A STATITICAL MODEL FOR PREDICTIN AUTO-CLAVE EXPANSION OF PORTLAND CEMENT

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Abstract:

The present study aims aimed to investigate factors affecting the soundness of Portland cement (in terms of autoclave expansion test). These factors are C_3S, C_2S, C_3A, C_4AF, fineness (in terms of specific surface measured by Blaine method), the minor oxides MgO, free CaO, SO_3, and the variables obtained from the chemical analysis of cement like silica modulus (SM), alumina ratio (AR), loss on ignition (LOI), insoluble residue (IR), and lime saturation factor (LSF). The autoclave expansion prediction models were built by using multiple linear regression analysis and based on (40) different cement samples taken from (7) different Iraqi cement factories, Indian cement, and Kuwaiti cement. (29) of the samples were ordinary Portland cement while the other (11) samples were sulphate resisting Portland cement. It was found that the multiple linear regression is very suitable for predicting the autoclave expansion of Portland cement. It was also found that the increase of fineness of cement, LSF, and LOI decreases the autoclave expansion, while the increase in the other factors increases the autoclave expansion. The correlation coefficients of the proposed models were (0.71002 and 0.98338) for the first model, (0.84366 and 0.98789) for the second model, and (0.85593 and 0.98872) for the third model, with and without intercept respectively.

Key words: soundness of cement, autoclave test, Portland cement, expansion, oxides of cement.

موديل إحصائي للتنبؤ بمقدار التمدد في فحص المحمم البخاري للسمنت البورتلاندي

الخلاصة:

الدراسة الحالية تهدف إلى تحري العوامل التي تؤثر على فحص الثبات (معبراً عنه بطريقة المحمم البخاري) للسمنت البورتلاندي. هذه العوامل هي (C_3S, C_2S, C_3A, C_4AF)، النعومة (معبراً عنها بالمساحة السطحية النوعية المقاسة بطريقة Blaine)، الاكاسيد الثانوية MgO،الجير الحر free CaO، SO_3، والمتغيرات التي يتم الحصول عليها من التحليل الكيميائي للسمنت مثل معامل السليكا (SM)، نسبة الالومينا (AR)، الفقدان أثناء الإيقاد (LOI)، المخلفات غير الذائبة (IR)، ومعامل الإشباع الجيري (LSF). إن نماذج تخمين التمدد بطريقة المحمم بنيت باستخدام تحليل الانحدار الخطي المتعدد و مستند على (40) من عينات السمنت المختلفة مأخوذة من (7) معامل سمنت عراقية مختلفة، سمنت هندي، و سمنت كويتي. (29) من العينات كانت سمنت بورتلاندي اعتيادي بينما الـ (11) عينة الأخرى كانت سمنت بورتلاندي مقاوم للكبريتات. لقد وجد ان الانحدار الخطي المتعدد ملائم جداً لتخمين تمدد السمنت البورتلاندي بطريقة المحمم. كذلك وجد ان الزيادة في نعومة السمنت، ومعامل الإشباع الجيري (LSF)، الفقدان أثناء الإيقاد(LOI) تقلل التمدد بطريقة المحمم، بينما الزيادة في العوامل الاخرى تزيد التمدد بطريقة المحمم. معامل الارتباط للنماذج المقترحة كان (0,71002 و 0,98338) للنموذج الاول، (0,84366 و0,98789) للنموذج الثاني، و(0.85593 و 0.98872) للنموذج الثالث، بوجود وعدم وجود ثابت التناسب على الترتيب.

Introduction:

It is essential that cement paste does not undergo a large change in volume. In particular, there must be no appreciable expansion which, under conditions of restraint, could result in a disruption of the hardened cement paste. Such expansion may take place due to the delayed or slow hydration, or other reaction of some compounds present in the hardened cement, namely free lime , magnesia, and calcium sulfate ***(Neville 1995 p.51)***.

The testing of the soundness of cements, so as to ensure that no material showing such a subsequent expansion shall be used, has always therefore been considered of prime importance (Lea 1976 p.366***)***.

Research Significance:

It is developing a statistical model for predicting the **Autoclave Expansion** that comprises most chemical factors and fineness of cement which affect this property. Such model help to assess the degree of Soundness of cement which a very substantial aspect of durability if the elaborate Autoclave test is unavailable.

Literature Review:

The autoclave expansion test described by ASTM C151 is used to detect soundness of neat cement paste. In this test a bar of 25 mm (1 in) square in cross section and with 250 mm (10 in) gauge length, is cured in humid air for 24 hours. The bar is then subjected to accelerated conditions (a steam pressure of about 2±0.07 MPa. (295 psi) and a temperature of 216˚C (240˚F)) for 3 hours. The expansion of the bar due to autoclaving must not exceed 0.8 per cent. The high steam pressure accelerates the hydration of both magnesia and lime **(Neville 1995 p.53).** MgO and free lime are the effective components in cement that can cause delayed expansion. This expansion is due to the formation of $Ca(OH)_2$ and $Mg(OH)_2$ upon hydration of free CaO and MgO respectively.

