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Alkali-Aggregate Reaction in Concrete

STUDY ON THE CALCULATION OF SODIUM EQUIVALENT IN AAR

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ABSTRACT

AAR expansion tests were carried out to study the widely accepted sodium equivalent formula. Two kinds of aggregates, four kinds of cement and two curing systems were used in the experiments. Cluster and graphing approaches to analyze the test data are presented in the paper. It is suggested that K_2O coefficient 0.658 is too high. The reasonable value is in between 0.4~0.5.

Keywords: Sodium equivalent, Alkali-Aggregate Reaction

To limit the total alkali content of concrete is one of the effective measures in preventing concrete from deteriorating due to AAR (Alkali-Aggregate Reaction). For practical purposes, the formula of sodium equivalent, $Na_2O_{eq}=Na_2O+0.658K_2O$, has been used to calculate the total alkali content of cement or concrete over the last 50 years.

The coefficient of K_2O, 0.658, in the formula of sodium equivalent is defined by the ratio of the molecular weight of Na_2O to that of K_2O. It was assumed that one mole of K_2O produces the same concentration of OH^- and cation as one mole of Na_2O. However, investigations found that not only the concentration of OH^- that has an effect on the expansion due to AAR. The cation species and their properties in concrete as well affect the expansion. These factors were ignored when the formula of sodium equivalent was derived.

In the study by one of the authors (Hmy) on the problem of fly ash in suppressing expansion due to AAR using the approach of fuzzy neural networks [1], it was found that the effect of Na_2O on the expansion due to AAR is much stronger than that of K_2O and that the coefficient of K_2O, 0.658, in the formula of sodium equivalent is too large. However, in those experiments a large amount of cement was replaced by different kinds of fly ash and KOH was the only added alkali. Thus, this makes it difficult to compare accurately the respective influence of K_2O and Na_2O on AAR expansion. In order to gain further information on the respective effects of K_2O and Na_2O on the expansion due to AAR and know the reasonable coefficient of K_2O in the formula of sodium equivalent, other 90 groups of experiments were done, where no fly ash was mixed, KOH and NaOH were used as added alkali, and both "rapid test"[2] and "80℃ curing" were adopted.

1. THE EXPERIMENTS BY RAPID TEST

1.1 Experimental works and the sample data

Three Portland cements of type P.I (grade 52.5) used in the experiments were produced by the manufactories in Jiangxi, Gansu and Henan provinces (labeled as YD, AA and BB, respectively). Their chemical compositions are shown in Table 1.

Table 1 Chemical Compositions of 3 Kinds of Portland Cement (%)

No	cement	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	SO_3	f-CaO	K_2O	Na_2O	LOI	Total
1	YD	21.45	4.47	63.83	3.13	2.38	2.36	1.03	0.83	0.05	1.39	99.89
2	AA	21.14	4.71	63.62	4.29	1.84	—	0.54	0.46	0.33	0.47	96.86
3	BB	20.40	5.79	61.85	3.88	1.91	2.60	—	1.15	0.14	—	97.72

The igneous rock obtained from Guangfeng, Jiangxi, was used as the reactive aggregate, in which the major reactive components were microcrystalline quartz, crypotocrystalline quartz and chalcedony. In the rapid expansion test[2] with cement-aggregate ratio 2:1 the expansion of the mortar bar containing the reactive aggregate was 0.142 percent.

In the experiments, the cement-aggregate ratio was 2: 1, and the water-cement ratio was 0.3. Various contents of KOH and NaOH, calculated as the percentage of K_2O and Na_2O, were added to the mixing water and five types of tests were conducted. (Table 2).

