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Statistical Model for Predicting the Optimum Gypsum Content in Concrete

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ABSTRACT

The problem of internal sulfate attack in concrete is widespread in Iraq and neighboring countries. This is because of the high sulfate content usually present in sand and gravel used in it. In the present study the total effective sulfate in concrete was used to calculate the optimum SO_3 content. Regression models were developed based on linear regression analysis to predict the optimum SO_3 content usually referred as (O.G.C) in concrete.

The data is separated to 155 for the development of the models and 37 for checking the models. Eight models were built for 28-days age. Then a late age (greater than 28-days) model was developed based on the predicted optimum SO_3 content of 28-days and late age. Eight developed models were built for all ages. The important results obtained from the developed models are the positive effect of C_3S, C_3A and C_4AF on optimum SO_3 content. The effect of C_3A on optimum SO_3 content is about twice that of C_4AF. The study also showed a trend of positive and important effect of the fineness of cement except in some models and this is due to statistical overlap.

Key wards: Optimum SO_3 content (O.G.C), total effective SO_3 content, 28-day age model, late age model, all age model

نماذج أحصائية لتخمين نسبة الجبس المثلى في الخرسانة

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الخلاصة

مشكلة مهاجمة الكبريتات الداخلية في الخرسانة منتشرة في العراق و البلدان المجاورة. هذا يعزى الى النسبة العالية لاملاح الكبريتات الموجودة في الرمال و الحصى المستخدم فيها. دراستنا الحالية أستعملت القيمة الكلية المؤثرة(الفعالة) للكبريتات في الخرسانة و التي تستعمل لحساب النسبة المثلى للكبريتات. تم تطوير نماذج رياضية بأستعمال طرق تحليل الانحدار ، للتنبؤ بنسبة الكبريتات المثلى و التي تعرف ب (O.G.C). البيانات قسمت الى 155 تدخل في بناء النموذج و 37 لتدقيق النموذج. صممت (8) نماذج لعمر 28-يوم. ثم طور نموذج للاعمار المتأخرة (أكبر من 28-يوم) و المعتمد على القيمة المثلى المتوقعة للكبريتات من عمر 28-يوم و الاعمار المتأخرة الاخرى. تم تصميم (8) نماذج أخرى و لكل الاعمار.

وكان من أهم النتائج التي تم التوصل اليها التأثير الايجابي ل (C_3S،C_3A و C_4AF) و كان تأثير (C_3A) حوالي ضعف تأثير (C_4AF). كما أظهرت الدراسة التأثير الايجابي و الفعال لنعومة السمنت على نسبة الكبريتات المثلى الا في بعض النماذج و هذا يعزى الى التداخلات الاحصائية. الكلمات الرئيسية:نسبة الجبس المثلى ، النسبة الكلية الفعالة للكبريتات، موديلات بعمر 28 يوم، الموديلات بالعمار المتأخرة، المديلات بكل الاعمار.

الكلمات الرئيسية: النسبة المثلى للجبس ، النسبة الكلية الفعالة للاملاح ، الموديلات بعمر 28 يوم ، المديلات بالاعمار المتأخرة ، المديلات بكل الاعمار

1. DETERMINATION OF THE STATISTICAL MODEL VARIABLES

1.1 Collecting Data

In order to build a regression predictive model, there should be sets of data that cover a wide range of variation of the independent variable. A survey was carried out to obtain the required data has been chosen to cover locally published literature from (1977 to 2002) as presented in Table 1.

1.2 The Independent Variables

The Followings are the selected data of the independent variables; the data were processed to obtain the information listed below and as presented in Table 2.

1. Total alkalis as equivalent Na_2O.
2. Main compounds of cement.
3. Cement surface area (Blaine fineness).

1.3 The Dependent Variables

The value of optimum SO_3 content has to be predicted from the relationship between compressive strength and different SO_3 content as detailed in the presented research items as shown in Table 3. The decision was based on the observed variation of SO_3 content with maximum compressive strength and the change of SO_3 content with age of the same mix.

1.4 Preliminary Statistical Analysis

The analysis focused on the calculation of the following measures of central tendency and dispersion of data and the number of data equal to 178.

1. Mean, median and mode (central tendency)
2. Minimum and maximum, range and standard deviation (dispersion).

The calculated measures of central tendency and dispersion are presented in Table 4.

1.5 Correlation Analysis

Two types of correlation coefficient obtained which were Person and Spearman [SPSS manual] between dependent and independent variables are presented in Table 5 and 6 respectively. First one is used for linear relationship while the second coefficient for non

User Page 244 1/13/2013linear relationships. This is achieved by comparison between calculated (r_c) and the critical correlation coefficient (r_c) at a specified level of significance [Bland (1985)] and can be calculated using the equation given below.

$$r_c = \frac{t_{\alpha/2}}{\sqrt{t_{\alpha/2}^2 + n - 2}}$$

Where: r_c= the critical correlation coefficient α= the level of significance, t = the standard t variable, n = number of sample data pairs.

2. DEVELOPED REGRESSION MODELS FOR CONCRETE

2.1 28-days model

Developments of predictive models for concrete are made in two stages based on age of the product. The first stage focused on data for the age of (28- days) and the second stage for late ages higher than 28-days. First descriptive statistic analysis presented in Table 7. The calculated coefficient for Person and Spearman correlation are presented in Tables 8 and 9 respectively.

Comparison between the values in the two Tables (8) and (9) and indicates that there is a high correlation between the independent variables. From the partial correlation presented in Table 10, it could be concluded in general that the coefficients of correlation of the linear relationship are higher than the critical coefficient of correlation except for the relation with total alk. , C_4AF and fineness Blaine, which is lower than the critical value and it is higher than the nonlinear relationship so the multiple linear regression analysis is used for model development.

Eight models were built for 28-days age presented in Table 11 and the number of data is equal to 33 when ignoring Abdul-Latif ` data (1997-2001) and this means no missing value for total alkalies for model (1-A,2-A,3-A) and 42 when used for models (1-B,2-B,3-B,4 and 5). The missing values for total alkalies were replaced by the average value for all other data.

Table 12 presents the ANOVA, R^2, root mean square of error, Durbin-Watson and ∑residual × predicted SO_3% for all models.

From Tables 11 and 12 the followings can be concluded:

1. The best statistical model is (1-A) since, it has the highest coefficient of determination, R^2 (0,992), lowest root mean square of error (0.3424) and the Durbin- Watson value within the accepted range of (1.5-2.5) although the T- value is not the best but it is still low despite that some independent variables not on the line of concrete technology.
2. For model 2-A, 2-B, the effect of L.O.I is removed because it is less effective in concrete, the following can be concluded:
   - Some independent variables not in the line of concrete technology.
   - High coefficient of determination, R^2 of (0,985 and 0.974), low root mean square of error (0.458 and 0.5816), and the Durbin- Watson is not within the ranges (1.36 and 0.952) and T- value is low value (-0.24 and 0.22).
3. For model 3-A and 3-B the effect of L.O.I and MgO are removed. The reason is that the collected data below the values mentioned in the ASTM specification (6%). Furthermore, examinations of the model suggest the following:
   - Some of the independent variables effect is not consistent with the current knowledge of concrete technology.
   - Low coefficient of determination R^2 of (0.954 and 0,952) in comparison with the other developed models. This is in addition to the high root mean square of error (0.7851 and 0.7753),and the Durbin-Watson statistic is not within the ranges(1.331 and 0.788) and T- value is low value (-0. 81 and 0.01).

4. For model 4 , The effect of total alkalies is removed in order to include Abdul- Latf's data (1997 -2001) , so the model become with no missing values .From this model the following can be observed :

- High coefficient of determination R^2 of (0.987), low root mean square of error (0.417), and the Durbin- Watson is not in within the rang but it is closest to the rang and T- value is the lowest value (0. 01).

5. For model 5 in general the independent effect is consistent with the current knowledge of concrete technology, but the shortcoming is on the statistical concept, it has low coefficient of determination R^2 of (0.952) compared with other model, the low root mean square of error (0.7686), and the Durbin- Watson is not within the range (0.726) despite the low T- value (-0. 01).

From the presented as above analysis it can be concluded that it is so difficult to choose the best acceptable model which satisfies the conditions of concrete science and regression analysis. Therefore, the decision was selected of 1-A, 3-B and 4 for more examination.

Examination of the scatter plots for C_3A and optimum predicted SO_3 versus the residuals are presented in Figs. 1 and 2 for model 1-A, Figs. 3 and 4 for model 3-B and Figs 5 and 6, indicates that model 3-B does not adequately represent the obtained data. Therefore this model is ignored in the following analysis.

