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# Thickening Time and Compressive Strength Correlations for Bentonitic- Class "G" Cement Slurries

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## Abstract
Empirical equations for estimating thickening time and compressive strength of bentonitic - class "G" cement slurries were derived as a function of water to cement ratio and apparent viscosity (for any ratios). How the presence of such an equations easily extract the thickening time and compressive strength values of the oil field saves time without reference to the untreated control laboratory tests such as pressurized consistometer for thickening time test and Hydraulic Cement Mortars including water bath ( 24 hours ) for compressive strength test those may have more than one day.

## الخلاصة
المعادلات التجريبية للتنبؤ بقيم زمن التثخن وقوه الصلابة لسمنت نوع "ج" المحضر بالبنتونايت والذ ي يمثل كدالة لنسبة الماء الى السمنت واللزوجة الظاهرية (لمختلف النسب). ان استعمال معادلات للتنبؤ بقيم زمن التثخن وقوه الصلابة في الحقل النفطي يوفر الوقت دون الرجوع الى الفحص المختبري واستعمال الاجهزة الخاصة لقياس زمن التثخن واعمدة السمنت والحمام المائي لمدة ( ٢٤ ساعة) لقياس قوة صلابة السمنت وكلها قد تحتاج الى اكثر من يوم.

## Keywords
Correlations, Thickening time, Compressive strength, Drilling, Cementing materials.

## Introduction
Physical and rheological properties of cement slurries with additives are important tools in cementing jobs.

Many investigation were made by researchers, manufactures and service companies to evaluate each addition in both the laboratory and the field.

Ibrahim [1] performed laboratory tests on class "G" cement slurries containing different bentonite to cement ratios (dry bentonite), his results were 28 different plots and two correlation equations for thickening time and free water content.

## Data
All cement slurries data from Ibrahim [1] (experimental work) , the range of data and data used are shown in Tables (1) and (2) respectively and the (m) values were calculated from this study.

## Correlations

### 1. Thickening Time Correlations

#### 1.1. Thickening time correlation(this study)

The following general relation of thickening time of cement slurries with its rheological properties was assumed.

Thickening Time = f (ú, m ) …(1)

Thickening Time $\propto$ ( 1/ú,m ) …(2)

Table (2) shows 30 experimental points that were used to develop the following correlation equation ( this study ) , non linear model was used to develop the following relation:

$$T.T = a_1 + \exp\left( a_2 + a_3/ú + a_4*m + a_5/ú^2 + a_6*m^2 + a_7/ú^3 + a_8*m^3 + a_9/ú^4 + a_{10}*m^4 + a_{11}/ú^5 + a_{12}*m^5 \right) \quad …(3)$$

where

| | |
|---|---|
| $a_1$ = - 9150.24 | $a_2$ = 9.360349 |
| $a_3$ = 4.384563 | $a_4$ = -1.60827 |
| $a_5$ = - 239.746 | $a_6$ = 3.909896 |
| $a_7$ = 6054.842 | $a_8$ = - 4.61193 |
| $a_9$ = - 68215.6 | $a_{10}$ = 2.641999 |
| $a_{11}$ = 285946.6 | $a_{12}$ = - 0.588621 |

#### 1.2. Thickening Time Correlation (Ibrahim[1])

Ibrahim [1] wrote the following equation using apparent viscosity range of 35 to 95 C.P . But in this study and for comparative purposes , the following equation was used for all data.

T.T = 134.1 - 0.427 * ú …(4)

He assumed

Thickening Time = f (ú ) …(5)

Thickening Time $\propto$ (ú ) …(6)

### 2. Compressive Strength Correlation (This Study)

Compressive strength = f (ú, m) …(7)

Compressive strength (ú,1/m) …(8)

Also Table (2) shows the 32 experimentally points that were used to write the following correlation equation(this study),also non linear model was used to write the following relation.