In each group of experiment six 10mm×10mm×40mm mortar bars were cast. The specimens were de-molded after 24 ± 2 hours and were measured at room temperature as the initial length. They were then pre-cured in 100℃ steam for 4 hours. The mortar bars with added KOH and NaOH were, respectively, immersed in 1mol/L KOH and NaOH solution, and then autoclaved at 150 ± 2℃ for 360 ± 5 minutes. The length of samples was measured at room temperature and their expansion calculated according to , $\frac{L_i - L_0}{35} \times 100\%$, where L_0 is the initial length and L_i the length after autoclaving. The results of the 60 groups of experiments are listed in Table 2.

Table 2 Test program and the expansion data

No (1)	Types of test (2)	Cement sources (3)	Added alkali K_2O (%) (4)	Added alkali Na_2O (%) (5)	Expansion (%) (6)	Y (7)	No (1)	Types of test (2)	Cement sources (3)	Added alkali K_2O (%) (4)	Added alkali Na_2O (%) (5)	Expansion (%) (6)	Y (7)
1	I	YD	1.0		0.035		37	IV	YD		1.0×0.658	0.053	1.5143
2			1.5		0.073		38				1.5×0.658	0.070	0.9589
3			2.0		0.168		39				2.0×0.658	0.165	0.9821
4			2.5		0.250		40				2.5×0.658	0.193	0.7720
5		AA	1.0		0.062		41		AA		1.0×0.658	0.089	1.4355
6			1.5		0.137		42				1.5×0.658	0.131	0.9562
7			2.0		0.184		43				2.0×0.658	0.320	1.7391
8			2.5		0.238		44				2.5×0.658	0.434	1.8235
9		BB	1.0		0.076		45		BB		1.0×0.658	0.148	1.9474
10			1.5		0.124		46				1.5×0.658	0.181	1.4597
11			2.0		0.158		47				2.0×0.658	0.388	2.4557
12			2.5		0.189		48				2.5×0.658	0.505	2.6720
							Mean of Y in type IV						**1.56**
13	II	YD		1.0×0.4	0.035	1.0000	49	V	YD		1.0×1	0.078	2.2286
14				1.5×0.4	0.046	0.6301	50				1.5×1	0.376	5.1507
15				2.0×0.4	0.080	0.4762	51				2.0×1	0.528	3.1429
16				2.5×0.4	0.121	0.4840	52				2.5×1	0.583	2.3320
17		AA		1.0×0.4	0.056	0.9032	53		AA		1.0×1	0.195	3.1452
18				1.5×0.4	0.070	0.5109	54				1.5×1	0.472	3.4453
19				2.0×0.4	0.098	0.5326	55				2.0×1	0.569	3.0924
20				2.5×0.4	0.242	1.0168	56				2.5×1	0.617	2.5924
21		BB		1.0×0.4	0.086	1.1316	57		BB		1.0×1	0.233	3.0658
22				1.5×0.4	0.100	0.8065	58				1.5×1	0.472	3.8065
23				2.0×0.4	0.115	0.7278	59				2.0×1	0.598	3.7848
24				2.5×0.4	0.210	1.1111	60				2.5×1	0.611	3.2328
Mean of Y in type II						**0.78**	**Mean of Y in type V**						**3.25**
25	III	YD		1.0×0.5	0.032	0.9143							
26				1.5×0.5	0.074	1.0137							
27				2.0×0.5	0.108	0.6429							
28				2.5×0.5	0.245	0.9800							
29		AA		1.0×0.5	0.051	0.8226							
30				1.5×0.5	0.074	0.5401							
31				2.0×0.5	0.192	1.0435							
32				2.5×0.5	0.405	1.7017							
33		BB		1.0×0.5	0.090	1.1842							
34				1.5×0.5	0.113	0.9113							
35				2.0×0.5	0.209	1.3228							
36				2.5×0.5	0.342	1.8095							
Mean of Y in type III						**1.07**							

The tests with K_2O is listed in Type Ⅰ, and tests with Na_2O in Type Ⅱ, Ⅲ, Ⅳ and Ⅴ. Column 6 is the expansion of the bars during the tests. Y in column 7 shows the expansion values of Type Ⅱ, Ⅲ, Ⅳ and Ⅴ tests divided by the corresponding expansion values of Type Ⅰ tests. In each Type of test Y is averaged and the mean is given at the bottom of each Type.