Further statistical analysis is made to find the best model among those described as above. The relationship between the observed and predicted SO_3 are presented in Fig. 7 and Fig. 9 for models 1-A and 4 respectively. The conclusion is that the developed models result in minimal random error. By contrast, Fig**.** 8 for model 3-B is less articulate.

Moreover, the distribution of residuals presented in Figs 10 ,11 and 12 for model 1-A , 3-B and 4 respectively provide further evidence to support the conclusion that model 3-B is not a reliable model. To conclude this section, it was decided that the data presented in Fig 12 provide the best fit between observed and predicted SO_3 values. The implication is that model 4 is the best to describe the obtained data.

2.2 Late Ages models (Greater Than 28-Days)

Following the development of 28-days models, a late age (greater than 28-days) model was developed based on the predicted optimum SO_3 content of 28-days and late age. The number of data is equal to 77.

Descriptive statistical analysis is presented in Table 13. The predicted models for late ages are presented in Table 14.

Optimum SO_3 %(Late ages)-model **4**= $0.976 \times SO_3$ (predicted for 28-days) +1.251E-03 $\times$ Time (late ages) eq. (1)

Table 15 shows that the standard error of estimate (R^2) is (0.97). This has the implication that 97.0% of the observed scatter in the data is explained by the adopted model. This conclusion is consistent with result of comparison of the calculated F (1206.493) with the tabulated critical F value of (3.127) at the 95% level of confidence.

Moreover, the calculated Durbin-Watson value is (1.939) which is within the range (1.5-2.5) and hence, a minimal random error would be expected. The value of T-statistics equal to (T= 0.08).

A prove to the conclusion that the developed model result is in a minimal random error can found by examination of Fig. 13.

Examination of Figs.14 and 15 which shows scatter plots of predicted optimum SO_3 and MgO, variables versus the residual. The presented data suggest the existence of random variation between variable values and its residual values.

Finally the distribution of the residuals is shown in Fig. 16**,** from this figure it is clear that the residuals are almost normally distributed.

From all statistical analysis presented above, it is also difficult to select model 4 as the best model for 28-days model since it contain some independent variables not in the line of concrete technology. So all age model may be the alternative model.

2.3 All- Age Concrete Models

Eight development models were built for all ages, and the number of data is equal to 132 when Abdul-Latif `s data (1997-2001) were ignored and 155 when entering them. The results of the preliminary descriptive statistical analysis are presented in **Table 16**.

Results of linear and non linear (Pearson and Spearman) correlation analysis are presented in the form of a matrix in Tables 17 and 18 respectively.

The data presented suggest that in general the linear model provides better fit for the data between the compounds and there are highly correlated with each other.

From the partial correlation presented in Table 19, in general the coefficients of correlation of the linear relationship are higher than the critical coefficient of correlation except for MgO and C_3A. For nonlinear relationship all independent variables are less than the critical value. Based on this result it was decided to use linear multiple regression technique for the developed required statistical model.

The regression equation coefficient obtained, t-value and the decision are presented in Table 20.

From Tables 20 and 21 we can conclude:

1. The best statistical model is (1-A) since ,it has the highest R^2 , lowest root mean square of error and the Durbin- Watson value within the range although the T-value is not the best but it is still a low value despite that some independent variables not on the line of concrete technology .
2. The model (1-B) may be selected as the best model for the following reasons:

- In general the regression coefficient is in the line of concrete technology except for total alkalies and this is because that we replace the value of Latif`s data (1997 and 2001) by mean value and this effect the final result.

- High coefficient of determination R^2 of (0.98) , low root mean square of error (0.4821) and the Durbin – Watson is not within the range , but it is still near the range and with low T- value (-0.49).

- The model includes all independent variables.

3. For model 2-A, 2-B ,3-A and 3-B it is clear from the Table presented above there is a shortcoming either in the statistical concept or that some independent variables contains all expected positive and negative factors and values .

- High coefficient of determination, R^2 (0.98), low root mean square of error (0.417), and the Durbin- Watson is not within the ranges but it is closest to the ranges and T- value is the lowest value (-0.08).

- The model including all independent variables except total alkalies.

5. For model 5 despite all independent variables are in the line of concrete technology ,but the shortcoming is on the statistical concept, it has low coefficient of determination , R^2 (0.962)compared with other model , the highest root mean square of error , and the Durbin- Watson is not within the rang despite the low T- value (0.08) .

Examination of Figs. 17 and 18 for model 4 and Figs.19 and 20 for model 5 which shows scatter plots for C_3S, C_3A, Blaine and age versus the residuals of each variable. The data presented suggest the existence of random variation between variable values and its residual values. The data presented provides further confirmation to the conclusion that the developed model 4 can be considered as the best selected model.

A proof to the conclusion that the developed model results in minimal random error can found by examination of Fig. 21 for model 4. The distribution of the residuals is shown in Fig 22 from this figure it is clear that the residuals are almost normally distributed.

3. CONCLUSIONS

3.1 Development of Models for (28 Days – Late Age And All Age Model) of Concrete:

1. The examination of the data presented for all variables indicates that the coefficients of correlation for linear

not in the line of concrete technology and this due to high correlated between the independent variables .

4. Model 4 is the best model for the following reasons:

- All independent variables is on the line with concrete technology understanding , as it

relationship are substantially higher than that for nonlinear relationship.

2. In general, statistically, it was also found that the MgO content of cement positively affects the optimum SO_3 content.
3. Increasing the SO_3 content in sand affects the optimum SO_3 content of concrete and this effect is more significant than that due to increasing the SO_3 content in coarse aggregate, so total effective SO_3 in concrete is preferred.

3.2 28 Days – Late Age Models:

In the 28-days model the relationship between the independent variables themselves and the optimum SO_3 content is overlapped resulting in the high correlation between them. From the presented regression analysis it is difficult to choose the best model because the regression models are either in the line of concrete technology or best statistical analysis. According to the results obtained from the models of 28-days, the following could be concluded:

1. In general, the trend for both C_3S and C_2S are positive and this is due to the positive influence effect for both C_3S and C_2S on 28-days strength.
2. For more confidence for the above conclusion, the value of regression coefficient C_2S is less than for C_3S in all positive effect models (1-b, 2-B, 3-B, 4, and 5).
3. It was proved statistically that the effect of C_3A is positive.
4. In general, the effect of C_4AF is positive.
5. In general the effect of C_3A is about double that of C4AF except for 1-A, 2-A and 3-A and this due to the combined effect between Abdul – Latif `s data and other authors data.
5. The trend of Blaine fineness is not clear, so it needs more study.

6. It is proved statistically that the optimum SO_3 content increases with increase of age in late age model.

3.3 All Age Models

For our best models 4 and 5, the following could be concluded:

1. The effect of C_3S is positive and of C_2S is negative.
2. The effects of C_3A and C_4AF are positive.
3. The effect of C_3A is about twice the effect of C_4AF.
4. The effects of C_3A and C_4AF are higher than the effects of C_3S and C_2S.
5. The positive effect of fineness Blaine.
6. The positive effect of time led to increase in optimum SO_3 content with increase of age.
7. Blaine fineness and C_3A were found as the major factors affecting the optimum SO_3 content.

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Table 1: The collected data from published literature

Author	No. of data	Type of cement
Al-Rawi (1977)	3	Approximately the same chemical composition and different in Blaine.
Ali (1980)	5	Same chemical composition with 1:2:4 mix and different SO_3 level
Yousif (1981)	6	(3-OPC with 1:2:4,1:3:6 and1:4:8 mix) and (3-SRPC with 1:2:4,1:3:6 and1:4:8 mix)
Zari (1981)	16	(8-OPC with 1:2, 1:3, 1:4, 1:5 mix) and (8-SRPC with 1:1:2, 1:1.33:2.68, 1:2:4 and 1:3:6 mix).
Abood (1988)	2	Same chemical composition with (1:2.75:3.18 and 1:1.84:2.46) mix
Al-Qissi (1989)	1	Chemical composition
Al-Salihi (1994)	7	Different chemical composition with schedule mixes
Abdul-latif (1997)	7	Different chemical composition
Abdul-latif (2002)	5	Different chemical composition

Table2: Selected independent variables, total alkalis, main cement compounds and surface published literatures.

