3.37	0	170	335	0	800	1059
PC2-1	II	Non	0.35	0.34	1.53	0.6	116	335	0	855	1059
PC2-2	II	Non	0.45	0.42	1.88	0.12	149	335	0	824	1063
PC2-3	II	Non	0.55	0.74	2.43	0	176	335	0	793	1083
PC5-1	V	Non	0.35	0.32	0.9	1	121	335	0	850	1058
PC5-2	V	Non	0.45	0.28	1.56	0.3	152	335	0	821	1058
PC5-3	V	Non	0.55	0.5	1.15	0	189	335	0	784	1058
2FA-11	II	(20)	0.35	0.34	1.91	0.9	108	269	55	885	1071
2FA-12	II	(20)	0.45	0.35	1.84	0.12	144	269	55	851	1071
2FA-13	II	(20)	0.55	0.35	1.84	0	178	269	55	818	1071
2FA-21	II	(30)	0.35	0.26	1.17	1.1	114	237	81	886	1069
2FA-22	II	(30)	0.45	0.24	0.95	0.12	151	237	81	853	1069
2FA-23	II	(30)	0.55	0.24	0.95	0	180	237	81	822	1069
2SF-11	II	(10)	0.35	0.28	1.34	0.9	112	295	25	885	1071
2SF-12	II	(10)	0.45	0.27	1.2	0.22	149	295	25	850	1071
2SF-13	II	(10)	0.55	0.27	1.2	0	182	295	25	820	1071
2SF-21	II	(20)	0.35	0.18	1.57	1.1	108	269	55	882	1070
2SF-22	II	(20)	0.45	0.26	0.82	0.4	149	269	55	854	1070
2SF-23	II	(20)	0.55	0.25	2.11	0	176	269	55	822	1070

F.A, C.A = fine and course aggregates. FA, SF = fly ash, silica fume.

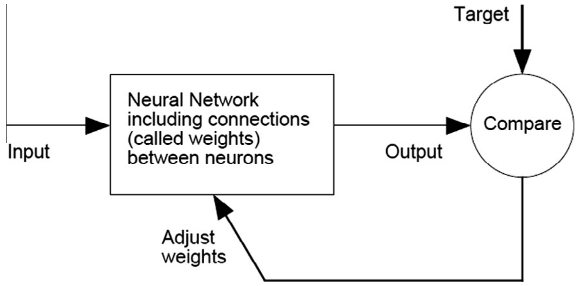

Fig. 1 Outline of simple neural network architecture.

containing various dosages of FA and SF, with 63 concrete cylinders specimens, 273 length measurements at various ages were considered. Description, mix condition, batch name, and fresh properties of all mortars are shown in Table 4.

The specimens required for USBR4908 are 76 × 152 mm cylinders for expansion measurements along with mass loss and 100 mm cubes for compressive strength and permeability tests. Concrete cylinders were made along with 132 cubes from each batch. Steel molds were used for casting all the cube specimens except the cylinder; single use plastic molds were used.

Techniques and procedures

The specimens were cured following the guideline established in the USBR4908 Method B procedures. 10% sodium sulfate (Na_2SO_4) solution can be used for sulfate exposure. The specimens remained at room temperature until a concrete compressive strength of 24.1 Mpa or more was reached. When this strength was established, all sulfate exposure cylinders were removed from the curing tank and immersed in a sulfate solution.

In this test program, upon reaching the strength of 24.1 MPa, the initial length of concrete cylinder specimens was measured; length measurements were made using a length comparator following the procedures of ASTM C490. A 30-cm reference bar made of a low coefficient of thermal expansion steel alloy was used to set the gage on the comparator to zero. The sodium sulfate solution was prepared at least one day before use. Twelve length measurements were taken for each batch. Initial measurements are required every month for 6 months and then every three months thereafter. The final measurements should be two years after the initial measurements were taken. Solution was replaced and containers were cleaned during each measurement to ensure a pH below 9.75 for the sulfate environment.

