# Modelling of Compressive Strength of Cement Slurry at different Slurry Weights and Temperatures

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## Abstract

*The effect of temperature and slurry weight on compressive strength was investigated. Tests were conducted for 70, 80, 90,100 and 105 °F as well as slurry weights of 1.96, 1.98 and 2.0kg/l for test periods of 12, 24, 72 and 168hrs respectively. Test results indicated that compressive strength is a function of temperature and slurry weight, at a higher temperature and slurry weight respectively, compressive strength development is faster and vice-versa. Model coefficients were obtained using DATA FIT Engineering software and models which predict compressive strength with respect to temperature and slurry weight were developed.*

*Results calculated from the model equation showed a good agreement with experimental values with less than 1% deviation. This will help predict compressive strength at different temperatures and slurry weights thereby saving time and rigour associated with actual laboratory pilot tests.*

## INTRODUCTION

**Kinetics and Modeling of Cement hydration Process:**The reaction of cement with water is referred to as cement hydration. As hydration occurs, the cement sets as a compact solid and consequently develops compressive strength. The process of hydration could take several days or even weeks at low temperatures. However, at high temperatures, maximum strength is attained after a few hours. The rate at which hydration occurs when water is mixed with cement can be altered using chemical additives[1.] The chemicals used to decrease the speed of hydration are called retarders, while those used to increase the speed of hydration are called accelerators. Each of the cement constituents participate in hydration reactions in the presence of water, but the rate of hydration can differ for each constituent. Cement hydration is recognized as a complex physicochemical process and many attempts have been made to describe and quantify the kinetics of hydration. Many of the developed models explicitly consider the effects of cement particle size distribution (PSD) and curing temperature on kinetics. Cement hydration is modelled as a three part process: 1) material dissolves from the original cement particle surfaces, 2) diffuses within the available pore space, and 3) ultimately reacts with water and other dissolved or solid species to form hydration products through aggregation. Therefore, in order to simulate the microstructure development of hydrating cement, the physical processes of dissolution, diffusion, and reaction must be simulated

The most widely used cement is Portland cement. The four major clinker phases present in Portland cement are tricalcium silicate ($C_3S$), dicalcium silicate ($C_2S$), tricalcium aluminate ($C_3A$), and tetra calcium aluminoferrite ($C_4AF$); the clinker is ground with gypsum ($CH_2$) Ionic composition of the solution also plays a significant role in the hydration process[2]

On reaction with water, $C_3S$ produces C-S-H and calcium hydroxide, CH, (also known as Portlandite.

This is a relatively fast reaction, causing setting and strength development in the first few weeks. The kinetics and hydration mechanism for $C_2S$ are similar to those of $C_3S$ except that the rate of reaction is much slower and is mainly responsible for strength growth after one week.[3] Tricalcium aluminate, $C_3A$, is generally the fastest reacting phase in Portland cement. In fact, gypsum is specifically added to Portland cement to slow down this reaction, thus avoiding 'flash set' of the material. Because the aluminate phase is critical to early hydration properties, it is of great interest in oil well cementing. When gypsum is not present in the system, $C_3A$ reacts with water to form a variety of crystalline hydration products, with hydrogarnet, $C_3AH6$, being the ultimately stable hydration product. The products formed on reaction of $C_3A$ in the presence of gypsum depend primarily on the availability of sulfate ions from the dissolution of gypsum. $C_3A$ will react with the gypsum to form ettringite, $C_6A_3\ H_{32}$, whose crystals are often observed to grow as needles within the cement paste.