Unsoundness due to the presence of free lime may arise from an over-limed mix, inadequate burning, or insufficiently fine grinding and mixing of the raw materials fed to the kiln (Lea 1976 p.368). On the other hand, lime added to cement does not produce unsoundness because it hydrates rapidly before the past has set (Neville 1995 p.51).

The reactivity of MgO depends on rate of cooling of clinker. Neville (1995 p.52) stated that only periclase is deleteriously reactive, and MgO present in glass is harmless. Up to about 2% of periclase (by mass of cement) combines with the main cement compounds, but excess periclase generally causes expansion and leads to slow disruption. Lea (1976 p.369-370) reported that clinkers that are cooled rapidly can carry more magnesia safely than slowly cooled clinkers. Cements with as much as 5 per cent magnesia will pass the autoclave test if quickly cooled, and the free lime is low. In slowly cooled clinkers, failure to pass the autoclave test may occur with magnesia content of 3 per cent. The quicker the clinker is cooled the smaller will be the periclase crystallization of the liquid. In addition, MgO content can be made up of magnesia held in solid solution in other clinker compounds or as small crystallization of the clinker liquid. The extent to which the periclase crystals may themselves have impurities in solid solution also appears to influence their speed of hydration.

The correlation between autoclave expansion and the (MgO + free CaO) content in cement is not strong enough to attribute such expansion entirely to the amount of MgO and free lime in cement. This means that there are other factors that affect autoclave expansion (Abdul-Latif 2001). The third compound liable to cause expansion is calcium sulfate. This expansion is attributed to the formation of calcium sulphoaluminate. This is harmless when formed in small amounts during the setting of cement, but if large amount of gypsum are present, such that formation of the sulphoaluminate salt continues after setting and hardening, expansion occurs. The maximum amount of gypsum that can safely be added is thus related to the ability of the cement to combine with it during the setting, or very early hardening period (Lea 1976 p.370). A study by Abdul-Latif (2001) showed that the autoclave expansion at first decreased as the SO3 content increased, while at higher SO3 contents there was an increase in expansion. He attributed the reduction in autoclave expansion to the formation of monosulfate phase. When SO3 is insufficient to allow C3A and C4AF to react completely to form ettringite, the hydration product of these components (i.e. C4AH13) reacts with ettringite under the autoclave test conditions. He suggested that such reaction leads to a decrease, rather than an increase, in solid volume. However, the results obtained by Al-Jabiri (2002) contradict this interpretation, she stated that an increase in SO3 content at low percentage of MgO (originally in cement) does not lead to a significant expansion in the autoclave test for cement paste when either O.P.C. or S.R.P.C. are used. In contrast, there is a tendency for a decrease of expansion with increasing SO_3 content in cement even at high percentages of SO_3. She, also, reported that Lawrence (1995) in his study on the effect of cement composition on the delayed ettringite formation observed that MgO content has a significant effect on expansion including that due to ettringite formation. He suggested that the expansive hydration of MgO during the elevated temperature hydration or during room temperature water storage may increase the sensitivity of cement to heat curing by acting as an initiator for subsequent ettringite recrystallizion pressure generation and expansion. This interpretation can also be applicable to the results of the autoclave test at high MgO percentages. The C-S-H gel may play a role in the expansion process. The condition of the autoclave test may generate the adsorption of SO_4^{-2} ions by C-S-H gel, which causes the decrease or no more expansion in cement pastes, $Mg(OH)_2$ may increase the alkalinity of the solution which leads to an expansion in the rate of hydration. More etringite can be formed and more SO_4^{-2} can be adsorbed in C-S-H gel that affects its structure and results in poor strength and then high expansion.

A further factor that influences the expansion in the autoclave test, though it does not lead to long term expansion in practice, is the content of C3A. Lea (1976 p.370) showed that even when the magnesia and free lime are low, the autoclave expansion increases as the calculated content rises about 8 per cent in well crystallized clinker and may exceed the permitted limit at about 14-16 per cent. The iron compound , C4AF, has little effect. It is well known that the formation of ettringite as a result of the chemical reaction of gypsum and alumina phase associated with expansion. However, there is still some uncertainty as to precise mechanism. It has been suggested for example, that the solid stage conversion of C3A.13H to C4AS.12H is responsible for sulfate expansion, but the evidence points to the presence of 19H, and not 13H hydrate of C3A in set cement. The conversion of 19H hydrate would lead to a decrease, not an increase in solid volume. There is, also, little correlation between the amount of ettringite formed and the degree of expansion observed (Lea 1976 p.347-348). From this discussion, it is clear that it is difficult to ascribe expansions directly to increased volume of solid.

Fineness of cement containing free CaO and MgO is the most interesting factor affecting the soundness of cement. As reported by Al-Jabiri (2002), Czenin in 1980 stated that little, but large, free lime particles in hardened paste will cause cracking and spalling, whereas, with increasing fine division of free lime the expansion will become less and more regular. He proved that by taking a neat cement prism with a high content of free lime 13 per cent and finely ground cement. The expansion which occurred was 20 per cent in length but without causing disintegration of the test specimen. The extremely fine distribution of the free lime prevent destruction of the prism. According to Lea (1976 p.369), Keil (1957) found that a content of 4 per cent periclase crystals below 5μ in size produced only about the same autoclave expansion as 1 per cent of crystals of 30μ-60 μ size.