1.2 Analysis of the test results

In Type of test Ⅳ (Table 2), the same mole percentage of Na_2O is added to replace the K_2O in Type of test Ⅰ (Na_2O_{eq}=0.658K_2O). The expansion of test with Na_2O addition is considerably greater than that of the test with K_2O addition.

Now the cluster and graphing approaches are used to analyze the rules of how K_2O and Na_2O affect the expansion due to AAR, and to determine the reasonable coefficient of K_2O for practical use.

1.2.1 Cluster analysis

The distances of the expansion due to AAR between the type Ⅰ and the type Ⅱ, Ⅲ, Ⅳ, Ⅴ are calculated separately using the approach of cluster analysis[3], by which the degree of similarity of every two types can be compared.

Suppose that m types of experiments and n elements in each type are to be compared, a matrix X of $m \times n$ can be defined:

$$X = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{bmatrix} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}$$

The different distances between vector x_r and x_s [4] are defined as follows:

Euclid distance:

$$d_{rs} = (x_r - x_s)(x_r - x_s)^T \qquad (1)$$

Standard Euclid distance:

$$d_{rs} = (x_r - x_s)D^{-1}(x_r - x_s)^T \qquad (2)$$

where D is an angle matrix, in which the angle elements are given by σ_j^2 that is the square deviation of variable x_j.

Absolute value distance:

$$d_{rs} = \sum_{j=1}^{n} \left| x_{rj} - x_{sj} \right| \qquad (3)$$

Minkowski distance:

$$d_{rs} = \left\{ \sum_{j=1}^{n} \left| x_{rj} - x_{sj} \right|^p \right\}^{1/p} \qquad (4)$$

The distances of the expansions due to AAR between the type Ⅰ and the type Ⅱ, Ⅲ, Ⅳ, Ⅴ are calculated by the formulas (1), (2), (3) and (4). They are:

Euclid distance:

$[d_{12}, d_{13}, d_{14}, d_{15}] = [0.20, 0.25, 0.47, 1.13]$

Standard Euclid distance:

$[d_{12}, d_{13}, d_{14}, d_{15}] = [0.036, 0.043, 0.085, 0.195]$

Absolute value distance:

$[d_{12}, d_{13}, d_{14}, d_{15}] = [0.51, 0.55, 1.12, 3.64]$

Minkowski distance:

$[d_{12}, d_{13}, d_{14}, d_{15}] = [0.14, 0.18, 0.33, 0.58]$

All the results of the above calculations show that of all the distances d_{12} is the smallest, d_{13} is slightly larger than d_{12}, and d_{14} is twice as larger as d_{12}. Thus, the expansion due to K_2O addition is close to the expansion caused by Na_2O addition with a weight 0.4-0.5 times the weight of K_2O (experiments Type II and Type III). Also, much larger expansion is measured with Na_2O added in an amount 0.658 (one mole Na_2O for one mole of K_2O) times the weight of K_2O (Experiment Type Ⅳ).

It can be deduced from the above calculations that the coefficient of K_2O, which is 0.658, in the formula of sodium equivalent is too large and it should be about 0.4~0.5.

1.2.2 Graphing analysis

In Fig. 1, a coordinate is defined in which the abscissa (x-axis) stands for the ratio of the content of the Na_2O (the data of types Ⅱ, Ⅲ, Ⅳ, Ⅴ in column 5) to the corresponding content of the K_2O (the data of type Ⅰ in column 4), and the values of ordinate (y-axis) are the means of types Ⅱ, Ⅲ, Ⅳ, Ⅴ in column 7 of Table 2.