C.S. = a1 + a2/m + a3*ú + a4/m2 + a5*ú 2 + a6/m3 + a7*ú 3 + a8/ m4 + a9*ú 4 …(9)

where

a1 =16934.070004
a2 = - 53758.83433
a3 = - 7.52898677
a4 = 62273.823273
a5 = - 0.1502096603
a6 =- 29671.46878
a7 = 0.0022956086
a8 = 5139.7132478
a9 = - 0.0000077643

## Statistical Analysis

The statistical parameter used for comparison equations for those parameters are given below:

### 1. Average Percent Relative Error

It is the measure of the relative deviation in percent from the experimental data and defined by:

$$Er = \frac{1}{N}\sum_{i=1}^{N} Ei \quad …(10)$$

where **Ei** is the relative deviation in percent of an estimated value from the experimental value

$$Ei = \left[\frac{Xest - X\exp}{X\exp}\right] \times 100 \quad i = 1,2,...N, \quad ...(11)$$

where X est and X exp represent the estimated and experimental values, respectively.

**2. Average Absolute Percent Relative Error**

It can be represented by the following formula

$$Ea = \frac{1}{N}\sum_{i=1}^{N}|Ei| \quad \ldots(12)$$

**3. Minimum and Maximum Absolute Percent Relative Error**

Calculation of both minimum and maximum values are scanned to know the range of error for each correlation.

$$E_{min} = \min_{i=1}^{N}|Ei| \quad \ldots(13)$$

$$E_{max} = \max_{i=1}^{N}|Ei| \quad \ldots(14)$$

**4. Standard Deviation (Sx)**

Standard deviation, Sx , is the measures of the data dispersion around zero deviation.

$$Sx^2 = \frac{1}{N-1}\sum_{i=1}^{N}Ei^2 \quad \ldots(15)$$

**5. Correlation Coefficient (r)**

The correlation coefficient, r , represents the degree of success in reducing the standard deviation by regression analysis.

$$r^2 = 1 - \left\{ \frac{\sum_{i=1}^{N}\left[(X\,est - X\,exp)_i\right]^2}{\sum_{i=1}^{N}\left[(X\,exp - \overline{X})_i\right]^2} \right\} \quad \ldots(16)$$

Where

$$\overline{X} = \frac{1}{N}\sum_{i=1}^{N}(X\,exp)_i \quad \ldots(17)$$

**Results and Analysis**

**1. Results and Discussion**

Tables (3, 4 and 5) show a the comparison between errors experimentally thickening time of 30 estimated data points and the experimentally compressive strength of 32 data points from two correlations of the thickening time and one correlation of the compressive strength. The correlation for thickening time of this study Eq.(3) achieved the lowest errors and standard deviation, with the highest correlation coefficient accuracy ( this study ) of 0.9957 comparison with the correlation coefficient accuracy ( Ibrahim[1] ) of 0.4335. The correlation for compressive strength Eq.(9) achieved the high correlation coefficient of 0.9904.

**2. Cross Plots**

The cross plots of estimated vs. experimental values for thickening time correlations are shown in Figs. (1) and (2) Most of the plotted points of this study's Fig. (1) correlation fall very close to the perfect correlation of $45^{o}$ line ( 0.79 rad ).

The correlation of Ibrahim[1] Fig.(2 ) reveal more overestimation than this study. Also the cross plot of estimated vs. experimental values compressive strength correlation are presented in Fig.(3) of the plotted data points of this study's.

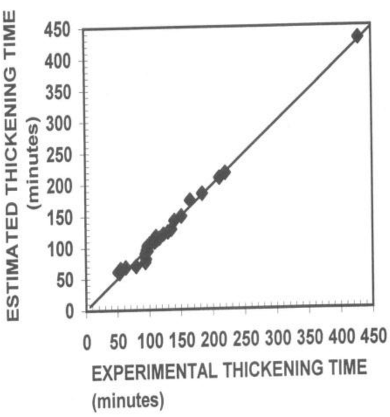


Fig. 1 -Crossplot for thickening time (this study's correlation).

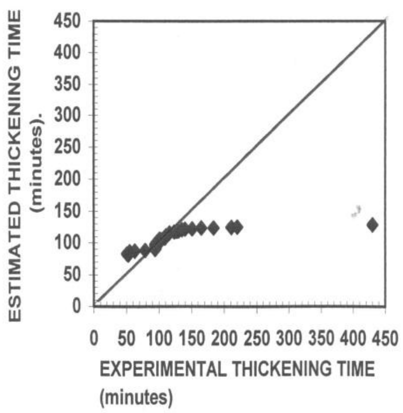


Fig. 2-Crossplot for thickening time (Ibrahim,M.I. correlation).