Author	Serial No. of selected data set	Calculated Total Alk. (%)	C_3S (%)	C_2S (%)	C_3A (%)	C_4AF (%)	Surface area(cm^2/gm)
Ali (1980)	1-5	0.94	41.10	34.8	8.8	8.5	3000
Yousif (1981)	1-3	0.86	34.00	38	10	9	3103
	4-6	0.65	49.00	26	2	16	2533
Zari (1981)	1-4	0.53	49.53	20.12	8.76	10.16	3278
	5-8	0.35	61.96	13.7	1.1	15.1	3124
Al-Rawi (1977)	1	0.34	62.00	13	12	11	2500
	2	0.34	62.00	13	12	11	3500
	3	0.34	62.00	13	12	11	4500
Al-Qissi (1989)	1	0.74	47.80	24.2	9.7	9.12	3125
Abood (1988)	1-2	0.58	58.44	15.83	5.22	9.39	3471
Al-Salihi (1994)	1-7	0.80	34.48	36.07	8.87	9.12	3420
Abdul-Latif (1997)	1	-	36.03	36.75	2.55	15.2	3660
	2	-	36.28	33.8	12.91	8.32	3840
	3	-	54.85	19.09	7.71	8.48	3600
	4	-	60.63	13.87	2.65	16.29	4000
	5	-	38.22	34.64	2.57	15.2	3540
	6	-	21.15	51.38	14.79	2.18	3660
	7	-	30.1	39.04	9.52	10.33	3350
Abdul-Latif (2002)	1	-	43.85	32.28	1.61	14.85	2620
	2	-	43.59	31.9	2.3	13.98	2750
	3	-	48.45	26.51	8.53	7.54	2600
	4	-	37.74	36.91	7.66	9.48	2570
	5	-	52.02	21.55	8.02	9.6	2470

Table 3: Optimum SO_3% of concrete at different ages (by weight of cement) from published literature.

Author	Serial	Optimum SO_3 content (%)							
		Time in days							
		7-days	14-days	28-days	56-days	90-days	120-days	181-days	365-days
Al-Rawi (1977)	1	.	.	2.00	.	.	.	2.00	.
	2	.	.	2.00	.	.	.	2.00	.
	3	.	.	2.00	.	.	.	5.70	.
Ali (1981)	1	1.50	.	1.5	2.5	2.00	.	.	1.50
	2	2.00	.	2.00	3.00	2.00	.	.	2.50
	3	2.50	.	2.50	2.20	2.50	.	.	3.00
	4	2.45	.	2.45	2.45	2.45	.	.	2.45
	5	2.70	.	2.70	2.70	2.70	.	.	2.70
Yousif (1981)	1	2.83	.	2.83	.	2.83	.	.	2.83
	2	3.1	.	3.1	.	3.1	.	.	3.1
	3	3.37	.	3.37	.	3.37	.	.	4.44
	4	2.53	.	2.53	.	2.53	.	.	3.07
	5	2.80	.	2.80	.	2.80	.	.	2.80
	6	3.07	.	3.07	.	3.07	.	.	4.14
Zari (1981)	1	.	4.22	4.22	4.22	4.22	.	.	.
	2	.	4.22	4.22	4.22	3.72	.	.	.
	3	.	3.47	4.22	4.22	3.74	.	.	.
	4	.	4.2	4.22	4.22	4.22	.	.	.
	5	.	3.72	4.22	3.72	4.22	.	.	.
	6	.	4.22	4.22	4.22	4.22	.	.	.
	7	.	3.72	3.72	3.72	3.72	.	.	.
	8	.	4.22	4.22	4.22	4.22	.	.	.
	9	.	3.22	3.22	3.47	3.22	.	.	.
	10	.	3.22	3.22	3.22	3.22	.	.	.
	11	.	3.2	3.22	3.72	4.22	.	.	.
	12	.	3.22	3.22	3.22	3.22	.	.	.
	13	.	3.22	3.22	3.47	3.22	.	.	.
	14	.	3.22	3.22	3.22	3.22	.	.	.
	15	.	3.22	3.47	3.22	3.47	.	.	.
	16	.	3.22	3.22	3.22	3.22	.	.	.
Abood (1988)	1	.	3.35	3.35	.	.	.	.	.
	2	.	3.20	3.20	.	.	.	.	.
Al-Qissi (1989)	1	3.39	.	3.94	.	.	3.94	.	.
Al-salihi (1994)	1	2.96	.	2.33	2.96	2.96	.	2.96	.
	2	2.54	.	2.54	3.09	3.09	.	3.09	.
	3	2.89	.	23.24	3.41	3.41	.	3.41	.
	4	3.24	.	3.24	3.24	3.24	.	3.73	.
	5	3.56	.	3.56	3.56	3.56	.	3.56	.
	6	3.88	.	3.88	3.88	3.88	.	3.88	.
	7	4.17	.	4.17	4.17	4.17	.	4.17	.
Abdul-Latif (1997)	1	3.4	.	3.4	.	.	3.4	.	.
	2	3.81	.	3.81	.	.	3.81	.	.
	3	4.47	.	4.47	.	.	4.47	.	.
	4	4.58	.	4.58	.	.	3.34	.	.
	5	3.24	.	3.24	.	.	3.24	.	.

	6	4.96	.	4.39	.	.	4.96	.	.
	7	4.12	.	4.52	.	.	4.12	.	.
Abdul-Latif(2001)	1	.	.	3.52	.	.	.	.	3.87*
	2	.	.	3.23	.	.	.	.	3.90*
	3	.	.	4.00	.	.	.	.	4.00*
	4	.	.	3.55	.	.	.	.	3.90*
	5	.	.	3.30	.	.	.	.	3.97*

* For 300 – days

Table 4: Descriptive statistics analysis for cement mortar (all data)

Compound	Central tendency			Dispersion			
	Mean	Median	Mode	Std. deviation	Range	Minimum	Maximum
MgO%	3.3153	3.400	4.110	0.831	3.300	0.9	4.20
Total Alk.[1]%	1.158	1.160	1.160	0.271	0.690	0.86	1.55
C_3S%	45.053	41.100	34.480	11.148	40.8	21.15	62.00
C_2S%	27.732	34.640	36.070	10.221	38.30	13.0	51.38
C_3A%	7.407	8.800	8.870	3.528	13.60	1.1	14.79
C_4AF%	10.551	9.120	9.120	2.768	14.10	2.18	16.29
L.O.I%	1.399	1.610	1.620	0.614	2.500	.20	2.70
Blaine gm/cm^2	3235.7	3201.0	3420.0	297.23	2030	2470	4500
Total eff. SO_3%	3.375	3.240	3.220	0.708	4.20	1.5	5.70

Table 5: Correlation matrix for dependent and independent variables (Person correlation)

Variable	MgO	Total Alk.	C_3S	C_2S	C_3A	C_4AF	L.O.I	Blaine	Ages	SO_3%
MgO	1.00	.239**	-.194**	.066	.255**	-.389**	.150	-.074	-.115	.379**
Total Alk.	.239**	1.00	-.901**	.957**	.593**	-.733**	-.430	-.078	.236**	-.334**
C_3S	-.194**	-.901**	1.00	-.974**	-.624**	.657**	-.048	.157*	-.159*	.101
C_2S	.066	.957**	-.974**	1.00	.541**	-.608**	-.084	-.161*	.191**	-.240**
C_3A	.255**	.593**	-.624**	.541**	1.00	-.919**	-.105	-.119	.084	.048
C_4AF	-.389**	-.733**	.657**	-.608**	-.919**	1.00	.098	.197**	-.080	-.040
L.O.I	.150	-.430	-.048	-.084	-.105	.098	1.000	.201	-.115	.539
Blaine	-.074	-.078	.157*	-.161*	-.119	.197**	.201	1.00	-.050	-.048
Ages	-.115	.236**	-.159*	.191**	.084	-.080	-.115	-.050	1.00	.040
SO_3%	.379**	-.334**	.101	-.240**	.048	-.040	.539	-.048	.040	1.00

Table 6: Correlation matrix for dependent and independent variables (Spearman correlation)

Variable	MgO	Total Alk.	C_3S	C_2S	C_3A	C_4AF	L.O.I	Blaine	Ages	SO_3%
MgO	1.00	.090	-.093	.060	.133	-.265**	.317	.364**	-.055	.471**
Total Alk.	.090	1.00	-.868**	.867**	.595**	-.874**	-.359	-.207**	.077	-.380**
C_3S	-.093	-.868**	1.00	-.987**	-.709**	.595**	-.050	-.148*	-.058	.122
C_2S	.060	.867**	-.987**	1.00	.666**	-.583**	.024	.079	.068	-.143*
C_3A	.133	.595**	-.709**	.666**	1.00	-.703**	-.060	.298**	.067	-.085
C_4AF	-.265**	-.874**	.595**	-.583**	-.703**	1.00	.113	-.055	-.049	.129
L.O.I	.317	-.359	-.050	.024	-.060	.113	1.000	.524	-.052	.521
Blaine	.364**	-.207**	-.148*	.079	.298**	-.055	.524	1.00	-.104	.190**
Ages	-.055	.077	-.058	.068	.067	-.049	-.052	-.104	1.00	.070
SO_3%	.471**	-.380**	.122	-.143*	-.085	.129	.521	.190**	.070	1.00