It is shown from Fig.1 that the relations between y and x are nearly linear, and the expansion when the content of added Na_2O was 0.658 times the content of added K_2O (experiments of type Ⅳ) is 1.56 times larger than the one when K_2O was the added alkali (experiments of type Ⅰ), from which it can be inferred that the coefficient of K_2O in formula of sodium equivalent is too large. In addition, it is

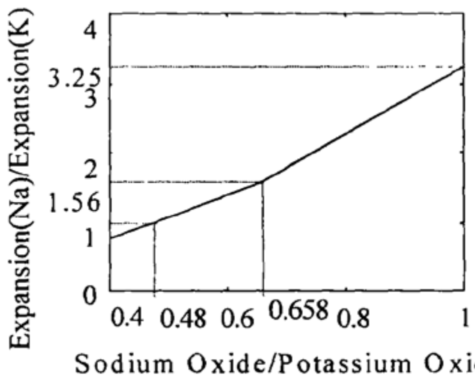

Fig.1 Relation of the AAR expansion resulted from sodium oxide and potassium oxide

calculated from Fig.1, that when the value of ordinate (y) is 1, the x is about 0.48. That is to say, 1% of K_2O generates the same amount of expansion as 0.48% of Na_2O does.

Thus, the coefficient of K_2O in the formula of sodium equivalent should be about 0.48. In summary, according to cluster analysis and graphing analysis on the data obtained by rapid test the similar conclusions are arrived at.

2. THE EXPERIMENT BY 80℃ CURING TEST

Another 30 groups of experiments were devised to study more extensively the coefficient of K_2O in the formula of sodium equivalent.

In this set of experiments a different reactive aggregate (zeolitized pearlite) was used. The curing temperature was set at 80℃.

2.1 Experimental works and the sample data

The Portland cements of type P.II (grade 52.5R) produced by the manufactory of Yadong, Jiangxi was used, in which 4 percent of limestone powder was mixed. Its chemical composition is shown in Table 3.

Table 3 Chemical Composition of Yadong Cement (%)

SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	SO_3	f-CaO	K_2O	Na_2O	LOI	Total
21.74	4.60	63.39	3.29	2.57	2.19	1.11	0.77	0.06	1.40	100.01

The zeolitized pearlite was obtained from Shandong., in which the major reactive components were glass and chalcedory. By the rapid test with cement-aggregate ratio 2: 1, the expansion of mortar bar containing this pearlite aggregate was 0.552 percent, which is larger than the expansion of mortar containing the igneous rock obtained from Guangfeng, Jiangxi. Therefore, the reactivity of zeolitized pearlite is higher than the aggregate from Guangfeng.

In the experiments here the cement-aggregate ratio was 2: 1, and the water-cement ratio was 0.3. Different contents of KOH and NaOH, calculated as the percentage of K_2O and Na_2O, were added to the mortar mixing water. Table 4 shows the contents of K_2O and Na_2O in each group.

In each group of experiment 6 specimens ($10mm \times 10mm \times 40mm$ in size) were made,. The mortar bars de-molded after 24 hours were measured at room temperature, and were then precured in 100℃ steam for 4 hours. After cooling down, the mortar bars were measured again at room temperature as initial length. The mortar bars with added KOH were immersed in 1mol/L KOH solution and the mortar bars with added NaOH immersed in 1mol/L NaOH solution at 80℃. The length of the samples cured for 1 day, 7 days, 14days, 21 days and 28days were measured at room temperature and their expansions were calculated according to $\frac{L_t - L_0}{35} \times 100\%$, where L_0 is initial length and L_t is the length after curing. The results of the 30 groups of tests were listed in Table 4.