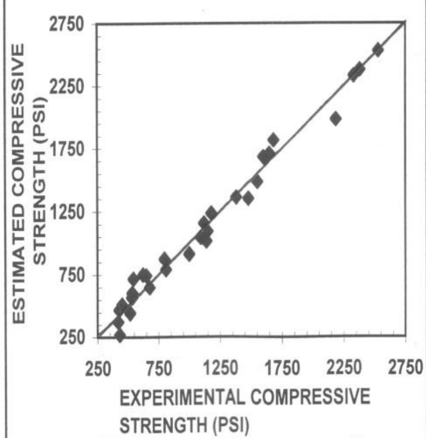


Fig. 3-Crossplot for compressive strength (this study's correlation).

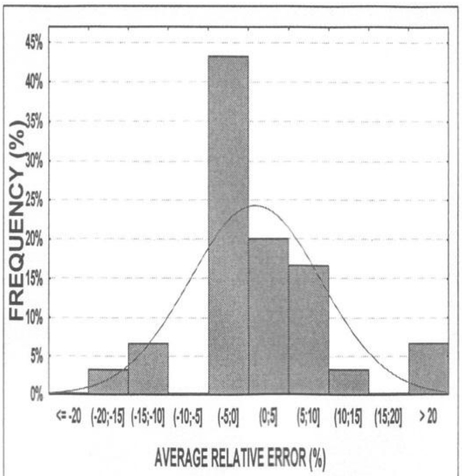


Fig. 4-Error distribution for thickening time (this study's correlation).

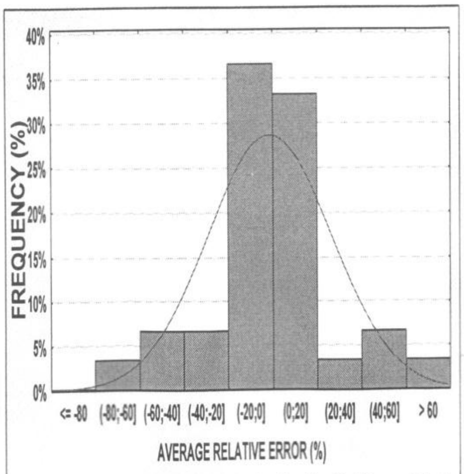


Fig. 5- Error distribution for thickening time (Ibrahim,M.I. correlation).

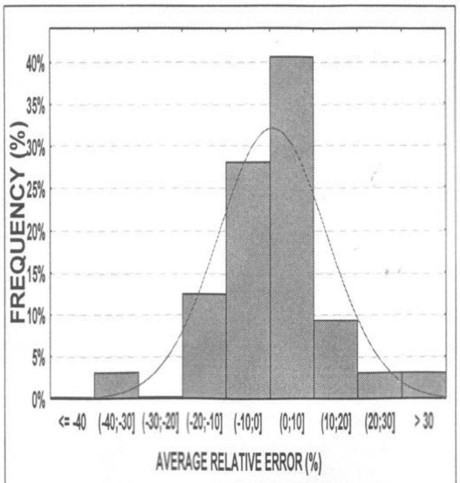


Fig. 6- Error distribution for compressive strength (this study's correlatio

## 3. Error Distribution

The statistical histograms with normal distribution curve for the thickening time correlation of this study and Ibrahim[1] are presented in Fig.( 4) and ( 5) . The error ranges of (± 20 ) and (+60 to -80 ) are used for this study's and Ibrahim[1]. Correlations respectively. Fig. (6) shows the distribution for this study's correlation for compressive strength is (+30) and ( -40).

## 4. Conclusion

1. Thickening time and compressive strength correlations for bentonitic – class "G" cement slurries have been estimated using equations (3) and (9) respectively.
2. Equations (3) and (9) can be used for estimating all water/cement ratios and apparent viscosity without using any devices .
3. Deviations from experimentally data, indicated as average percent relative error , average absolute percent relative error, minimum and maximum absolute percent relative error and standard deviation were lower for this study than for estimation based on the correlation of Ibrahim[1].
4. The correlation coefficients of the correlations of this study that are excellent and near one.