**, Correlation is significant at the 0.01 level (2-tailed)*, Correlation is significant at the 0.05 level (2-tailed)
$r_c = 0.118$ for N= 192 for all variable except for total Alk. $r_c = 0.1875$ for N= 113

Table 7: Descriptive statistics analysis for concrete (28-days)

Variables	Mean	Stan. deviation	Minimum	Maximum
MgO%	3.106	0.959	0.900	4.200
Total Alk. %	0.617	0.215	0.340	0.940
C_3S%	46.956	11.326	21.150	62.000
C_2S%	26.101	10.375	13.000	51.380
C_3A%	7.022	3.857	1.100	14.790
C_4AF%	10.931	3.115	2.180	16.290
L.O.I%	1.424	0.623	0.200	2.700
Blaine gm/cm^2	3193.47	408.900	2470.00	4500.00
Total eff. SO_3%	3.209	0.684	1.500	4.220

No. of data = 42 for all variables except for total Alk. No. of data = 33

Table 8: Person correlation values for 28-days for concrete

Variables	MgO	Tot. AlK.	C_3S	C_2S	C_3A	C_4AF	L.O.I	Blaine	SO_3%
MgO	1.000	0.114	-0.054	-0.015	-0.004	-0.172	0.194	0.343*	0.527**
Tot. AlK.	0.114	1.000	-0.913**	0.912**	0.508**	-0.854**	-0.279	-0.174	-0.222
C_3S	-0.054	-0.913**	1.000	-0.985**	-0.615**	0.642**	-0.136	-0.093	0.048
C_2S	-0.015	0.912**	-0.985**	1.000	0.555**	-0.613**	0.138	0.006	-0.074
C_3A	-0.004	0.508**	-0.615**	0.555**	1.000	-0.698**	-0.047	0.242	-0.156
C_4AF	-0.172	-0.854**	0.642**	-0.613**	-0.698**	1.000	0.032	-0.021	0.031
L.O.I	0.194	-0.279	-0.136	0.138	-0.047	0.032	1.000	0.328	0.559
Blaine	0.343*	-0.174	-0.093	0.006	0.242	-0.021	0.328	1.000	0.095
SO_3%	0.527**	-0.222	0.048	-0.074	-0.156	0.031	0.559	0.095	1.000

**, Correlation is significant at the 0.01 level (2-tailed): *, Correlation is significant at the 0.05 level (2-tailed)

Table 9: Spearman correlation values for 28-days for concrete

Variables	MgO	Tot. AlK.	C_3S	C_2S	C_3A	C_4AF	L.O.I	Blaine	SO_3%
MgO	1.000	0.257	-0.124	0.006	0.057	-0.223	0.133	0.174	0.493**
Tot. AlK.	0.257	1.000	-0.907**	0.951**	0.532**	-0.712**	-0.332	-0.116	-0.262
C_3S	-0.124	-0.907**	1.000	-0.977**	-0.598**	0.646**	-0.16	-0.062	0.078
C_2S	0.006	0.951**	-0.977**	1.000	0.520**	-0.601**	0.061	-0.017	-0.208
C_3A	0.057	0.532**	-0.598**	0.520**	1.000	-0.891**	-0.051	0.242	-0.044
C_4AF	-0.223	-0.712**	0.646**	-0.601**	-0.891**	1.000	-0.142	-0.142	-0.039
L.O.I	0.133	-0.332	-0.16	0.061	-0.051	0.0021	1.000	0.108	0.626*
Blaine	0.174	-0.116	-0.062	-0.017	0.242	-0.142	0.108	1.000	-0.063
SO_3%	0.493**	-0.262	0.078	-0.208	-0.044	-0.039	0.626*	-0.063	1.000

**, Correlation is significant at the 0.01 level (2-tailed): *, Correlation is significant at the 0.05 level (2-tailed)

r_c = 0.304 for N=42 for all variables except for total Alk. r_c = 0.3442 for N=33

Table 10: Partial correlation for concrete model (28-days) between optimum SO_3% and other compounds

Variables	Person correlation	Spearman correlation
MgO	0.4829	0.0508
Total alkalies	0.1719	0.0000
C_3S	0.6765	0.0220
C_2S	-0.6841	-0.0150
C_3A	-0.3044	-0.0805
C_4AF	-0.0155	0.0000
L.O.I	0.4554	0.0000
Blaine	-0.078	-0.0768

No.of data = 42 for all variables except for total Alk. No. of data = 33

Table 11: Regression equation coefficients and other statistical measures for concrete (28-days).

Model	1-A			1-B		
Independent variable	Regression coefficient	t- vale	Decision (5%)	Regression coefficient	t- vale	Decision (5%)
MgO%	-0.150	-0.718	Accept	0.380	4.644	Reject
Total Alk%	4.417	2.773	Reject	-0.167	-0.22	Accept
C_3S%	3.307E-02	0.914	Accept	3.008E-02	2.562	Reject
C_2S%	-7.458E-02	-1.400	Accept	1.003E-02	0.570	Accept
C_3A%	3.344E-02	0.616	Accept	6.843E-02	1.691	Accept
C_4AF%	-7.394E-02	-0.529	Accept	2.964E-02	0.614	Accept
L.O.I%	1.649	4.64	Reject	0.730	5.739	Reject
Blaine gm/cm^2	-8.779E-05	-0.379	Accept	-4.344E-04	-2.434	Reject
Model	2-A			2-B		
Independent variable	Regression coefficient	t- vale	Decision (5%)	Regression coefficient	t- vale	Decision (5%)
MgO%	0.751	07.302	Reject	0.557	5.321	Reject
Total Alk%	3.728	1.757	Reject	-2.390	-2.695	Reject
C_3S%	-8.954E-02	-2.706	Reject	3.266E-02	2.013	Reject
C_2S%	-0.171	-2.613	Reject	5.322E-02	2.416	Reject
C_3A%	0.210	4.064	Reject	7.724E-02	1.545	Accept
C_4AF%	0.445	3.978	Reject	6.222E-02	0.938	Accept
L.O.I%	-	-	-	-	-	-

Blaine gm/cm^2	1.787E-04	0.596	Accept	-3.705E-04	-1.504	Accept
Model	3-A			3-B		
Independent variable	Regression coefficient	t- vale	Decision (5%)	Regression coefficient	t- vale	Decision (5%)
MgO%	-	-	-	-	-	-
Total Alk%	3.067	0.844	Accept	-0.663	-606	Accept
C_3S%	-5.880E-02	-1.045	Accept	4.284E-02	2.005	Reject
C_2S%	-0.109	-0.979	Accept	3.901E-02	1.345	Accept
C_3A%	8.392E-02	1.004	Accept	2.429E-02	0.374	Accept
C_4AF%	0.258	1.379	Reject	-8.292E-03	-0.096	Accept
L.O.I%	-	-	-	-	-	-
Blaine gm/cm^2	1.065E-03	2.266	Accept	1.563E-04	0.523	Accept
Model	4			5		
Independent variable	Regression coefficient	t- vale	Decision (5%)	Regression coefficient	t- vale	Decision (5%)
MgO%	0.371	5.26	Reject	-	-	
Total Alk%	-	-		-	-	
C_3S%	2.942E-02	1.425	Accept	3.845E-02	1.530	Accept
C_2S%	6.903E-03	0.658	Accept	2.57E-02	1.37	Accept
C_3A%	6.786E-02	1.206	Accept	2.496E-02	0.388	Accept
C_4AF%	2.945E-02	0.69	Accept	-1.204E-03	-0.014	Accept
L.O.I%	0.745	2.934	Reject	-	-	-
Blaine gm/cm^2	-4.277E-04	-1.465	Accept	1.745E-04	0.592	Accept

Table 12: General statistical concept for concrete (28-days)