It will be apparent that expansion in the autoclave test is the integrated effect of a number of separated factors. The test gives, therefore, no more a broad indication of the risk of long-term expansion in practice, it is not an exact guide and various anomalies are apparent in the available data (Neville 1995 p.53 and Lea 1976 p.370).

Abdul-Latif (2001) proposed a statistical model for predicting autoclave expansion from MgO content, free lime content, C_3A content, and fineness in terms of Blaine specific surface. This model was as follows:

Auto. = 0.06811*Free CaO% + 0.04394*MgO% - 0.0000577*Blaine (cm^2/gm) + 0.01943*C_3A% …..eq.(1)

This model is based on 35 observations. The correlation coefficient, standard error, and F_{value} are 0.812, 0.1023, and 14.965 respectively.

Experimental Work:

In this study, (40) different cement samples were tested, (29) of them were ordinary Portland cement while the other (11) samples were sulphate resisting Portland cement. **Table (1)** shows the cement sources and the type of their production with the number of samples taken from each factory. **Tables (2)** shows the chemical analysis and physical properties of the cements used in this study. And **Tables (3)** shows the chemical analysis and physical properties limits of the cements used in this study. The autoclave test was used to determine the unsoundness of the cement samples used throughout the present study. The results of this test were obtained from Consultant Engineering Bureau of University of Babylon, and it was accomplished according to the Iraqi standard specification (IQS No.5 : 1984).

Model Development:

The multiple linear regression analysis was used to build the present models. The general purpose of regression analysis is to learn more about the relationship between one or several independent or predictor variables and a dependent or criterion variable. The regression equation or the best-fitting line is determined by minimizing the sum of squares of the residuals between the actual and predicted values of the dependent variables ***(stat soft 2003)***.

The various elements of the multiple linear regression equation can be illustrated from the general form of the following equation:

$$Y = a_0 + a_1x_1 + a_2x_2 + \ldots + a_nx_n$$

Where:

Y: the predicted value of the dependent variable.

$x_1, x_2, \ldots, x_n$: the independent variables (predictors).

a_0: the intercept coefficient (constant).

$a_1, a_2, \ldots, a_n$: the partial regression coefficients of the independent variables.

n: the number of independent variables included in regression equation.

The statistical analysis was done with the aid of computer software **STATISTICA** version **6-2001**.

Three methods of regression were applied. They are:

1. Backward elimination.
2. Forward regression.
3. Standard method or all variables regression.

To evaluate the proposed models, the following statistical factors are used:

Multiple R: The coefficient of multiple correlation is the positive square root of R-square (the coefficient of multiple determination). This statistical factor is useful in multivariate regression (i.e. multiple independent variables) when it is wanted to describe the relationship between the variables.

R-square: This coefficient of multiple determination measures the reduction in the total variation of the dependent variable due to the (multiple) independent variables.

$$R^2 = 1 - [\text{Residual SS}/\text{Total SS}]$$

Where:
Residual SS: is the error sums of square.
Total SS: is the total sums of square.
The R-square value is an indicator of how well the model fits the data, R-square close to 1.0 indicates that it has accounted for almost all of the variability with the variables specified in the model.

Adjusted R-square: The R-square is adjusted by dividing the error sum of squares and total sums of square by their respective degrees of freedom.

$$\text{adjusted } R^2 = 1 - [(\text{Residual SS}/\text{dfr})/(\text{Total SS}/\text{dft})]$$

Std. Error of estimate: This statistic coefficient measures the dispersion of the observed values about the regression line.

F-value: The F-value is used as a test of the relationship between the dependent variable and the set of independent variables.

$$F = \text{Regression Mean Square}/\text{Residual Mean Square.}$$

The range of difference (df) between the actual and predicted Autoclave expansion values was calculated for each model within confidence interval of 0.95. This means that there is a probability of 95% of difference between the actual and the predicted values falls within a range of ±df, thus, the actual values equals to predicted values ± df

<u>Independent Variables:</u>

The following variables are selected to be as the independent variables:

1. The four main compounds of Portland cement (i.e. C_3S, C_2S, C_3A, and C_4AF) which were calculated using Bogue`s equations.
2. The fineness of cement (in terms of Blaine specific surface).
3. Chemical analysis parameters (i.e. MgO, Free CaO, SO_3, LOI, IR, and LSF).
4. Silica modulus and alumina ratio.