The porosity was determined to evaluate the degradation and the changes in the pore structure of the concrete specimens. The test was carried out on 100 mm concrete cubes at 28 days, and after exposure to sulfate solution at all ages mentioned before. The specimens were weighed in saturated-surface-dry condition "W_1" and then oven dried at 105 °C for 24 h. The values of oven-dried weight of specimens "W_2" and volume were measured. The porosity was then calculated using Eq. (1). The average results of triplicate specimens are as follows [18]

$$\text{Porosity, } \% = [(W_1 - W_2)/V] \times 100. \tag{1}$$

Water absorption by capillary action at 28 days was also measured before and after exposure to the sulfate solution to evaluate the degradation of surface layers. The test was carried out using a plastic container filled with water up to a depth of 20 mm. Steel bars of 18 mm diameter were placed at the

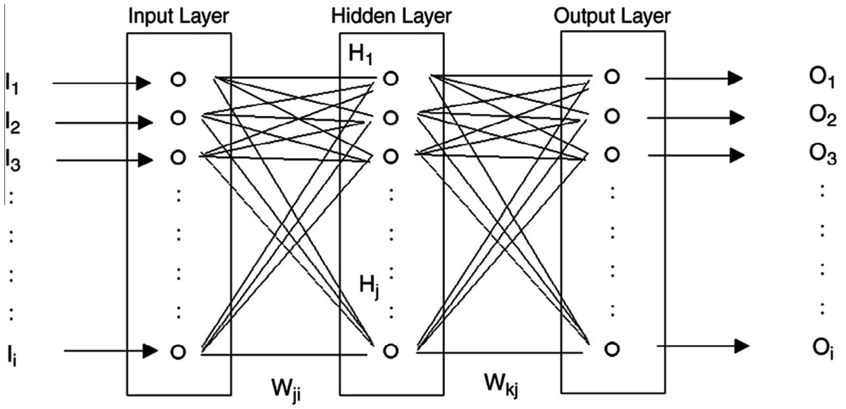

Fig. 2 Outline of simple neural network architecture.

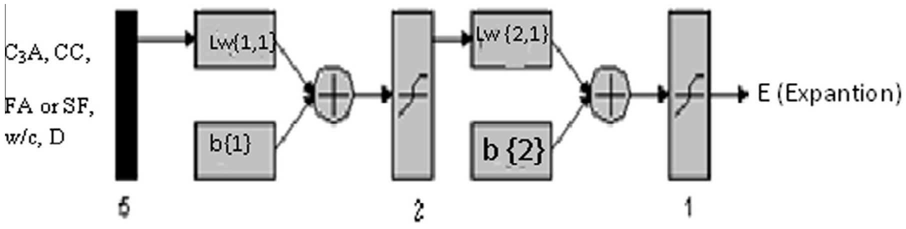

Fig. 3 The model designed by the network of ANN.

bottom of container to maintain the water level to just above the top surface of the steel bars. The oven dried specimens were weighed "W_2" after greasing and placing in the container over the steel bars for two hours such that the water level in the container was not more than 5.0 mm above the surface. The specimen was taken out from water and the surface water was removed using a damp cloth. The weight of the specimen was then recorded as "W_3", followed by estimating the % of surface absorption using Eq. (2). The average results of triplicate specimens are as follows.

$$\text{Water absorption, } \% = [(W_3 - W_2)/W_2] \times 100. \tag{2}$$

Spalling (loss of mass) was carried out on 76 × 152 mm cylinder specimens. The cylinders were weighed in saturated-surface-dry condition before exposure to sulfate solution "W_1" while "W_2" is the weight of cylinder specimens after exposure to the sulfate solution at all ages of expansion measurement. The spalling was calculated as in Eq. (3)

$$\%\text{of spalling} = (W_1 - W_2)/W_1. \tag{3}$$

Estimation of expansions with neural network algorithm

Artificial neural networks (ANN) are composed of simple elements operating in parallel. These elements are inspired by biological nervous systems. As in nature, the network function is determined largely by the connections between elements. We can train a neural network to perform a particular function by adjusting the values of the connections (weights) between elements. Commonly neural networks are adjusted, or trained, so that a particular input leads to a specific target output. Such a situation is shown in Figs. 1 and 2. There, the network is adjusted, based on a comparison of the output and the target, until the network output matches the target [19–21].