Model	ANOVA					R^2	Root mean square of error	Durbin-Watson	∑Re.× predicted SO_3%
	Source	D.F.	Sum of squares	Mean square	F value				
1-A	Model(Reg.)	8	355.491	44.436	379.004	0.992	0.3424	1.549	0.07
	Error(Res.)	25	2.931	0.117					
	Total	33	358.422						
1-B	Model(Reg.)	8	445.716	55.714	311.736	0.987	0.4228	1.313	0.12
	Error(Res.)	34	6.077	0.179					
	Total	42	451.792						
2-A	Model(Reg.)	7	352.967	50.424	240.334	0.985	0.4580	1.360	-0.24
	Error(Res.)	26	5.455	0.210					
	Total	33	358.422						
2-B	Model(Reg.)	7	439.830	62.833	183.839	0.974	0.5846	0.952	0.22
	Error(Res.)	35	11.962	0.342					
	Total	42	451.792						
3-A	Model(Reg.)	6	341.781	56.963	92.420	0.954	0.7851	1.331	-0.81
	Error(Res.)	27	16.642	0.616					
	Total	33	358.422						
3-B	Model(Reg.)	6	430.154	71.692	119.278	0.952	0.7753	0.788	0.01
	Error(Res.)	36	21.638	0.601					
	Total	42	451.792						
4	Model(Reg.)	7	445.707	63.672	366.205	0.987	0.417	1.327	0.01
	Error(Res.)	35	6.085	0.174					
	Total	42	451.792						
5	Model(Reg.)	5	429.934	85.987	145.551	0.952	0.7686	0.726	-0.01
	Error(Res.)	37	21.858	0.591					
	Total	42	451.792						

Table 13: Descriptive statistics analysis for concrete (Late age) for model 4

Compound	Mean	Standard deviation	Minimum	Maximum
Time (Late age)-days	148.64	119.96	56	365
Total eff. SO_3%	3.3487	0.6952	1.5	5.7
Opt. SO_3% predicted(28-days)	3.2155	0.5656	1.61	4.08

No. of data for model 4= 77

Table 14: Regression equation with standard error for each compound

Independent variable	Regression coefficient	Standard error
Time (late ages)-days	1.251E-03	0.031
Opt.SO_3(predicted for 28-days)%	0.976	0.001

Table 15: General statistical concept for concrete models (late age) for model 4

ANOVA					R^2	Root mean square of error
Source	D.F.	Sum of squares	Mean square	F value		
Model(Reg.)	2	873.058	436.529	1206.493	0.97	0.6015
Error(Res.)	75	27.136	0.362			
Total	77	900.195				

Table 16: Result of descriptive statistical analysis for concrete (All ages)

Variables	Mean	Stan. deviation	Minimum	Maximum
MgO%	3.259	0.872	0.900	4.200
Total Alk.%	0.643	0.216	0.340	0.940
C_3S%	46.113	11.047	21.150	62.00
C_2S%	26.811	10.124	13.000	51.380
C_3A%	7.011	3.731	1.100	14.790
C_4AF%	10.904	3.044	2.180	16.290
L.O.I%	1.396	0.606	0.200	2.700
Blaine gm/cm^2	3197.194	345.864	2470.000	4500.000
All ages-days	82.000	103.964	7.000	365.00
Total eff. SO_3%	3.273	0.671	1.500	5.700

No. of data = 155 for all variables except for total Alk. No. of data =132

Table 17: Person correlation values for all ages concrete data

Variables	MgO	Total Alk.[1]	C_3S	C_2S	C_3A	C_4AF	L.o.I	Blaine	All ages	SO_3%
MgO	1.000	.051	-.036	-.013	.048	-.163*	.318**	.383**	-.053	.446**
Tot.AlK[1]	.051	1.000	-.877**	.876**	.646**	.67**	.018	.076	.068	-.189*
C_3S	-.036	-.877**	1.000	-.987**	-.756**	.67**	-.026	-.142	-.059	.167*
C_2S	-.013	.876**	-.987**	1.000	.702**	-.639**	.018	.076	.068	-.189*
C_3A	.048	.646**	-.756**	.702**	1.000	-.738**	-.04	.256**	.060	-.114
C_4AF	-.163*	-.89**	.67**	-.639**	-.738**	1.000	.148	.011	-.060	.162*
L.O.I	.318**	-.401**	-.026	.018	-.04	.148	1.000	.537**	-.044	.565**
Blaine	.383**	-.218*	-.142	.076	.256**	.011	.537**	1.000	-.117	.263**
All ages	-.053	.079	-.059	.068	.06	-.06	-.044	-.117	1.000	.085
SO_3%	.446**	-.405**	.167*	-.189*	-.114	.162*	.565**	.263**	.085	1.000

Table 18: Spearman correlation values for all ages concrete data

Variables	MgO	TotalAlk	C_3S	C_2S	C_3A	C_4AF	L.O.I	Blaine	All ages	SO_3%
MgO	1.000	.195*	-.152	.026	.19*	-.297**	.129	.24**	-.124	.324**
Tot. AlK.[1]	.195*	1.000	-.904**	.957**	.632**	-.755**	-.473**	-.086	.250**	-.394**
C_3S	-.152	-.904**	1.000	-.974**	-.69**	.715**	-.035	-.131	-.163*	.158*
C_2S	.026	.957**	-.974**	1.000	-.609**	-.67**	-.098	.037	.195*	-.294**
C_3A	.190*	.632**	-.69**	-.609**	1.000	-.922**	-.052	.276**	.099	.036
C_4AF	-.297**	-.755**	.715**	-.67**	-.922**	1.000	.076	-.198*	-.097	-.004
L.O.I	.129	-.473**	-.035	-.098	-.052	.076	1.000	.272**	-.12	.552**
Blaine	.240**	-.086	-.131	.037	.276**	-.198*	.272**	1.000	-.177*	.146
All ages	-.124	.25**	-.163*	.195*	.099	-.097	-.120	-.177*	1.000	.032
SO_3%	.324**	-.394**	.158*	-.294**	.036	-.004	.552**	.146	.032	1.000

No. of data = 155; [1], means number of data =132
$r_c = 0.1565$ for No. of data =155 , $r_c = 0.1694$ for No. of data =132 .
**, Correlation is significant at the 0.01 level (2-tailed): *, Correlation is significant at the 0.05 level (2-tailed)

Table 19: Partial correlation for concrete model (all ages) between optimum SO_3% and other compounds

Variables	Person correlation	Spearman correlation
MgO	0.0678	-
Total alkalies[1]	0.2685	0.0000
C_3S	0.4806	0.0421
C_2S	-0.4979	0.0250
C_3A	-0.0194	0.0639
C_4AF	0.1598	0.000
L.O.I	0.1995	0.0000
Blaine	0.3144	-
Ages	0.2173	0.1556

No. of data = 155 , [1] means No. of data = 132 , $r_c = 0.1565$ for No. of data =155 , $r_c = 0.1694$ for No. of data =132 .

Table 20: Regression equation coefficients and other statistical measures for concrete (all age).

Model	1-A			1-B		
Independent variable	Regression coefficient	t- vale	Decision (5%)	Regression coefficient	t- vale	Decision (5%)
MgO%	-0.112	-0.81	Accept	0.275	5.096	Reject
Total Alk%	4.32	3.952	Reject	-0.568	3.28	Reject
C_3S%	-3.071E-02	-1.188	Accept	2.580E-02	0.51	Accept
C_2S%	-0.126	-3.519	Reject	5.910E-03	1.605	Accept
C_3A%	8.164E-02	1.177	Accept	9.341E-02	1.29	Accept
C_4AF%	0.116	1.202	Accept	4.275E-02	6.607	Reject
L.O.I%	1.001	4.187	Reject	0.581	-1.523	Accept
Blaine gm/cm^2	7.603E-04	1.657	Accept	1.982E-04	0.959	Accept
Time(All ages)-days	9.014E-04	2.433	Reject	1.164E-03	-1.127	Accept
Model	2-A			2-B		
Independent variable	Regression coefficient	t- vale	Decision (5%)	Regression coefficient	t- vale	Decision (5%)
MgO%	0.416	6.841	Reject	0.404	2.225	Reject
Total Alk%	3.585	1.235	Accept	-2.601	2.759	Reject
C_3S%	-0.111	-6.091	Reject	1.912E-02	1.534	Accept
C_2S%	-0.183	-5.175	Reject	3.341E-02	2.361	Reject
C_3A%	0.198	7.363	Reject	0.112	0.517	Accept
C_4AF%	0.451	1.65	Accept	8.528E-02	2.976	Reject
L.O.I%	-	-	-	-	-	-
Blaine gm/cm^2	9.936E-04	3.24	Reject	4.995E-06	-5.523	Reject
Time(All ages)-days	9.307E-04	1.021	Accept	1.349E-03	1.641	Accept
Model	3-A			3-B		
Independent variable	Regression coefficient	t- vale	Decision (5%)	Regression coefficient	t- vale	Decision (5%)
MgO%	-			-		
Total Alk%	3.594	2.677	Reject	-1.568	3.263	Reject
C_3S%	-0.107	-5.027	Reject	3.257E-02	1.608	Accept
C_2S%	-0.174	-4.196	Reject	2.754E-02	4.914	Reject
C_3A%	0.156	5.732	Reject	0.144	1.113	Accept
C_4AF%	0.381	5.113	Reject	9.049E-02	-0.523	Accept
L.O.I%	-	-	-	-	-	-
Blaine gm/cm^2	1.639E-03	0.796	Accept	-5.930E-06	1.435	Accept
Time(All ages)-days	5.599E-04	1.226	Accept	7.448E-04	-2.926	Reject
Model	4			5		
Independent variable	Regression coefficient	t- vale	Decision (5%)	Regression coefficient	t- vale	Decision (5%)
MgO%	0.245	5.2	Reject	-	-	-
Total Alk%	-	-	-	-	-	-
C_3S%	2.432E-02	3.133	Reject	1.377E-02	1.396	Accept
C_2S%	-4.311E-03	-0.598	Accept	-1.311E-02	-1.399	Accept
C_3A%	8.911E-02	1.631	Accept	9.77E-02	2.951	Reject
C_4AF%	3.909E-02	1.184	Accept	6.824E-02	1.6	Accept
L.O.I%	0.641	9.099	Reject	-	-	-
Blaine gm/cm^2	1.78E-04	1.379	Accept	4.628E-04	1.043	Accept
Time(All ages)-days	1.11E-03	1.365	Accept	8.815E-04	1.672	Accept