The Proposed Models:

The following statistical models are obtained:

1. Model (1):

In this model, backward stepwise method was applied. The final form of this model is as follows:

With intercept: **Auto. exp. = 0.09929 + 0.076702*MgO%** ....eq.(2)

R = 0.71002 R^2 = 0.50412 adjusted R^2 = 0.49107 S.E.= 0.064467

F_{value} = 38.63166

Without intercept: **Auto. exp. = 0.061130*MgO% + 0.061591*SO_3%** ....eq.(3)

R = 0.98338 R^2 = 0.96704 adjusted R^2 = 0.96530 S.E.= 0.06201

F_{value} = 557.4398

2. Model (2):

Forward stepwise method was used in developing this model. The final form of this model is as follows:

With intercept: **Auto. exp. = 2.91305 + 0.06627*MgO% + 0.07888*IR% + 0.113195*SO_3% - 2.96120*LSF% -0.02958*LOI% - 0.10252*SM - 0.00925*C_2S%** .....eq.(4)

R = 0.84366 R^2 = 0.71176 adjusted R^2 = 0.64871 S.E.= 0.05356

F_{value} = 11.28843

Without intercept: **Auto. exp. = 0.05756*MgO% + 0.06185*IR% + 0.15899*SO_3% - 1.38250*LSF% -0.01368*LOI% + 0.01482*C_3S% + 0.09823*AR + 0.00700*C_2S%** .....eq.(5)

R = 0.98789 R^2 = 0.97594 adjusted R^2 = 0.96993 S.E.= 0.05774

F_{value} = 162.2572

3. Model (3):

Standard method in which all possible factors are included in this model:

With intercept: **Auto. exp. = 3.07983 + 0.05393*MgO% + 0.12288*SO_3% - 0.01306*FreeCaO% - 0.03444*LOI% + 0.07678*IR% - 3.28013*LSF% - 0.13571*SM + 0.00301* AR + 0.00757*C_3S% - 0.00472* C_2S% - 0.00272*C_3A% - 0.01667* C_4AF% - 0.00013*Blaine(m^2/kg)** ....eq.(6)

R = 0.85593 R^2 = 0.73261 adjusted R^2 = 0.59892 S.E.= 0.05723

F_{value} = 5.47972

Without intercept: **Auto. exp. = 0.06236*MgO% + 0.15717*SO_3% + 0.04806*Free CaO% - 0.01037*LOI% + 0.04256*IR% - 1.84275*LSF% + 0.10076*SM + 0.07660* AR + 0.01478*C_3S% + 0.00510* C_2S%+ 0.01761*C_3A% + 0.01648* C_4AF% - 0.00038*Blaine(m^2/kg)** ....eq.(7)

R = 0.98872 R^2 = 0.97756 adjusted R^2 = 0.96675 S.E.= 0.06071

F_{value} = 90.4699

Comparison Between Models With and Without Intercept:

As mentioned earlier, two models were developed for each method of regression (i.e. Backward stepwise (model (1)), Forward stepwise(model (2)), and standard method or all variables in model (model (3))) using the same data and the same independent variables, to prove that regression through the origin is more suitable for the data. The first model passes through the origin and the other had an intercept (a_0) of 0.09929, 2.91305, and 3.07983 for the three method of regression respectively. **Table (4)** shows R, R^2, adjusted R^2, F_{value}, S.E., and df for the models with and without intercept. It is obvious that R, R^2, adjusted R^2, F_{value}, S.E., and df for models with intercept are less than that of models without intercept. It is decided that the models which pass through the origin (without intercept) are more suitable and recommended.

Models Examination:

Model examination was done for the models which pass through the origin (without intercept), which were found to be more suitable. The distribution of residuals is shown in **Figure (1)**. From this figure it is clear that the residuals are almost normally distributed. It is also clear that the residuals gathered around zero. This indicates that there are no evidences that the models are inadequate, or there is an error in analysis.

In **Figure (2)** the observed values of the autoclave expansion test are plotted against the predicted values. It is clear that the points roughly follow a straight line. This indicates that the models are appropriate for the data, and they are correctly specified.

To check the validity of the proposed models to predict the autoclave expansion of cement, Two samples of Portland cement were tested. One of them is sulphate resisting Portland cement while the other is ordinary Portland cement. The details of these cements are given in **Table (5). Table (6)** gives the observed and predicted values of the autoclave expansion. From this table it is clear that the maximum difference between the observed and predicted values is about +0.07. Thus, it may be concluded that the present model is appropriate to predict the autoclave expansion with a good accuracy.

Discussion:

As mentioned earlier, the models which pass through the origin (without intercept) are more suitable and recommended. From these models the following points have been recorded:

1. It is obvious that the correlation coefficients, F_{value}, and the standard error of the three models are very close.
2. As explained earlier, fineness of cement is the most interesting factor affecting the soundness of cement. From the third model, it is clear that the autoclave expansion decreases with the increase in cement fineness. This result is in agreement with the results obtained by (Czenin 1980).
3. From the three models, it can be deduced that the increase in MgO and SO_3 contents increase the autoclave expansion. The free CaO has the same effect but at a lesser degree. This result seems acceptable as they play a role in cement paste volume change as mentioned earlier.
4. As expected C_3A and C_4AF increase the autoclave expansion, this is obvious from the correlation coefficient in third model. This may be attributed to the fact that these two compounds cause expansion of cement paste as discussed earlier. This is online with what was demonstrated by Lea (1976 p.370).