## Nomenclature.

APRE = average percent relative error, (%) ,Eq. (10)
C.S. = compressive strength,(PSI) Eq.(9)
C.S.est = estimated compressive strength, (PSI)
Ea = average absolute percent relative error, (%), Eq.(12)
Ei = percent relative error, (%), Eq.(11)
$E_{max}$ = maximum absolute percent relative error, (%), Eq.(14)
$E_{min}$ = minimum absolute percent relative error, (%), Eq. (13)
Er = average percent relative error, (%) , Eq.(10)
f = function
F.W = free water content, (%)
m = water to cement ratio (by weight), dimensionless
mo = bentonite to cement ratio (by weight), dimensionless
ms = water to solid ratio (by weight), dimensionless
N = number of variables
r = correlation coefficient, Eq.(16)
*Sx* = Standard deviation, Eq. (15)

T.T. = thickening time,(minutes),Eq.(3,4)
T.T.est = estimated thickening time, (minutes)
T.T.exp = experimental thickening time, (minutes)
ú = apparent viscosity = Ø600/2 ,c.p [pa.s]
$\bar{X}$ = average value of $x_{exp}$, Eq.(17)
$X_{est}$ = estimated value of X,
$X_{exp}$ = experimental value of X
ρ = slurry density, gm/cc

## Subscriptes

est estimated from correlation
exp experimental
max maximum
min minimum

## SI Metric Conversion Factors

| | | | |
|---|---|---|---|
| atm | × | 1.013 250* E + 05 | = Pa |
| CP | × | 1.0 * E – 03 | = Pa·s |
| $^{O}$F | | ($^{o}$F + 459.67)/1.8 | = K |
| Psi | × | 6.894 757 E + 00 | = kP |

## References

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Rheological Properties. M.sc Thesis Baghdad University , College of Engineering , Department of Petroleum Engineering, Iraq.

2. London: W.H. Aleen and Co., Ltd. (1973). Hayslett , H.T.,Statistics Made Simple

3. Naji Tawfik. and Rashid Al – Salihi, (1989). Engineering Statistics. . Baghdad University , College of Engineering. Iraq : Higher Education Publication.

Table 1, Range of Data

| | | | |
|---|---|---|---|
| Bentonite/Cement ratio, dimensionless | 2/98 | to | 12/88 |
| Water/Solid ratio, dimensionless | 0.4 | to | 1.05 |
| Water/Cement ratio, dimensionless | 0.408 | to | 1.136 |
| Apparent viscosity, C.P | 9.5 | to | 138 |
| Slurry density, gm/cc | 1.49 | to | 1.94 |
| Thickening time, minutes | 51 | to | 430 |
| Compressive strength, PSI | 420 | to | 2530 |
| Free water content, % | Nil | to | 19 |

Table 2 , Slurry and Set Class "G" Cement Properties at Variable Bentonite and Water Proportions (IBRAHIM[1])

**mo=2/98**

| Sample NO. | ms | m | ú (at 80 °F) C.P | ρ gm/cc | Thickening Time (at 125°F, 5200psi) minutes | Compressive Strength (at 140°F and 24-hures) Psi | F.W % |
|---|---|---|---|---|---|---|---|
| A1! | 0.40 | 0.408 | 120.5 | 1.94 | ---- | ---- | Nil |
| A2*" | 0.50 | 0.510 | 80.0 | 1.83 | 94 | 2530 | 0.6 |
| A3*" | 0.60 | 0.612 | 56.0 | 1.74 | 109 | 2187 | 1.8 |
| A4*" | 0.70 | 0.714 | 36.0 | 1.67 | 123 | 1600 | 2.3 |
| A5*" | 0.80 | 0.816 | 21.5 | 1.61 | 184 | 1480 | 5.4 |
| A6*" | 0.90 | 0.918 | 12.0 | 1.56 | 430 | 1093 | 12.0 |
| A7" | 1.00 | 1.02 | 9.50 | 1.51 | ---- | 812 | 19.0 |