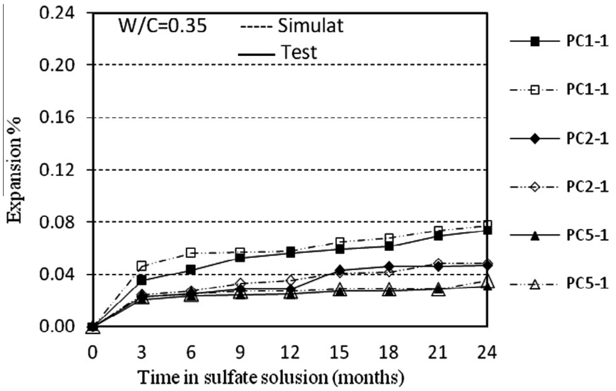

Fig. 4 Sulfate expansion of three types of cement with 0.35 *w/c*.

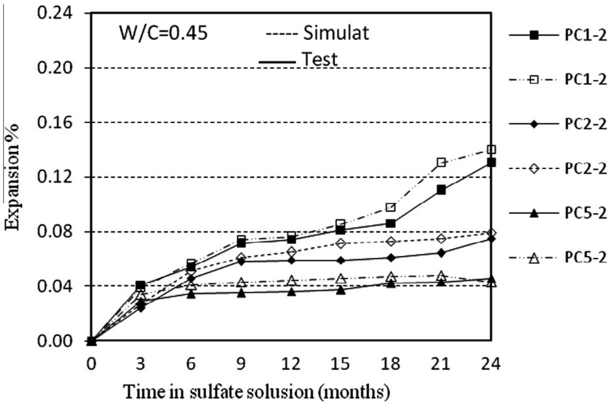

Fig. 5 Sulfate expansion of three types of cement with 0.45 *w/c*.

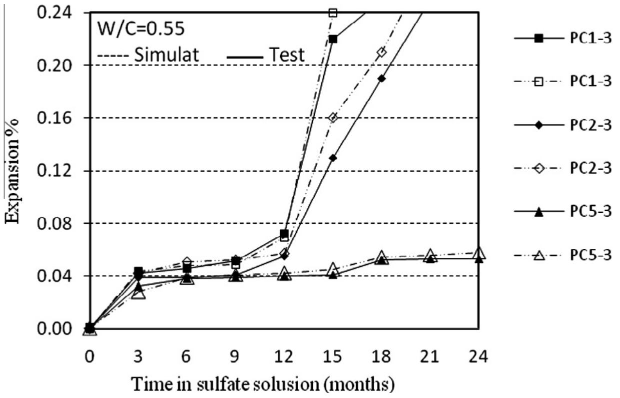

Fig. 6 Sulfate expansion of three types of cement with 0.55 *w/c*.

Five input parameters that were used to build and train the model namely, (C_3A), cement content (CC), replacement level of FA or SF, *w/c* ratio, and age of the measuring (D), were considered, while expansions (E) that resulted from specimens at various ages in the experimental program were considered as a target.

The ANN models designed by the network of ANN according to these parameters are shown in Fig. 3. This figure is the flowchart that the network of ANN was constructed before training. The Neuron numbers in the hidden layer were chosen after several trying and a network of two neurons were chosen as it yielded the most appropriate result to develop this flow chart.

Results and discussion

Plain Portland cement concrete

The analysis was made between the expansions predicted by ANN model and those of the experimental data for nine types of concrete cylinder mixes, with different values of C_3A content, 12%, 7% and 0%, for Type I, Type II, and Type V cements, respectively, along with 0.35, 0.45 and 0.55 *w/c* ratios for each cement type. As illustrated in Figs. 4–6, it was generally found that, there was a high correlation between the experimental data and the expansions predicted by ANN model.