5. On the basis of the present models, it is proven statistically that the autoclave expansion increases when the contents of C_3S and C_2S are increased. This behavior may be explained in the light of the fact that the hydration of silicates is associated with a volume increase.
6. Depending on the present models, The autoclave expansion increases with the increase in IR (Insoluble Residual) content. IR is defined the amount of amorphuse silica present in the clay minerals of the raw materials used in cement manufacture (since this silica is not soluble in hydrochloric acid unlike most of cement constituents). In addition, IR gives an indication on the efficiency of the burning process. On the basis of this discussion the effect of IR seems reasonable.
7. It is clear that LOI negatively affects the autoclave expansion. This behavior seems acceptable as LOI refers to the extent of carbonation and hydration of free magnesia due to the exposure of cement to the atmosphere (Neville 1995 p.11).
8. The appearance of AR and SM as positive factors to autoclave expansion in the present models may be explained as alumina and iron oxides are the main fluxes in cement burning process. When the content of them are low the amount of liquid formed at clinkering temperature becomes insufficient to permit sufficiently rapid combination of the remaining CaO (Lea 1976 p.135).
9. Lime saturation factor LSF appears as a negative factor in the second and the third models. This seems reasonable as lime saturation factor represents the factors obtained by equation (8). The increase in (Al_2O_3 and Fe_2O_3) results in a decrease in LSF and subsequently in an increase in the autoclave expansion.

$$LSF = \frac{(CaO - 0.7SO3)}{(2.8SiO2 + 1.2Al2O3 + 0.65Fe2O3)} \quad .....(8)$$

Conclusion:

1. The multiple linear regression is found to be very suitable for predicting the autoclave expansion of Portland cement.
2. It is found that the models which pass through the origin (without intercept) are more suitable and recommended.
3. The increase in MgO and SO_3 contents increases the autoclave expansion. The free CaO has the same effect but at a lesser degree.
4. The increase in fineness of cement, LSF, and LOI decreases the autoclave expansion, while the increase in the other factors increases the autoclave expansion.
5. The correlation coefficients of the proposed models were (0.71002 and 0.98338) for the first model, (0.84366 and 0.98789) for the second model, and (0.85593 and 0.98872) for the third model, with and without intercept respectively.

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Table (1): Sources of the cement samples used in the analysis

No.	Factory	Type of cement	No. of samples
1	Al-Najaf Al- Ashraf cement plant	O.P.C.	5
2	New cement plant of Kufa	O.P.C.	5
3	Al- Sada cement plant	O.P.C.	7
4	South cement plant	O.P.C.	6
5	Um-Qaser grinding station	O.P.C.	4
6	Lion cement -India	O.P.C.	2
7	Al-Muthana cement plant	S.R.P.C.	5
8	Kerbala cement plant	S.R.P.C.	5
9	Kuwait cement plant	S.R.P.C.	1

Table (2): Chemical analysis and physical properties of the cement samples

No.	FACTORY	TYPE	Chemical Analysis										Physical Properties			
			CaO%	SiO_2%	Al_2O_3%	Fe_2O_3%	MgO%	SO_3%	Free lime%	L.O.I.%	IR%	L.S.F.%	IST (min)	FST (min)	Blaine (m^2/kg)	Auto. Exp.
1	Al-Najaf AL-Ashraf	O.P.C.	61.8	21.65	5.44	3.20	3.35	2.43	1.27	1.57	0.53	0.85	125	225	314.4	.40
2	Al-Najaf AL-Ashraf	O.P.C.	63.03	21.20	5.08	3.80	2.55	2.48	1.29	1.23	0.92	0.90	140	240	288.0	.36
3	Al-Najaf AL-Ashraf	O.P.C.	62.23	21.50	4.66	3.80	3.55	2.41	1.40	1.32	1.04	0.86	145	225	302.7	.45
4	Al-Najaf AL-Ashraf	O.P.C.	61.5	21.66	4.62	3.96	3.82	2.32	0.95	1.13	0.73	0.87	110	200	296.6	.34
5	Al-Najaf AL-Ashraf	O.P.C.	62.23	21.20	4.72	3.76	3.51	2.60	1.17	1.35	1.30	0.88	125	215	298.1	.43
6	New Kufa	O.P.C.	62.78	20.10	4.94	3.44	3.87	2.47	1.19	1.61	0.78	0.93	145	245	323.0	.49
7	New Kufa	O.P.C.	62.64	20.64	6.06	3.30	2.93	2.63	1.35	1.55	0.81	0.88	170	265	314.8	.42
8	New Kufa	O.P.C.	62.23	20.94	5.94	3.28	3.11	2.57	1.60	1.61	1.35	0.85	160	235	306.1	.44
9	New Kufa	O.P.C.	62.06	20.06	5.82	3.24	4.43	2.75	0.88	0.92	0.58	0.9	120	210	290.9	.23
10	New Kufa	O.P.C.	61.87	20.68	5.98	3.20	4.41	2.33	1.17	.94	0.65	0.9	160	230	327.3	.33
11	Al-Sada	O.P.C.	61.43	20.84	4.44	3.08	3.28	2.77	1.34	3.30	1.22	0.89	100	190	386.2	.32
12	Al-Sada	O.P.C.	61.10	21.18	4.76	3.60	2.71	2.40	1.29	3.53	1.40	0.86	140	245	328.4	.33
13	Al-Sada	O.P.C.	61.38	21.38	4.76	3.60	3.15	2.40	1.46	2.61	1.15	0.86	120	230	349.6	.37
14	Al-Sada	O.P.C.	61.69	21.64	5.30	3.00	3.45	2.61	1.77	1.93	1.30	0.85	120	220	339.6	.40
15	Al-Sada	O.P.C.	63.35	21.06	6.14	3.08	3.20	2.54	1.42	1.24	0.55	0.89	100	170	398.4	.22
16	Al-Sada	O.P.C.	61.23	21.38	5.38	3.24	4.19	2.44	0.9	1.19	0.63	0.87	100	190	291.5	.24
17	Al-Sada	O.P.C.	61.69	21.12	4.48	3.80	3.41	2.61	2.02	2.22	0.80	0.86	95	155	391.0	.40
18	South	O.P.C.	62.78	21.14	4.30	4.32	2.73	2.38	1.22	1.77	1.15	0.89	100	230	297.0	.33
19	South	O.P.C.	62.91	21.24	4.28	4.16	2.56	2.18	1.23	2.31	1.40	0.89	150	260	284.7	.30
20	South	O.P.C.	63.32	21.72	3.58	4.68	2.37	2.39	1.40	1.39	0.86	0.88	140	230	305.7	.34