**mo=4/96**

| Sample NO. | ms | m | ú (at 80 °F) C.P | ρ gm/cc | Thickening Time (at 125°F , 5200 Psi) minutes | Compressive Strength (at 140°F and 24-hures) Psi | F.W % |
|---|---|---|---|---|---|---|---|
| B1*" | 0.50 | 0.521 | 99.0 | 1.83 | 63 | 2380 | Nil |
| B2*" | 0.60 | 0.625 | 72.0 | 1.73 | 96 | 1683 | 1.3 |
| B3*" | 0.70 | 0.729 | 48.0 | 1.66 | 111 | 1553 | 1.8 |
| B4*" | 0.80 | 0.833 | 32.0 | 1.60 | 130 | 1120 | 3.7 |
| B5*" | 0.90 | 0.938 | 22.0 | 1.55 | 165 | 800 | 5.7 |
| B6*" | 1.00 | 1.042 | 19.0 | 1.51 | 220 | 678 | 7.2 |

Table 2 , Slurry and Set Class "G" Cement Properties at Variable Bentonite and Water Proportions (IBRAHIM[1]) (continued)

**mo=6/94**

| Sample NO. | ms | m | ú (at 80 °F) C.P | ρ gm/cc | Thickening Time (at 125°F , 5200 Psi) minutes | Compressive Strength (at 140°F and 24-hures) Psi | F.W % |
|---|---|---|---|---|---|---|---|
| C1" | 0.50 | 0.532 | 138.0 | 1.83 | ---- | 2330 | Nil |
| C2*" | 0.60 | 0.638 | 97.0 | 1.73 | 79 | 1650 | Nil |
| C3*" | 0.70 | 0.745 | 71.0 | 1.66 | 97 | 1180 | 0.95 |
| C4*" | 0.80 | 0.851 | 48.0 | 1.60 | 111 | 1000 | 1.70 |
| C5*" | 0.90 | 0.957 | 28.5 | 1.55 | 135 | 650 | 3.80 |
| C6*" | 1.00 | 1.064 | 19.5 | 1.51 | 211 | 533 | 5.40 |
| C7! | 1.05 | 1.117 | 17.0 | 1.49 | ---- | ---- | 7.40 |

**mo=8/92**

| Sample NO. | ms | m | ú CP at 80 °F | ρ gm/cc | Thickening Time (at 125°F,5200 Psi) minutes | Compressive Strength Psi (at 140°F and 24-hures) | F.W % |
|---|---|---|---|---|---|---|---|
| D1! | 0.50 | 0.543 | ---- | 1.83 | ---- | 2212 | Nil |
| D2" | 0.60 | 0.652 | 128.0 | 1.73 | ---- | 1620 | Nil |
| D3*" | 0.65 | 0.707 | 109.0 | 1.69 | 51 | 1381 | Nil |
| D4*" | 0.70 | 0.761 | 91.0 | 1.66 | 95 | 1150 | 0.20 |
| D5*" | 0.80 | 0.870 | 62.0 | 1.60 | 104 | 543 | 0.60 |
| D6*" | 0.90 | 0.978 | 39.0 | 1.55 | 116 | 533 | 1.45 |
| D7*" | 1.00 | 1.087 | 25.0 | 1.51 | 151 | 450 | 4.00 |

**mo=10/90**

| Sample NO. | ms | m | ú (at 80 °F) C.P | ρ gm/cc | Thickening Time (at 125°F, 5200 Psi) minutes | Compressive Strength Psi (at 140°F and 24-hures) | F.W % |
|---|---|---|---|---|---|---|---|
| E1! | 0.50 | 0.556 | ---- | 1.83 | ---- | 2190 | Nil |
| E2! | 0.60 | 0.667 | ---- | 1.73 | ---- | 1590 | Nil |
| E3*" | 0.70 | 0.778 | 111.5 | 1.66 | 53 | 1140 | Nil |
| E4*" | 0.75 | 0.833 | 94.5 | 1.63 | 94 | 622 | Nil |
| E5*" | 0.80 | 0.889 | 75.5 | 1.60 | 98 | 530 | 0.3 |
| E6*" | 0.90 | 1.00 | 46.0 | 1.55 | 113 | 515 | 0.8 |
| E7*" | 1.00 | 1.111 | 26.5 | 1.51 | 140 | 428 | 3.5 |