The expansion performance limit was derived from a long-term study by the US Portland Cement Association (PCA), of concretes immersed in sodium sulfate solution [22–25], an expansion performance limit of 220 microstrain (0.022%) per year within the first three years of exposure has been found to indicate long-term dimensional stability of the concrete. The expansion defined for the USBR4908 test is graphically depicted in the Figs. 4–6 by a horizontal gridline. Moreover, the predicted results of expansion are represented by the dotted line, and the laboratory results of the experiment are

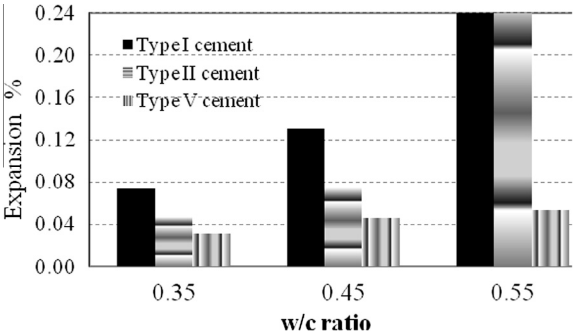

Fig. 7 Two year expansion of three types of cement along with variable *w/c*.

represented by the solid line. According to the limits, concrete having two year expansion of less than 0.044% meets the requirements for a severe sulfate environment, concrete with two years expansion slightly more than 0.044% meets the requirements for a moderate sulfate environment.

As illustrated in Fig. 4, comparing between experimental and simulation data cylinder expansion after 0, 1, 3, 6, 9, 12, 15, 18, 21 and 24 months of continuous immersing in the sodium sulfate solution for concrete cylinders containing 0.35 *w/c* for the three types of cement, the cylinder containing Type I cement (PC1-1) had two year expansions more than 0.044% for both experimental and prediction results, two year expansions of 0.074% and 0.077% were obtained.

Type II concrete cylinder (PC2-1) had lower expansions than PC1-1; the two year expansion was 0.047% and 0.048% for both experimental and numerical data, respectively. The concrete mix PC5-1 for Type V cement had the lowest 2 year expansion, 0.031% and 0.035% for both experimental and numerical data, respectively, were well below 0.044%. This meets the severe sulfate environment. Generally, the numerical results are in a good agreement with the experimental data. Some numerical data show more two year expansion than the experimental and it is expected that the slightly higher expansion but slight difference does not cause any change in the category of cement according to the expansion limits defined for PCA studies [22–25].

Fig. 5 shows the concrete cylinders expansion, containing 0.45 *w/c*; this is for the three types of cement. The cylinders containing Type I cement (PC1-2) had two year expansions more than 0.1% for both experimental and prediction results, two year expansions of 0.13% and 0.14% were obtained. Type II concrete cylinders (PC2-2) had lower expansions than PC1-2; the two year expansions were 0.075% and 0.079% for both experimental and numerical data, respectively. The concrete mix PC5-2 for Type V cement had the lowest two year expansion, 0.046% and 0.043% for both experimental and numerical data, respectively, and were in the range of 0.044% and this meets the severe sulfate environment. Generally, the numerical results are in a good agreement with the experimental data.

Fig. 6 shows the expansion of the concrete cylinders containing 0.55 *w/c* for the three types of cement, but in this case of high *w/c*, the cylinders containing Type I cement (PC1-3) had fifteen month expansions more than 0.25% for both experimental and prediction results, i.e. the rate of expansion in one year is greater than the limit of 0.022 according to the expansion limits defined. The same behavior for Type II concrete cylinders (PC2-3), the eighteen month expansion was greater than 0.2 for both experimental and numerical data. The concrete mix PC5-3 for Type V cement had the least two year expansion, 0.053% and 0.058% for both experimental and numerical data, respectively, were in range above 0.044% and this does not meet the severe sulfate environment. This is because of increasing permeability when *w/c* is higher; moreover, the experimental results and model data found out that the ultimate expansion values for Type I, II and V would be similar but were obtained in the longest times in type V cement, this is because the expansion from sulfate attack is mostly governed by C_3A content which is the lowest in Type V and could hence be accelerated using Type I. The interesting implication obtained from these results is that there was a high correlation between the experimental data and the expansions predicted by the ANN model.