Table 4 Test program and the expansion data

No (1)	Type (2)	Added alkali: K_2O(%) (3)	Added alkali: Na_2O(%) (4)	Expansion (%): 1d (5)	7d (6)	14d (7)	21d (8)	28d (9)	Y_1 (10)	Y_2 (11)	Y_3 (12)	Y_4 (13)	Y_5 (14)
1	I	0.4		0.023	0.470	0.711	0.891	1.043					
2		0.6		0.034	0.471	0.745	0.846	0.937					
3		0.8		0.047	0.504	0.770	0.909	0.977					
4		1.0		0.060	0.620	0.907	1.097	1.153					
5		1.2		0.095	0.708	0.970	1.124	1.221					
6	II		0.4×0.4	0.020	0.292	0.550	0.720	0.903	0.8696	0.6213	0.7736	0.8081	0.8658
7			0.4×0.6	0.031	0.316	0.711	0.872	1.184	0.9118	0.6709	0.9544	1.0307	1.2636
8			0.4×0.8	0.039	0.415	0.820	0.897	1.366	0.8298	0.8234	1.0649	0.9868	1.3367
9			0.4×1.0	0.059	0.520	0.904	1.196	1.475	0.9833	0.8387	0.9967	1.0902	1.2793
10			0.4×1.2	0.078	0.598	0.915	1.352	1.563	0.8211	0.8446	0.9433	1.2028	1.2801
Mean of Y_1, Y_2, Y_3, Y_4, Y_5 in type II									0.8831	0.7598	0.9466	1.0237	1.2051
11	III		0.5×0.4	0.028	0.322	0.836	0.955	1.230	1.2174	0.6851	1.1758	1.0718	1.1793
12			0.5×0.6	0.034	0.435	0.825	1.134	1.363	1.0000	0.9236	1.1074	1.3404	1.4546
13			0.5×0.8	0.043	0.598	1.052	1.303	1.498	0.9149	1.1865	1.3662	1.4334	1.5333
14			0.5×1.0	0.085	0.705	1.195	1.400	1.523	1.4167	1.1371	1.3175	1.1851	1.3209
15			0.5×1.2	0.084	0.696	1.275	1.513	1.725	0.8842	0.9831	1.3144	1.3461	1.4128
Mean of Y_1, Y_2, Y_3, Y_4, Y_5 in type III									1.0866	0.9831	1.2563	1.2754	1.3802
16	IV		0.658×0.4	0.035	0.438	0.993	1.273	1.422	1.5217	0.9319	1.3966	1.4287	1.3634
17			0.658×0.6	0.054	0.552	1.169	1.370	1.573	1.5882	1.1720	1.5691	1.6194	1.6788
18			0.658×0.8	0.056	0.692	1.202	1.500	1.676	1.1915	1.3730	1.5610	1.6502	1.7155
19			0.658×1.0	0.087	0.789	1.291	1.574	1.667	1.4500	1.2726	1.4234	1.4348	1.4458
20			0.658×1.2	0.115	0.777	1.297	1.633	1.792	1.2105	1.0975	1.3371	1.4528	1.4676
Mean of Y_1, Y_2, Y_3, Y_4, Y_5 in type IV									1.3924	1.1694	1.4575	1.5172	1.5342
21	V		0.8×0.4	0.036	0.480	1.182	1.418	1.694	1.5652	1.0213	1.6624	1.5915	1.6242
22			0.8×0.6	0.056	0.667	1.300	1.588	1.736	1.6471	1.4374	1.7450	1.8771	1.8527
23			0.8×0.8	0.082	0.796	1.255	1.602	1.795	1.7447	1.5794	1.6299	1.7624	1.8373
24			0.8×1.0	0.089	0.758	1.328	1.629	1.852	1.4833	1.2226	1.4642	1.4850	1.6062
25			0.8×1.2	0.152	1.187	1.571	1.782	1.876	1.6000	1.6766	1.6196	1.5854	1.5364
Mean of Y_1, Y_2, Y_3, Y_4, Y_5 in type V									1.6081	1.3874	1.6242	1.6603	1.6914