No.	FACTORY	TYPE	Chemical Analysis										Physical Properties			
			CaO%	SiO_2%	Al_2O_3%	Fe_2O_3%	MgO%	SO_3%	Free lime%	L.O.I.%	IR%	L.S.F.%	IST (min)	FST (min)	Blaine (m^2/kg)	Auto. Exp.
21	South	O.P.C.	62.59	21.28	4.50	4.80	2.66	2.23	1.04	1.62	0.92	0.88	120	210	300.2	.33
22	South	O.P.C.	61.96	21.0	4.88	3.72	3.75	2.67	0.95	1.30	0.51	0.89	110	210	290.9	.32
23	South	O.P.C.	62.45	21.8	4.52	4.39	2.76	2.73	0.78	1.04	0.32	0.87	125	240	292.5	.28
24	Um-Qaser	O.P.C.	60.79	20.52	5.10	3.32	3.85	2.75	1.40	3.00	0.95	0.87	135	240	341.8	.43
25	Um-Qaser	O.P.C.	61.38	20.80	5.78	3.40	3.31	2.23	1.23	2.55	0.83	0.87	145	235	347.0	.39
26	Um-Qaser	O.P.C.	61.10	20.96	4.20	3.60	3.55	2.66	1.20	3.56	1.00	0.89	150	235	305.7	.31
27	Um-Qaser	O.P.C.	62.23	20.42	4.84	3.60	4.28	2.21	1.68	1.98	1.09	0.90	105	205	342.2	.40
28	Lion cement -India	O.P.C.	62.71	21.00	5.34	4.16	1.85	2.49	1.35	1.90	0.79	0.88	145	225	281.6	.23
29	Lion cement -India	O.P.C.	62.50	20.30	5.55	4.20	1.90	2.41	1.10	2.50	0.90	0.90	150	250	293.8	.24
30	Al-Muthana	S.R.P.C.	62.71	21.00	5.34	4.16	1.85	2.49	1.35	1.90	0.79	0.88	145	225	281.6	.23
31	Al-Muthana	S.R.P.C.	62.98	21.53	3.55	5.40	2.00	1.89	1.29	2.10	0.73	0.89	175	280	265.0	.24
32	Al-Muthana	S.R.P.C.	62.50	21.20	3.72	5.80	1.95	2.03	1.35	2.33	1.35	0.88	145	260	303.0	.22
33	Al-Muthana	S.R.P.C.	64.03	21.60	3.06	5.68	2.14	1.85	1.47	1.41	1.05	0.90	170	230	291.0	.23
34	Al-Muthana	S.R.P.C.	61.18	22.00	4.36	3.16	3.20	2.03	0.61	2.50	1.30	0.86	135	215	309.0	.22
35	Kerbala	S.R.P.C.	63.47	21.60	3.94	5.20	1.40	1.92	1.51	1.80	0.92	0.88	165	270	290.0	.23
36	Kerbala	S.R.P.C.	63.75	21.42	3.04	5.90	1.87	2.15	1.52	1.21	1.30	0.90	150	275	281.0	.23
37	Kerbala	S.R.P.C.	63.75	21.72	3.68	5.32	1.71	1.90	1.57	1.16	1.17	0.88	130	240	300.4	.22
38	Kerbala	S.R.P.C.	62.42	21.90	3.22	5.60	2.00	2.05	0.81	0.81	0.54	0.88	80	180	316.3	.22
39	Kerbala	S.R.P.C.	64.40	21.56	3.58	5.44	1.72	1.90	1.23	1.23	0.42	0.90	140	225	284.7	.24
40	Kuwait cement plant	S.R.P.C.	63.50	22.10	3.60	5.50	1.40	2.16	1.20	1.20	0.70	0.87	145	260	284.0	.30

Table (3): Chemical analysis and physical properties Limits of the cement samples