Fig. 7 shows the model expansion patterns of concrete cylinder Portland cement in sulfate solution, after two years. As expected, this figure denotes that the C_3A content of the Portland cement is an important factor affecting its expansion pattern regardless the *w/c* ratio. The columns observed in this figure are similar to the trend that is observed in Figs. 4–6. Type I cement has the highest expansion pattern in all *w/c* ratios. The difference in behavior of Type V cement was less noticeable in all *w/c* ratios. In fact, the lowest expansion was observed for Type V cement which has low C_3A.

Generally the Figs. 4–7 show the expansion patterns of the three types of Portland cements when subjected to sulfate solutions along with a variable *w/c* ratio. In this model, the trend is relatively consistent. Expansion decreased when the C_3A and *w/c* of the cylinder decrease. This suggests that expansion type reactions between hardened concrete and sulfate solutions are still important factors at all *w/c* levels.

Application of the model to explain limits of C_3A with respect to ASTM C 150 specifications for categorizing sulfate resistant cement

The most important Portland cement phase affecting sulfate resistance is the C_3A content of the cement and permeability of concrete. With training ANN model, nine types of cement with different C_3A contents ranging from 0 to 12% were trained. Fig. 8 provides a plot of the numerical results of two year expansions for the nine plain Portland cement mortars versus the C_3A content of the cements in the concrete along with a different *w/c* ratio.

The vertical gridlines in Fig. 8 represent the Portland cement C_3A content limits established in the ASTM C 150 specifications for categorizing sulfate resistant cement. A line is provided at 5% C_3A to represent the maximum allowable C_3A content of severe sulfate resistance Type V cement. Another line is provided at 8% to represent the maximum allowable content for the moderate sulfate resistant Type II cement. The horizontal gridline at two year expansion of 0.044% delineates between moderate and severe sulfate resistances according to the PCA studies, expansion limits of long-term expansion of concrete immersed in sodium sulfate solution, while the line at an expansion of 0.082% can be considered as delineating between moderate and mild sulfate resistance depending on the intersection of this line with the point of

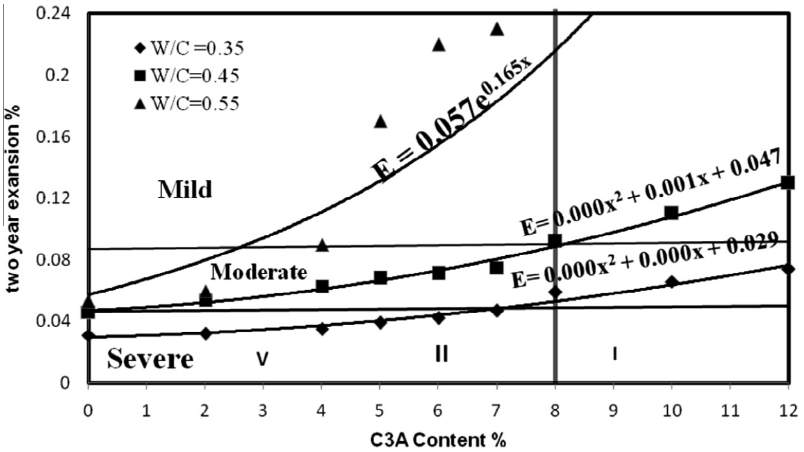

Fig. 8 Two year expansion versus cement C_3A content for plain Portland cement concrete cylinder along with *w*/*c* ratio.

maximum allowable C_3A content of moderate sulfate resistance at 8% and the trend line with a 0.45 *w*/*c* ratio.