No (1)	Type (2)	Added alkali K₂O(%) (3)	Added alkali Na₂O(%) (4)	Expansion (%) 1d (5)	7d (6)	14d (7)	21d (8)	28d (9)	Y_1 (10)	Y_2 (11)	Y_3 (12)	Y_4 (13)	Y_5 (14)
26	VI		1.0×0.4	0.046	0.467	1.234	1.620	1.730	2.0000	0.9936	1.7356	1.8182	1.6587
27			1.0×0.6	0.080	0.825	1.401	1.675	1.842	2.3529	1.7516	1.8805	1.9799	1.9658
28			1.0×0.8	0.086	0.810	1.397	1.643	1.833	1.8298	1.6071	1.8143	1.8075	1.8762
29			1.0×1.0	0.098	0.934	1.457	1.678	1.989	1.6333	1.5065	1.6064	1.5296	1.7251
30			1.0×1.2	0.187	1.226	1.683	1.825	1.977	1.9684	1.7316	1.7351	1.6237	1.6192
Mean of Y_1, Y_2, Y_3, Y_4, Y_5 in type VI									1.9569	1.5181	1.7544	1.7518	1.7690

In Table 4, column 5 to column 9 show the expansion of tests at different ages. The Y_1~Y_5 in column 10 to column 14 are the ratios of the expansion caused by Na_2O as against the corresponding expansion caused by K_2O, i.e. the expansion values of types II, III, IV, V, VI (column 5 to column 9) divided by the corresponding expansion values of type I. The mean of Y is listed at the end of each Type.

2.2 Analysis of the test results

Table 4 shows that in general the AAR expansions when the content of Na_2O was 0.658 times the content of K_2O (experiments of type IV) are larger than the expansions caused by K_2O (experiments of type I). In other words, the coefficient of K_2O in the formula of sodium equivalent is too large.

Now the approaches of cluster and graphing are used to analyze the rules of how K_2O and Na_2O affect the expansion due to AAR, and to determine the reasonable coefficient of K_2O.

2.2.1 Cluster analysis

According to the data in Table 4 the distances of the expansions due to AAR between the type I and the type II, III, IV, V, VI are calculated by formula (1) and (2) and are shown below:

Euclid distance:

1 day:

$[d_{12}, d_{13}, d_{14}, d_{15}, d_{16}] = [0.019, 0.028, 0.042, 0.077, 0.12]$

7 days: $[d_{12}, d_{13}, d_{14}, d_{15}, d_{16}] = [0.293, 0.200, 0.276, 0.613, 0.765]$

14 days:

$[d_{12}, d_{13}, d_{14}, d_{15}, d_{16}] = [0.181, 0.527, 0.837, 1.142, 1.381]$

21 days:

$[d_{12}, d_{13}, d_{14}, d_{15}, d_{16}] = [0.303, 0.659, 1.121, 1.423, 1.608]$

28 days:

$[d_{12}, d_{13}, d_{14}, d_{15}, d_{16}] = [0.640, 0.937, 1.276, 1.628, 1.815]$

Standard Euclid distance:

1 day:

$[d_{12}, d_{13}, d_{14}, d_{15}, d_{16}] = [0.0008, 0.0006, 0.0011, 0.0026, 0.0042]$

7 days:

$[d_{12}, d_{13}, d_{14}, d_{15}, d_{16}] = [0.048, 0.024, 0.045, 0.144, 0.168]$

14 days:

$[d_{12}, d_{13}, d_{14}, d_{15}, d_{16}] = [0.049, 0.141, 0.227, 0.320, 0.374]$

21 days:

$[d_{12}, d_{13}, d_{14}, d_{15}, d_{16}] = [0.089, 0.204, 0.352, 0.452, 0.516]$

28 days:

$[d_{12}, d_{13}, d_{14}, d_{15}, d_{16}] = [0.197, 0.292, 0.405, 0.520, 0.577]$

All the results of the above calculations show nearly the same trend, which is $d_{12} < d_{13} < d_{14} < d_{15} < d_{16}$ at 1 day, 14days, 21 days and 28days, and d_{14} is 2~6 times d_{12}. The expansions caused by K_2O (experiments of type I) are very similar to the ones when Na_2O was added in the amount 0.4 times the content of K_2O (experiments of type II), and they are much smaller than the ones when Na_2O was the added alkali and its adding content was 0.658 times the content of K_2O (experiments of type IV). Besides, d_{13} is smallest at 7 days, which indicates that the expansions when K_2O was the added alkali (experiments of type I) are most similar to the ones when Na_2O was the added alkali and its adding content was 0.5 times the content of K_2O (experiments of type III). Thus it can be deduced from above calculations that the coefficient of K_2O, 0.658, in the formula of sodium equivalent is too large and it should be about 0.4~0.5.

2.2.2 Graphing analysis

In Fig.2 through Fig.6, the values of the abscissa are the ratios of the data of types II, III, IV, V, VI in column 4, to the corresponding data of type I in col umn 3. The values of the ordinate are the means of Y (column 10 to 14) in Types II, III, IV, V, VI.

It is shown from Figures 2, 4, 5 and 6 that when x is equal to 0.658, the Y values at 1 day, 14 days, 21 days and 28 days are very close.

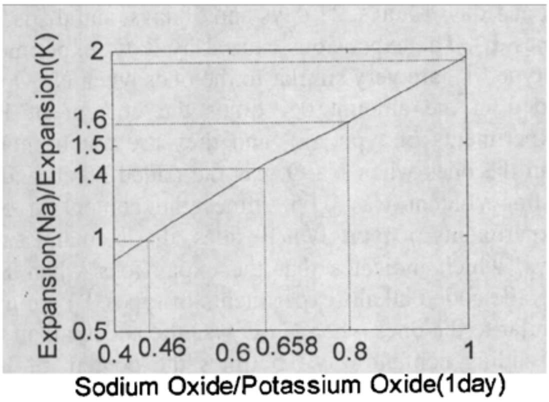

Fig.2 Relation of the AAR expansion resulted from sodium oxide and potassium oxide

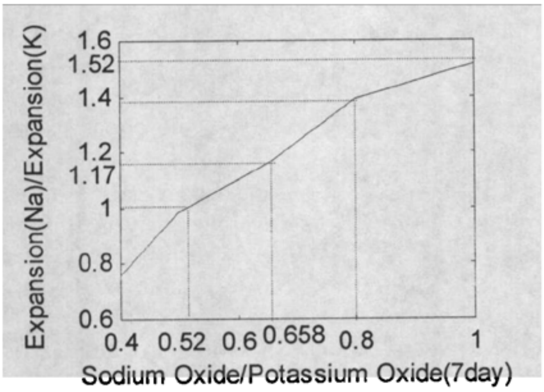

Fig.3 Relation of the AAR expansion resulted from sodium oxide and potassium oxide

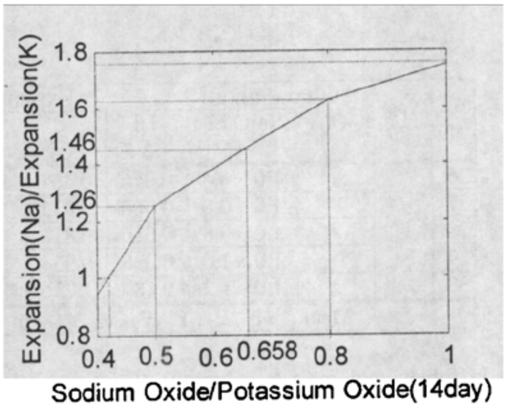

Fig.4 Relation of the AAR expansion resulted from sodium oxide and potassium oxide