Table 21: General statistical concept for concrete (All ages)

Model	ANOVA					R^2	Root mean square of error	Durbin-Watson	∑Re.> predicted SO_3%
	Source	D.F.	Sum of squares	Mean square	F value				
1-A	Model(Reg.)	9	1475	163.907	939.65	0.986	0.4177	1.725	-4.45
	Error(Res.)	123	21.45	0.174					
	Total	132	1496.6						
1-B	Model(Reg.)	9	1696.7	188.472	812.33	0.98	0.4817	1.223	-0.49
	Error(Res.)	146	33.874	0.232					
	Total	155	1730						
2-A	Model(Reg.)	8	1472.1	184.013	930.81	0.984	0.4446	1.474	-15.05
	Error(Res.)	124	24.514	0.198					
	Total	132	1496.6						
2-B	Model(Reg.)	8	1686.0	210.759	703.36	0.975	0.5474	0.912	2.59
	Error(Res.)	147	44.04	0.3					
	Total	155	1730						
3-A	Model(Reg.)	7	1462.8	208.979	773.63	0.977	0.5197	1.216	-2.05
	Error(Res.)	125	33.766	0.270					
	Total	132	1496.6						
3-B	Model(Reg.)	7	1667.7	238.251	565.44	0.962	0.6491	0.66	-0.69
	Error(Res.)	148	62.361	0.421					
	Total	155	1730.1						
4	Model(Reg.)	8	1695.95	211.994	912.035	0.98	0.4821	1.246	-0.08
	Error(Res.)	147	34.169	0.232					
	Total	155	1730.12						
5	Model(Reg.)	6	1666.8	277.809	654.26	0.962	0.6516	1.021	0.08
	Error(Res.)	149	63.267	0.425					
	Total	155	1730.1						