The numerical results from training the model that simulate USBR4908 confirmed the well-supported fact that the C_3A content of cement greatly impacts its sulfate resistance, as well as the *w*/*c* ratio. The second degree polynomial trend lines shown in Fig. 8 points display a clear increase in expansion and thus decrease in sulfate resistance as the cement C_3A content increased. Moreover, a clear increase in expansion and thus decrease in sulfate resistance as the *w*/*c* ratio increased was seen.

Comparison between the levels of sulfate resistance determined from training the model and the USBR4908 expansion criteria versus the ASTM C 150 C_3A content limits. Type I cement was found to be only adequate in mild sulfate environments according to the modeling of USBR4908, because of its high 2 year expansion of 0.3% and 0.13% along with 0.55 and 0.45 *w*/*c* ratios, respectively, and according to its high C_3A content of 12%. But when Type I cement had low 0.35 *w*/*c* ratio, the two year expansion of 0.074 was found, this result seems adequate in Type I cement in moderate sulfate environments according to the USBR4908 model. But this result must be verified after three years of exposure.

Type V cement proved to be adequate for severe sulfate environments according to the modeling of USBR4908, because its two year expansion showed lows of 0.039% and 0.068% along with 0.35 and 0.45 *w*/*c* ratio, respectively, and according to ASTM C150 because of its C_3A content of 5%. But when Type V cement had a high 0.55 *w*/*c* ratio, the two year expansion of 0.17 was found, this result shows adequate Type V cement in moderate sulfate environments at 0–2.5% C_3A content and makes it a mild sulfate environment at 2.5–5% C_3A content, this is according to the USBR4908 model.

The Type II cement met the requirements for moderate sulfate environments according to modeling of USBR4908 because of its two year expansion of 0.059 with 0.35 *w*/*c* ratio and according to ASTM C 150 because of its C_3A content of 8%. But in the case of Type II cement had 0.55 *w*/*c* ratios, the two year expansion of 0.25 was found, this result makes Type II cement adequate in mild sulfate environments at all *w*/*c* ratios greater than 0.45 according to USBR4908 model. When Type II cement had 0.45 *w*/*c* ratio, the two year expansion was 0.092, this result shows Type II cement adequate in mild sulfate environments at 6–8% C_3A content and makes it a moderate sulfate environment at 5–6% C_3A content, this is according to the USBR4908 model.

From the details mentioned above, it would be unreasonable to recommend an increase in USBR4908 expansion limits, two year sulfate expansion limit values based on these model results. A more realistic interpretation of the results is that they provide a warning to engineers that caution should be taken when using borderline cements with C_3A contents between 2.5–5% and 6–8% along with a *w*/*c* ratio greater than 0.45. The cement may have a high gypsum content or other characteristics that may push the cement to a lower category of sulfate resistant behavior. The best approachthat an engineer can take is to avoid the use of the borderline 2.5–5% C_3A content cements in severe sulfate environments and borderline 6–8% C_3A content cements in moderate sulfate environments. If this cannot be avoided, the engineer should test the borderline cement using the USBR4908 procedures and current expansion criteria to ensure the cement is adequate.

Effect of mineral admixtures along with w/c ratio

The type of cement, C_3A content was maintained constant while the effect of mineral admixtures and *w*/*c* ratio were investigated in terms of expansion, porosity, surface absorption and spalling. The results indicated that, admixture type has a minor effect on the concrete resistance to sulfate. However 20% SF with 0.35 *w*/binder ratio provided the highest resistance to sulfate while 20% FA with 0.55 *w*/bender ratio gave the least resistance. The low *w*/*c* ratio improved the porosity, and surface absorption results as well as the concrete resistance to spalling.