No.	FACTORY	TYPE	Chemical Analysis										Physical Properties			
			CaO%	SiO_2%	Al_2O_3%	Fe_2O_3%	MgO%	SO_3%	Free lime%	L.O.I.%	IR%	L.S.F.%	IST (min)	FST (min)	Blaine (m^2/kg)	Auto. Exp.
1	Al-Najaf AL-Ashraf	O.P.C.	61.05-63.03	21.66-21.20	4.62-5.44	3.20-3.96	2.55-3.82	2.32-2.60	0.95-1.29	1.13-1.57	0.53-1.30	0.85-0.90	110-145	200-240	288-314.4	.34-.45
2	New Kufa	O.P.C.	61.87-62.78	20.06-20.94	4.94-6.06	3.2-3.44	2.93-4.41	2.33-2.75	0.88-1.60	0.92-1.61	0.58-0.81	0.85-0.93	120-170	210-230	290.9-327.3	.23-.49
3	Al-Sada	O.P.C.	61.10-63.35	20.84-21.64	4.44-5.38	3.0-3.80	2.71-4.19	2.4-2.77	0.9-2.02	1.19-3.53	0.55-1.40	0.86-0.89	95-140	155-245	291.5-398.4	.22-.4
4	South	O.P.C.	61.96-63.32	21.0-21.8	3.58-4.88	3.27-4.80	2.37-3.75	2.18-2.73	0.78-1.4	1.04-2.31	0.32-1.40	0.87-0.89	100-150	210-260	284.7-305.7	.28. 34
5	Um-Qaser	O.P.C.	60.79-62.23	20.42-20.96	4.20-5.78	3.40-3.60	3.31-4.28	2.21-2.75	1.20-1.68	1.98-3.56	0.83-1.09	0.87-0.90	105-150	205-240	305.7-347.0	.31-.43
6	Lion cement - India	O.P.C.	62.50-62.71	21.0-20.3	5.34-5.55	4.16-4.20	1.85-1.90	2.41-2.49	1.10-1.35	1.90-2.50	0.79-0.90	0.88-0.90	145-150	225-250	281.6-293.8	.23-.24
7	Al-Muthana	S.R.P.C	61.18-64.03	21.0-22.0	3.06-5.34	3.16-5.80	1.85-3.20	1.85-2.49	0.61-1.47	1.41-2.50	0.73-1.35	0.86-0.90	135-175	215-280	265.0-309.0	.22-.24
8	Kerbala	S.R.P.C	62.42-63.75	21.42-21.9	3.04-3.94	5.20-5.90	1.40-2.00	1.9-2.15	0.81-1.57	0.81-1.80	0.42-1.30	0.88-0.90	80-165	180-275	281.0-316.3	.22-.24
9	Kuwait cement plant	S.R.P.C	63.50	22.10	3.60	5.50	1.40	2.16	1.20	1.20	0.70	0.87	145	260	284.0	.30

Table (4): R, R^2, adjusted R^2, F_{value}, and S.E. for the models with and without intercept.

Model		R	R^2	Adjusted R^2	F_{value}	S.E.	df
1	with intercept	0.71002	0.50412	0.49107	38.63166	0.06446	±0.080
	without intercept	0.98338	0.96704	0.96530	557.4398	0.06201	±0.075
2	with intercept	0.84366	0.71176	0.64871	11.28843	0.05356	±0.073
	without intercept	0.98789	0.97594	0.96993	162.2572	0.05774	±0.068
3	with intercept	0.85593	0.73261	0.59892	5.47972	0.05723	±0.072
	without intercept	0.98872	0.97756	0.96675	90.4699	0.06071	±0.070

Table (5) Property of cement used for checking the proposed models.

No.	Factory	Type	Chemical Analysis										Physical Properties	
			CaO%	SiO_2%	Al_2O_3%	Fe_2O_3%	MgO%	SO_3%	Free lime%	L.O.I%	IR%	L.S.F.%	Blaine (m^2/kg)	Auto. Exp.
1	Al-Sada	O.P.C.	61.48	20.96	5.92	3.0	3.55	2.41	1.23	2.17	1.18	0.86	348.5	0.36
2	Kerbala	S.R.P.C.	64.5	2.2	3.67	5.54	1.5	2.06	1.68	0.5	1.13	0.91	320	0.25

Table (6) Observed and predicted autoclave expansion.

No.	Factory	Observed Auto. Exp.	Predicted Auto. Exp.					
			Model(1)		Model(2)		Model(3)	
			With intercept	Without intercept	With intercept	Without intercept	With intercept	With intercept
1	Al-Sada	0.36	0.371	0.365	0.351	0.390	0.32	0.38
2	Kerbala	0.25	0.214	0.218	0.181	0.20	0.180	1.181