Model 1-A

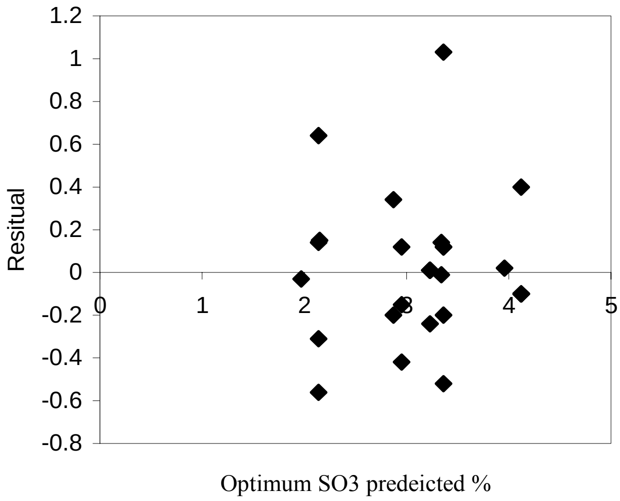

Fig. 1:Relationship between optimum SO3-predicted and resituals

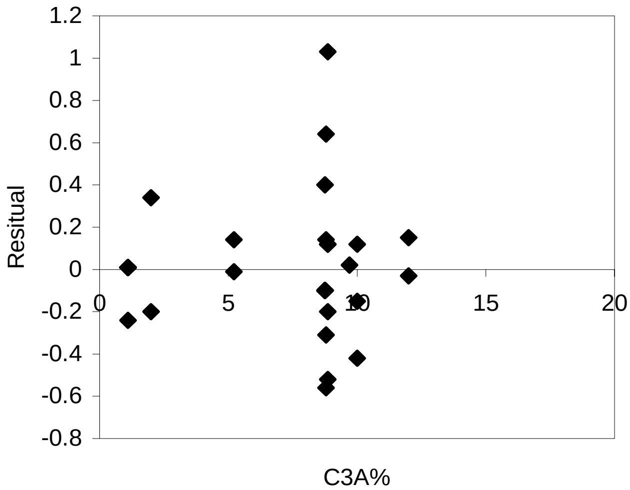

Fig. 2 :Relationship between C3A and resituals

Model 3-B

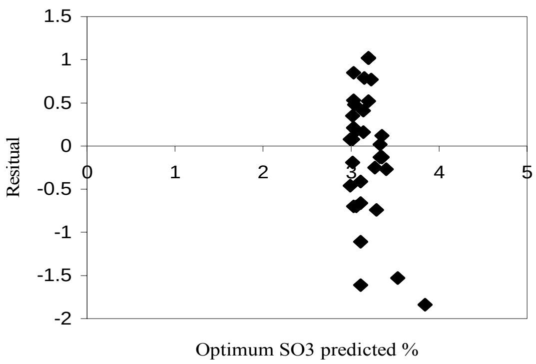

Fig. 3 :Relationship between optimum SO3-predicted and resituals

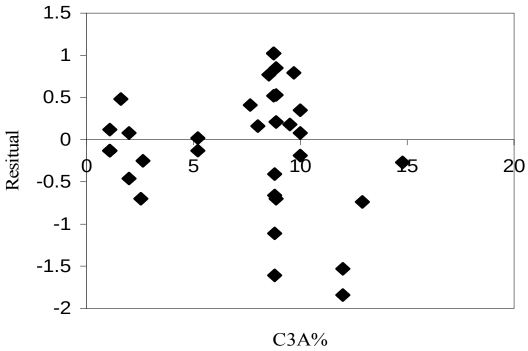

Fig. 4:Relationship between C3A and resituals

Model 4

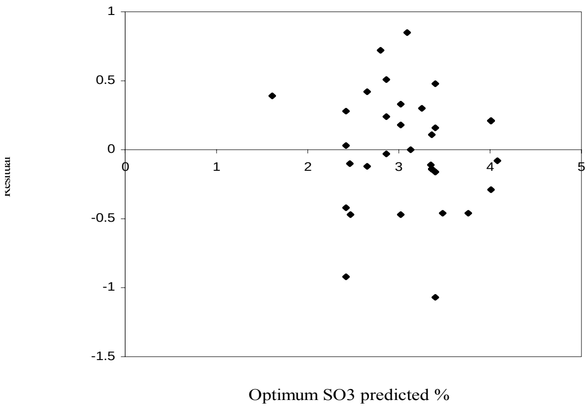

Fig. 5 :Relationship between optimum SO3-predicted and resituals

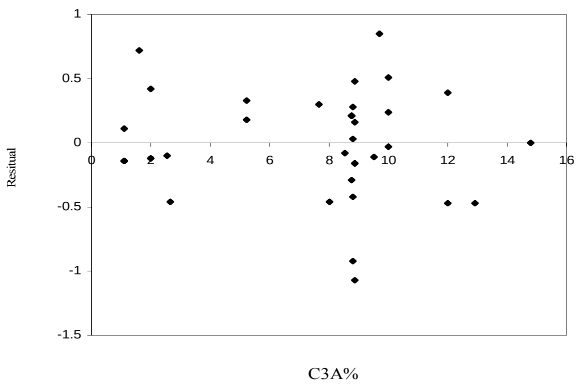

Fig. 6 :Relationship between C3A and resituals

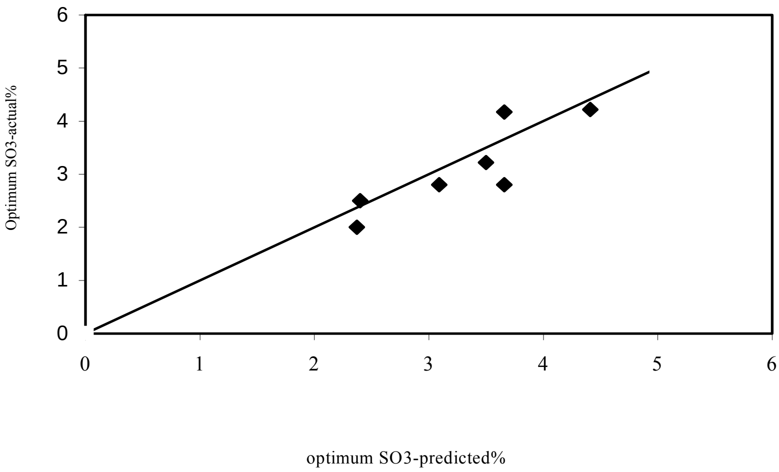

Fig. 7 : Relationship between optimum SO3-predic and actual for concrete model -28-days (1-A model)

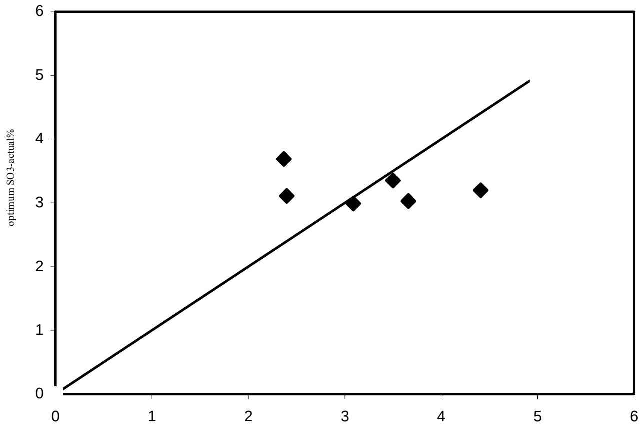

Fig. 8 : Relationship between optimum SO3-predicted and actual for concrete model -28-days (3-B model)

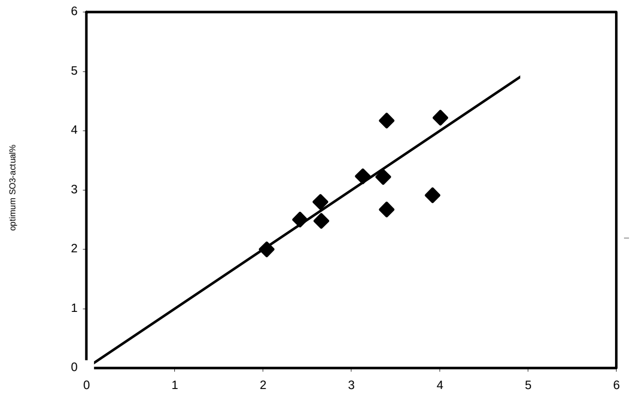

Fig. 9 : Relationship between optimum SO3-predic and -actual for concrete model -28-days (4 model)

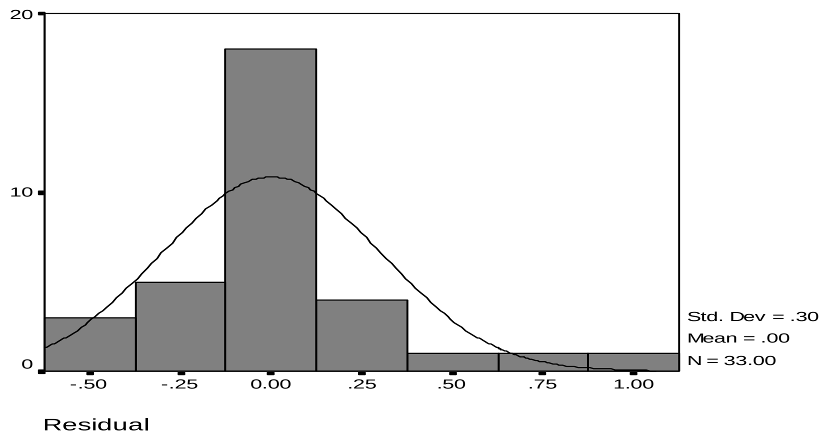

Fig. 10: Residual distribution for 28-days model (1-A)

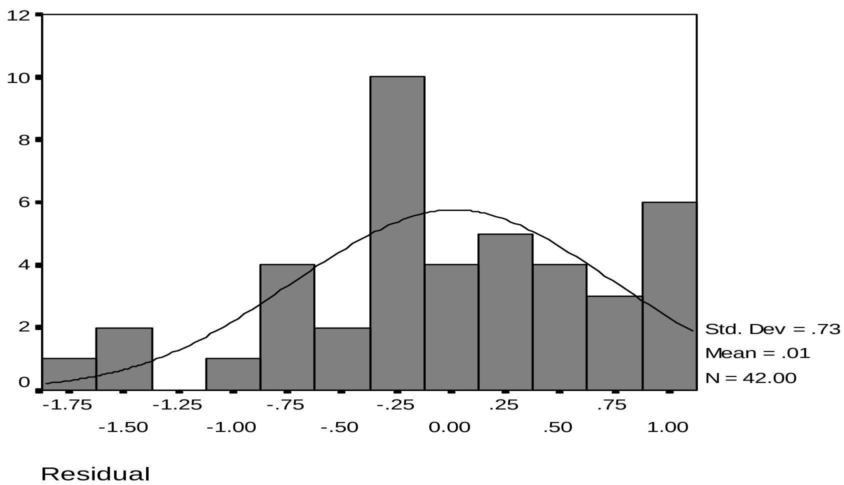

Fig. 11: Residual distribution for 28-days (3-B)

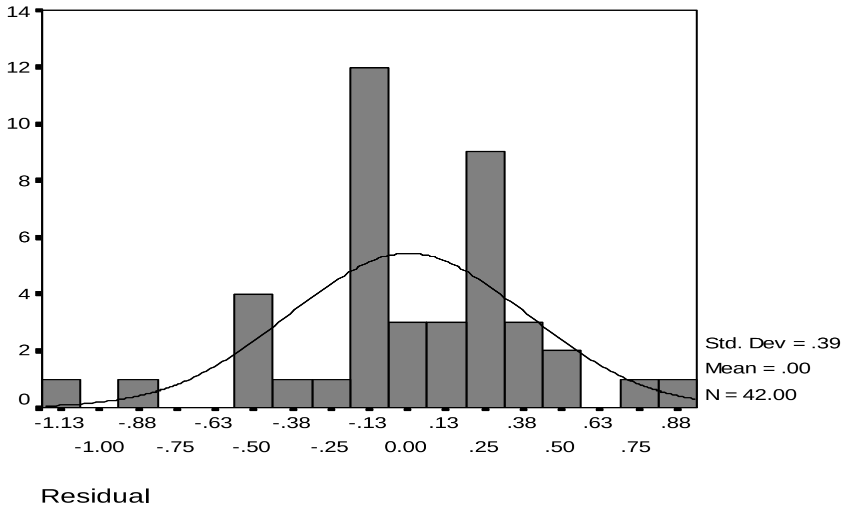

Fig. 12: Residual distribution for 28-days model (4)

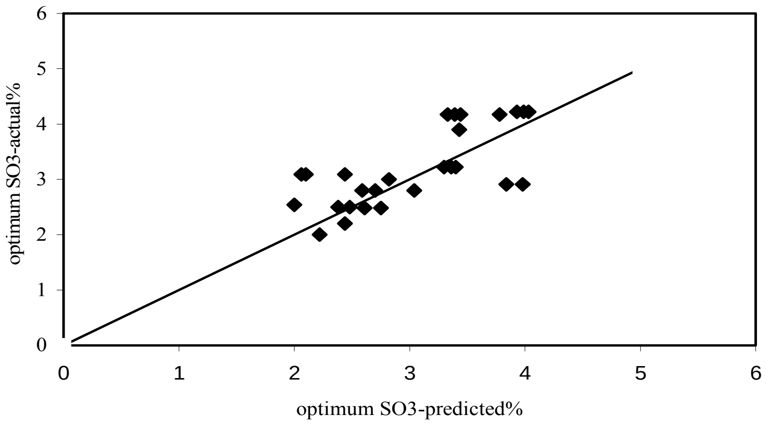

Fig. 13 : Relationship between optimum SO3-predic and actual for concrete model -late ages-model 4