**mo=12/88**

| Sample NO. | ms | m | ú (at 80 °F) C.P | ρ gm/cc | Thickening Time (at 125°F , 5200 Psi) minutes | Compressive Strength Psi (at 140°F and 24-hures) | F.W % |
|---|---|---|---|---|---|---|---|
| F1! | 0.50 | 0.568 | ---- | 1.83 | ---- | 2175 | Nil |
| F2! | 0.70 | 0.795 | ---- | 1.66 | ---- | 1087 | Nil |
| F3*" | 0.80 | 0.909 | 101.5 | 1.60 | 55 | 516 | Nil |
| F4* | 0.85 | 0.966 | 78.0 | 1.57 | 94 | ---- | 0.3 |
| F5*" | 0.90 | 1.023 | 60.0 | 1.55 | 101 | 431 | 0.6 |
| F6*" | 1.00 | 1.136 | 33.0 | 1.51 | 127 | 420 | 2.3 |

(*) used in the thickening time correlation equation.
(") used in the compressive strength correlation equation.
(!) not used.
The (m) values were calculated from this study.

| Table 3, Comparision of Thickening Time Estimated by Correlations from This Study and IBRAHIM[1] | | | | | | | |
|---|---|---|---|---|---|---|---|
| NO. | Experimental Thickening Time (T.T.exp) minutes | Estimated Thickening Time (T.T.est) minutes | | Deviation in Percent of Estimated Thickening Time (APRE) | | T.T.est - TT.exp (this study) minutes | T.T.est - TT.exp Ibrahim minutes |
| | | This study | Ibrahim | This Study | Ibrahim | | |
| 1 | 94 | 90.158 | 96.340 | -4.088 | 2.490 | -3.842 | 2.340 |
| 2 | 109 | 108.884 | 107.668 | -0.106 | -1.222 | -0.116 | -1.332 |
| 3 | 123 | 121.079 | 117.108 | -1.562 | -4.790 | -1.921 | -5.892 |
| 4 | 184 | 184.690 | 123.952 | 0.375 | -32.635 | 0.690 | -60.048 |
| 5 | 430 | 430.059 | 128.436 | 0.014 | -70.131 | 0.059 | -301.56 |
| 6 | 63 | 68.360 | 87.372 | 8.508 | 38.686 | 5.360 | 24.37 |
| 7 | 96 | 96.317 | 100.116 | 0.330 | 4.288 | 0.317 | 4.116 |
| 8 | 111 | 117.914 | 111.444 | 6.229 | 0.400 | 6.914 | 0.444 |
| 9 | 130 | 124.822 | 118.996 | -3.983 | -8.465 | -5.178 | -11.004 |
| 10 | 165 | 174.184 | 123.716 | 5.566 | -25.021 | 9.184 | -41.284 |
| 11 | 220 | 216.987 | 125.132 | -1.370 | -43.122 | -3.013 | -94.868 |
| 12 | 79 | 70.564 | 88.316 | -10.679 | 11.792 | -8.436 | 9.316 |
| 13 | 97 | 102.247 | 100.588 | 5.409 | 3.700 | 5.247 | 3.588 |
| 14 | 111 | 116.522 | 111.444 | 4.975 | 0.400 | 5.522 | 0.444 |
| 15 | 135 | 128.811 | 120.648 | -4.584 | -10.631 | -6.189 | -14.352 |
| 16 | 211 | 209.792 | 124.896 | -0.572 | -40.808 | -1.208 | -86.104 |
| 17 | 51 | 61.343 | 82.652 | 20.279 | 62.063 | 10.343 | 31.652 |
| 18 | 95 | 81.402 | 91.148 | -14.314 | -4.055 | -13.598 | -3.852 |
| 19 | 104 | 107.817 | 104.836 | 3.670 | 0.804 | 3.817 | 0.836 |
| 20 | 116 | 114.617 | 115.692 | -1.192 | -0.266 | -1.383 | -0.308 |
| 21 | 151 | 149.603 | 122.300 | -0.925 | -19.007 | -1.397 | -28.700 |
| 22 | 53 | 59.849 | 81.472 | 12.923 | 53.721 | 6.849 | 28.472 |
| 23 | 94 | 76.459 | 89.496 | -18.660 | -4.791 | -17.541 | -4.504 |
| 24 | 98 | 94.545 | 98.464 | -3.525 | 0.473 | -3.455 | 0.464 |
| 25 | 113 | 112.884 | 112.388 | -0.103 | -0.542 | -0.116 | -0.612 |
| 26 | 140 | 142.588 | 121.592 | 1.848 | -13.149 | 2.588 | -18.408 |
| 27 | 55 | 66.048 | 86.192 | 20.087 | 56.713 | 11.048 | 31.192 |
| 28 | 94 | 89.475 | 97.284 | -4.813 | 3.494 | -4.525 | 3.284 |
| 29 | 101 | 106.202 | 105.780 | 5.150 | 4.733 | 5.202 | 4.780 |
| 30 | 127 | 126.582 | 118.524 | -0.329 | -6.674 | -0.418 | -8.476 |