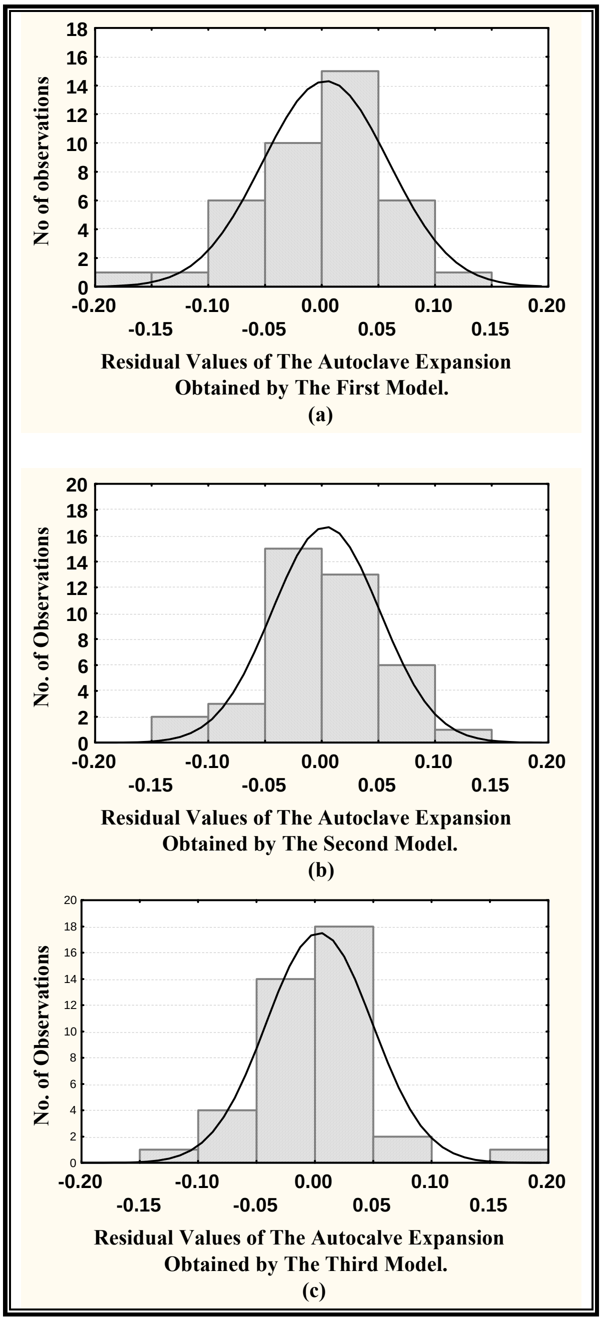

Fig. (1) The Residuals Distribution of The Autoclave Expansion Obtained by The Present Models.

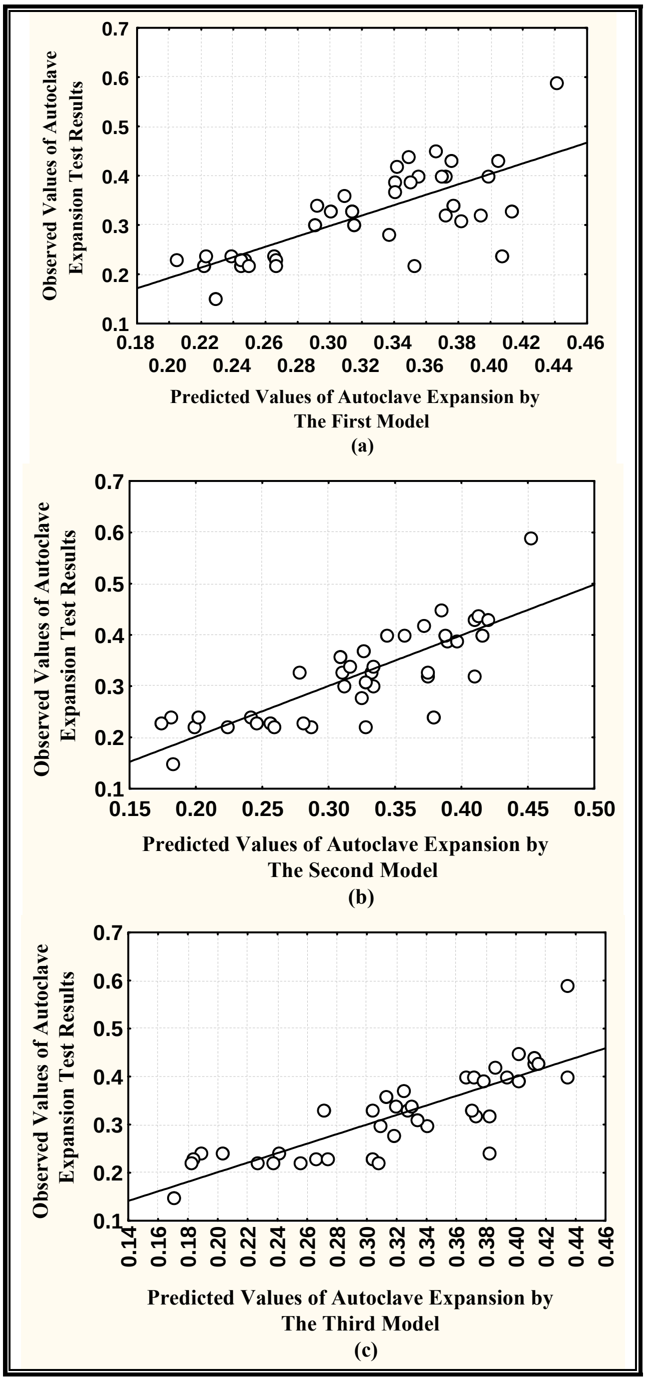

Fig. (2) The Predicted Values of The Autoclave Expansion Against the Predicted Values Obtained by The Present Models.