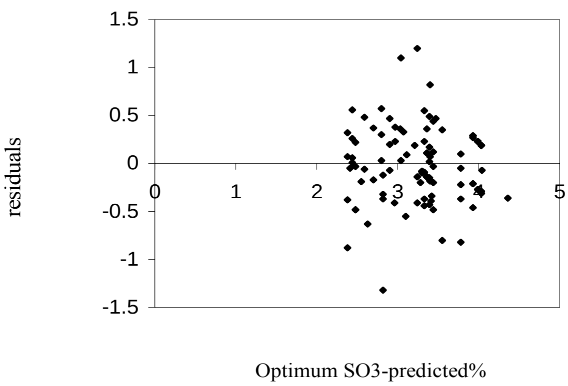

Fig. 14: Relationship between optimum predicte SO3 and residuals

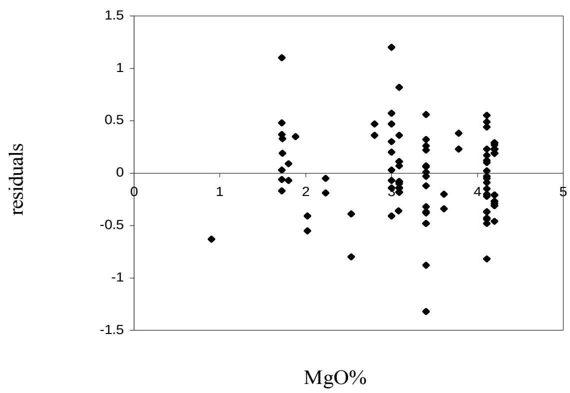

Fig. 15: Relationship between MgO and residuals

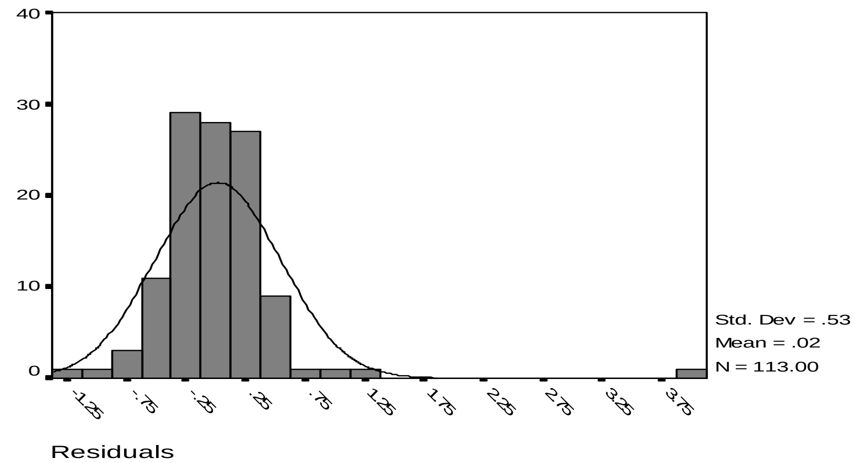

Fig. 16: Residual distribution for any age concrete model NO. 4

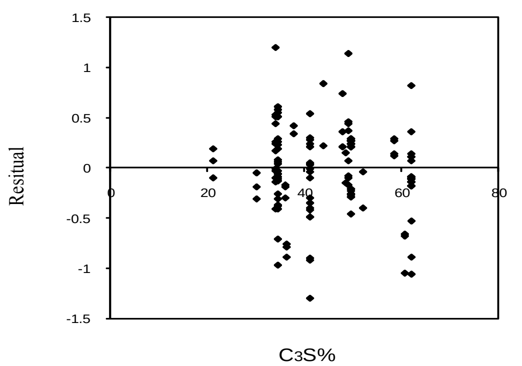

Fig. 17:Relationship between C3S and resituals

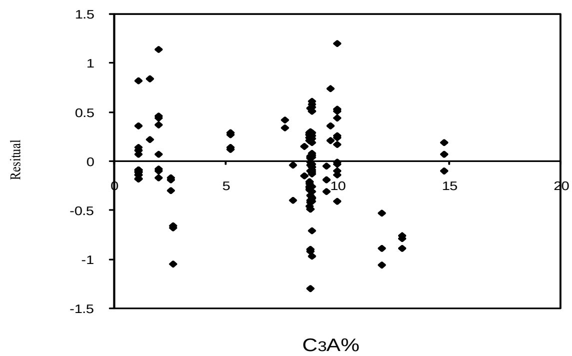

Fig. 18:Relationship between C3A and resituals

Model 4:

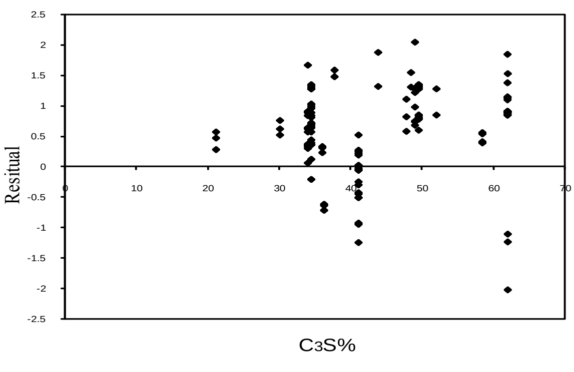

Fig. 19:Relationship between C3S and resituals

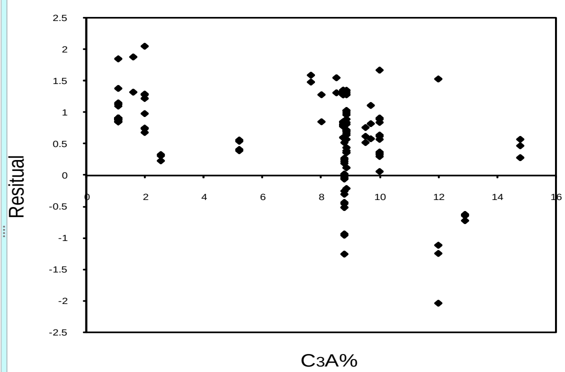

Fig. 20:Relationship between C3A andresituals

Model 5:

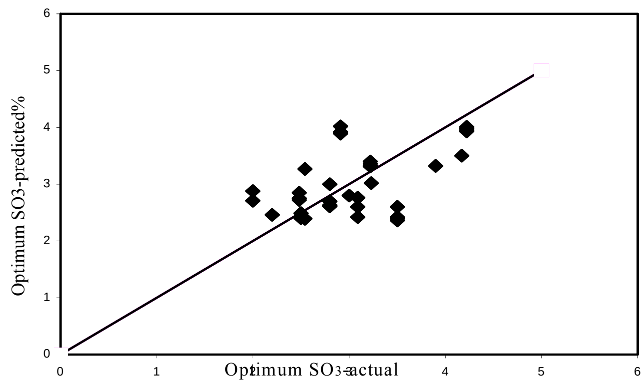

Fig. 21:Relationship between optimum SO3 actual and predicted

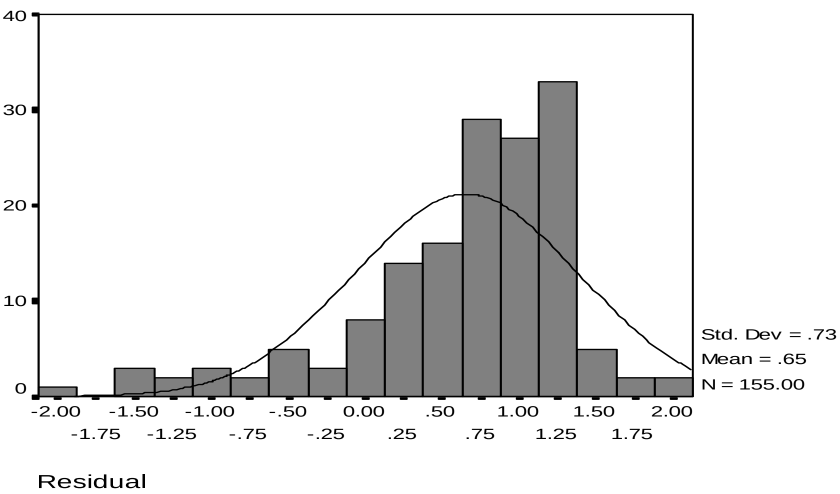

Fig. 22: Residuals distribution for concrete (all Age) - model 4