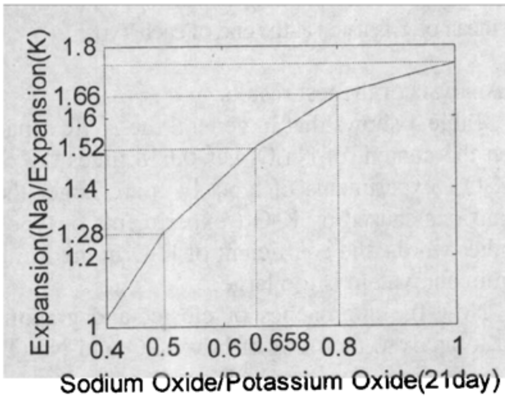

Fig.5 Relation of the AAR expansion resulted from sodium oxide and potassium oxide

The mean is:

$$\frac{1.40+1.46+1.52+1.53}{4}=1.48$$. When Na_2O was added in an amount 0.658 times the content of K_2O (experiments of type IV) the expansion is 1.48 times the ones

when K_2O was the added alkali (experiments of type I). In addition, it is calculated from Fig.2 to Fig. 6 that when the value of ordinate Y is 1, the x values are 0.46, 0.52, 0.42, 0.39 and 0.36, the mean of which is 0.43. Thus, the expansion caused by K_2O is about 0.43 times the expansion caused by Na_2O.

In summary, by cluster analysis and graphing analysis on the data obtained by "80℃ curing test", we arrived at the same conclusion that the coefficient of K_2O in the formula of sodium equivalent is about 0.4~0.5.

3. DISCUSSION

From the above analysis it is known that the coefficient of K_2O 0.658 in the widely used formula of sodium should be 0.4~0.5 when the expansion is caused by ASR. To verify the results the authors consulted some relevant literatures [5, 6] and experts. Monica Prezzi at el [5], Mei Laibao[7], and Katayama [6] showed the same trend. Furthermore, the experiments of Mei Laibao and Katayama show similar trend for ACR.

The coefficient of K_2O, 0.658, in the formula of sodium equivalent is the ratio of the molecular weight of Na_2O to K_2O. It was assumed that equal mol concentration of K_2O and Na_2O produced the same concentration of OH^- and cation. However, experiments show that not only the concentration of OH^-, but also the cation species and their properties in concrete play an important role in the expansion due to AAR. These effects were not given due consideration when the formula of sodium equivalent was derived. The consequence is that the expansions due to AAR may not increase as the calculated total alkali increases, which may result in confusion in real concrete engineering.

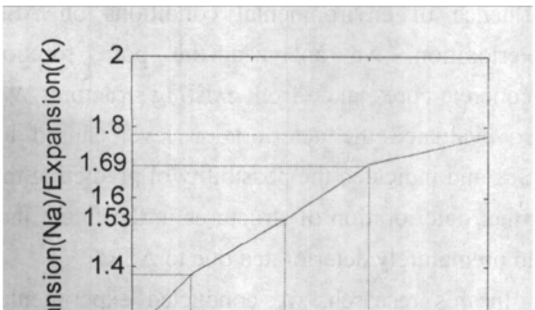

Fig.6 Relation of the AAR expansion resulted from sodium oxide and potassium oxide

It is still not clear why different cations have different effects on AAR expansion. One of the authors (HMY) [1] had a preliminary analysis using the double-layer theory proposed by Monica Prezzi at el [8,5], but further investigation is needed.

The above experiments are confined to a few cement and aggregate sources. Besides, the samples were stored in alkali solution at high temperature (150 ℃ and 80℃). To get a universal formula of sodium equivalent it is necessary to monitor the long-term expansion of mortar bars or concrete microbars cured at room temperatures and more varieties of cement and aggregate should be used.

4. CONCLUSIONS

In summary, therefore, based on the cluster analysis and the graphing analysis on the expansions due to AAR with 2 kinds of aggregate, 4 kinds of cement, and 2 kinds of experiment methods, the following conclusions are derived:

(1) The coefficient of K_2O in the formula of sodium equivalent used worldwide is too large.

(2) The coefficient should be 0.4~0.5. In other words, the formula of sodium equivalent should be $Na_2Oeq = Na_2O + (0.4 \sim 0.5) K_2O$.

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