| Table 4, Compressive Strength Estimated by Correlation from This Study | | | | |
|---|---|---|---|---|
| NO. | Experimental Compressive Strength C.S.exp) Psi | Estimated Compressive Strength (C.S.est) Psi | Deviation in Percent of Estimated Compressive Strength (APRE) | C.S.est - C.S.exp (this study) Psi |
| 1 | 2530 | 2532.983 | 0.118 | 2.983 |
| 2 | 2187 | 1985.923 | -9.194 | -201.077 |
| 3 | 1600 | 1684.385 | 5.274 | 84.385 |
| 4 | 1480 | 1350.439 | -8.754 | -129.561 |
| 5 | 1093 | 1044.076 | -4.476 | -48.924 |
| 6 | 812 | 790.021 | -2.707 | -21.979 |
| 7 | 2380 | 2380.695 | 0.029 | 0.695 |
| 8 | 1683 | 1817.612 | 7.998 | 134.612 |
| 9 | 1553 | 1486.151 | -4.305 | -66.849 |
| 10 | 1120 | 1156.986 | 3.302 | 36.986 |
| 11 | 800 | 871.182 | 8.898 | 71.182 |
| 12 | 678 | 647.981 | -4.428 | -30.019 |
| 13 | 2330 | 2332.903 | 0.125 | 2.903 |
| 14 | 1650 | 1711.682 | 3.738 | 61.682 |
| 15 | 1180 | 1233.688 | 4.550 | 53.688 |
| 16 | 1000 | 912.552 | -8.745 | -87.448 |
| 17 | 650 | 741.044 | 14.010 | 91.044 |
| 18 | 533 | 605.800 | 13.660 | 72.800 |
| 19 | 1620 | 1666.823 | 2.890 | 46.823 |
| 20 | 1381 | 1362.628 | -1.330 | -18.372 |
| 21 | 1150 | 1090.424 | -5.181 | -59.576 |
| 22 | 543 | 717.781 | 32.190 | 174.781 |
| 23 | 533 | 567.872 | 6.543 | 34.872 |
| 24 | 450 | 512.419 | 13.870 | 62.419 |
| 25 | 1140 | 1014.273 | -11.030 | -125.727 |
| 26 | 622 | 749.834 | 20.550 | 127.834 |
| 27 | 530 | 567.029 | 6.987 | 37.029 |
| 28 | 515 | 441.807 | -14.210 | -73.193 |
| 29 | 428 | 468.579 | 9.481 | 40.579 |
| 30 | 516 | 448.031 | -13.170 | -67.969 |
| 31 | 431 | 269.753 | - 37.412 | -161.247 |
| 32 | 420 | 374.646 | -10.800 | -45.354 |

| Table 5, Statistical Accuracy ot Thickening Time and Compressive Strength Correlations | | | |
|---|---|---|---|
| | Thickening time | | Compressive strength |
| | This study | Ibrahim[1] | This study |
| Average relative error , % | 0.8186 | -1.3851 | 0.5771 |
| Average absolute relative error , % | 5.5389 | 17.6353 | 9.0610 |
| Minimum absolute relative error , % | 0.0136 | 0.2655 | 0.0292 |
| Maximum absolute relative error, % | 20.2794 | 70.1312 | 37.4122 |
| Standard deviation , % | 8.1341 | 27.3976 | 12.2285 |
| Correlation coefficient | 0.9957 | 0.4335 | 0.9904 |