It was also recorded that the spalling and permeation properties of concrete specimens increase with the *w*/*c* ratio without mineral admixture. It is worth mentioning that, the performance of concrete specimens containing mineral admixture and low *w*/*c* ratio, exposed to sulfate solution is better than that of concrete free mineral admixture and high *w*/*c* ratio. This is due to interfacial transition zone, ITZ, effects, capillary porosity and higher rates of diffusion also due to the positive effect of mineral admixture in improving the microstructure of ITZ. They consume the available Ca $(OH)_2$ in the hydrated cement paste and forms secondary C–S–H, thus increasing overall C–S–H formation, reducing permeability and increasing sulfate resistance. In addition the dilution of C_3A content due to the overall reduction of cement in concrete. The proposed model based on C_3A content, mineral admixture, duration of exposure, cement content and *w/c* ratio was found to be effective in predicting the level of damage, function in expansion, for blended cement concrete.

Figs. 9 and 10, present the experimental and numerical expansion results for the concrete cylinder containing combinations of Type II cement with two different types, ratio of SF and FA along with 0.35, 0.45 and 0.55 *w/c* ratios. The expansion for the concrete cylinder is also presented in each figure such that an observation can be made as to whether the mineral admixture increased or decreased sulfate resistance.

In general, all concrete cylinder mixes containing the FA and SF along with 0.35 and 0.45 *w/c* ratio, had average two year expansions below 0.044% for both experimental and numerical expansion results, these values meet the requirements for a severe sulfate environment according to PCA studies. But in the case of 0.55 *w/c* ratio, the expansion in concrete cylinder was in range of 0.08% more than the rate of expansion of 0.022% per year for severe sulfate environment.

As illustrated in Fig. 12, the model expansion patterns of Type II cement concrete in sulfate solution, after two years, are obtained. As expected, this figure denotes that the mineral admixture replacement of the Portland cement is an important factor affecting its expansion regardless of the effect of the *w/c* ratio. The columns in this figure are similar to the trend in Figs. 9–11. Type II cement only, (PC2) is the highest expansion pattern in all *w/c* ratios. The difference in behavior of Type II combined with 20% and 30% FA or SF was less noticeable in all *w/c* ratios. In fact, the lowest expansion was for Type II cement combined with 30% SF, 2SF2, which has low cement content, C_3A, and low *w/c* ratio. From these results, it was generally found that, there was a high correlation between the experimental data and the expansions predicted by the ANN model.

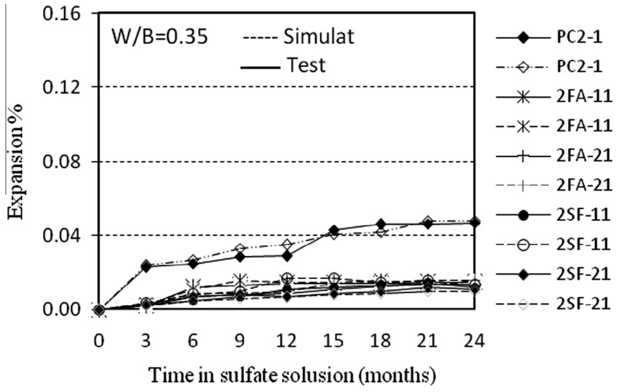

Fig. 9 Sulfate expansion of Type II cement with and without variable dosage of mineral admixture.

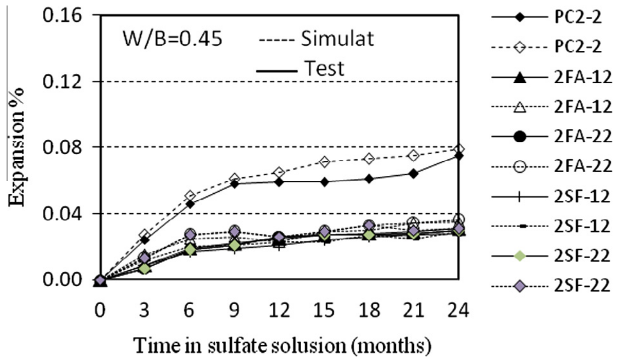

Fig. 10 Sulfate expansion of Type II cement with and without variable dosages of the mineral admixture.

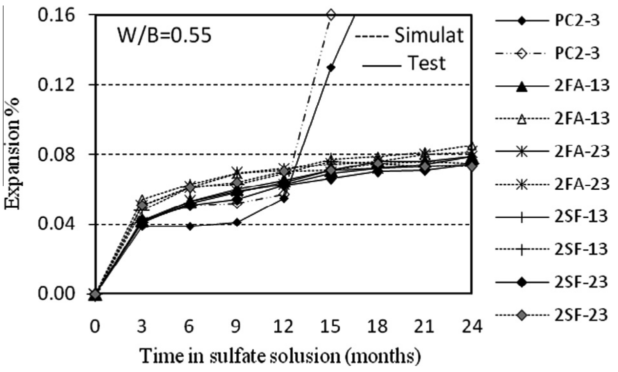

Fig. 11 Sulfate expansion of Type II cement with and without variable dosages of the mineral admixture.

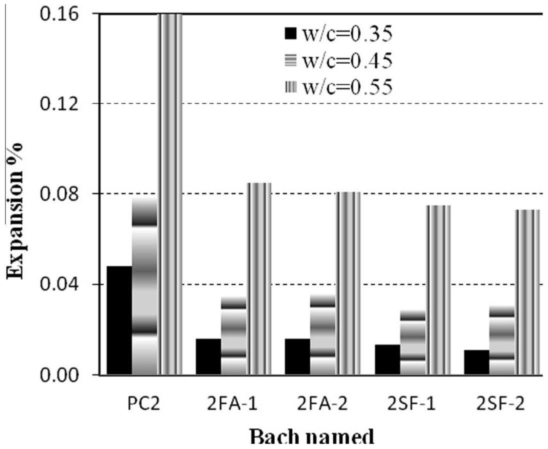

Fig. 12 Two year expansion of Type II cement with and without variable dosages of the mineral admixture.

Conclusions

The ultimate goal of the prediction ANN model was to determine its suitability in performance modeling for evaluating the sulfate resistance of Portland cement and Portland cement mineral admixture combination. The modeling can be evaluated by investigating the consistency, reliability of results obtained from training model. Also the accuracy and effectiveness of the modeling expansion results criteria are used for determining the level of sulfate resistance of the concrete cylinder. The conclusions of this study are as follows.

(1) A quite high correlation was found between the results of experimental USBR4908 and the simulation from modeling by ANN. It can be suggested that the ANN modeling

technique can reliably predict the value of the expansion of concrete cylinder. These values remained within the range of the experimental USBR4908 tests found in previous studies.

(2) ANN modeling technique can help us for analysis of the effect of ordinary Portland cement as well as blended cements with FA or SF on the sulfate attack of concrete, dependent on the value of expansion that was obtained from neural network algorithm, more readily, faster, and more accurately.

(3) ANN modeling technique overcame the deficiencies of the USBR 4908 test method, lengthy measuring period, insensitivity of the measurement tool to the progression of sulfate attack, the effect of curing and pH change during the time in the solution. Moreover it is powerful, and has low cost.

(4) Expansion in the concrete cylinder can be estimated successfully through a neural network algorithm having two neurons and five input parameters in mixture design and one output parameter. For a 273 data-set of expansion, the average of difference between estimated results from ANN model and experimental data is evaluated to be 2–5%.

(5) Sulfate expansion of the USBR 4908 modeling-training Portland cement concrete confirmed that the impact of tricalcium aluminate C_3A content has an effect on sulfate resistance as increasing C_3A content yielded increased expansion.

(6) Results predicted from the ANN model for the concrete cylinder which contains FA or SF showed the FA and SF significantly reduced sulfate expansions as each concrete cylinder met the ASTM C1012 expansion criteria for severe sulfate resistance.

(7) The engineer can avoid the use of the borderline 2.5–5% C_3A content cements in severe sulfate environments and borderline 6–8% C_3A content cements in moderate sulfate environments. If this cannot be avoided, the engineer should test the borderline cement using the USBR 4908 procedures and current expansion criteria to ensure the cement is adequate.

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