This reaction is complete after 1-2 days. When all of the gypsum is consumed, the ettringite may decompose, reacting with more of the $C_3A$ to form the monosulphate phase, $C_4AH_{12}$. The reactions of the ferrite phase, C4AF, are the least well understood of those occurring during Portland cement hydration. The ferrite phase is often said to react slowly (in comparison to the other phases) and only contributes to long-term properties of cements (although exceptions to this have been noted in the presence of special additives[3]

In general, the relative hydration rate follows the sequence: $C_3A > C_3S > C_4AF > C_2S$. The development of compressive strength is primarily dictated by the two major cement components, $C_3S$ and $C_2S$. $C_3S$ is the constituent primarily responsible for the development of early (1 to 28 days) compressive strength, while $C_2S$ is responsible for the development of later (28 + day) compressive strength. The hydration rate for cement is also highly dependent on the cement particle size (controlled during the process of grinding the clinker) and the temperature experienced by the slurry during setting. It is possible to control the hydration rate, to some degree, by using accelerating and retarding additives. The hydration of cement is an exothermic process (i.e., heat is liberated during the reactions), and each of the cement components has a characteristic heat of hydration that contributes to the overall heat liberated on hydration. The overall heat of hydration depends on the relative quantities of each of the constituents in the cement[4].

The objective of the project was to investigate the effect of temperature and slurry weight on cement compressive strength development , hence, develop model equations to predict test result trend for further application thereby saving time and rigor associated with actual laboratory pilot test.

**Research methodology:** A series of tests were performed to evaluate the performance compressive strength. All tests were conducted in line with the specification for materials and testing for Well Cements[5,6.] The test equipment used, procedure are indicated below and testing conditions are specified in **(Table-1)**

## Equipment and testing procedures

**Compressive Strength:** The pressure it takes to crush the set cement was measured in this test. The cement slurry was poured into Ultra Sonic Cement analyzer (UCA) for non-destructive test. In a non-destructive test, sonic speed is measured through the cement as it sets. This value is then converted into compressive strength. The UCA cell is equipped with a heating jacket, temperature controller, pressure system, cooling system, transducers and rated at 204°C / 400°F and 30,000 psi. The system measured the strength development by measuring the speed of the Ultra Sonic Signals being sent through the cement while it sets up. The speed of the signals was calculated and correlated to a compressive strength in psi.

## Results and Discussions

Table-1 and Fig- 2 show the effect of temperature on compressive strength. Tests were conducted for 70, 80, 90, 100 and 105 °F and compressive strength monitored for 12 and 24hrs respectively. Test results indicated that the compressive strength increased steadily with increase in temperature. The 12hrs strength for the specified test temperatures above were 1090, 1301, 1408, 1490 and 1520psi while the 24hrs strength were 2250, 2705, 2842, 3100, 3450 psi respectively. This is in line with established previous findings that hydration reaction is accelerated thermally, so at higher temperatures, cement will take less time to set.[7, 8]

Attempt was made to develop a model equation to predict the compressive strength at different temperatures. In the model equations, all possible models (logarithmic, power, linear, exponential) among others were tested based on high multiple correlation coefficient $R^2$. The compressive strength was then assumed to vary with temperature as shown in equation 2 for compressive strength time of 12 and 24hrs. It was therefore established that the compressive strength can be predicted with temperature using equations 2 and 3

$CS=1397.432+1466605/T^{1.5}-1.4E-07/T^2 R^2=0.999$ (2)

$CS=3423.949+1336778/T^{1.5}-1.7E-07/T^2 R^2=0.980$ (3)

Where CS is the compressive strength in psi, T is the temperature in $^{o}F$

Fig 3 and Fig 4 shows good agreement and with less than 1.0% deviation between experimental compressive strength and empirical compressive strength at different temperature for compressive time of 12hrs and 24 hrs

Table-2 and Fig 5 show effect of slurry weight on compressive strength at different compressive strength time at test temperature of $13^{o}C$. Tests were conducted for slurry weights of 1.96, 1.98 and 2.0kg/l for test period of 12, 24, 72 and 168hrs respectively.

Test results indicated that the compressive strength increased generally with time and slurry weight. However, there was no change of strength development for 12 and 24hrs respectively for all the weights. In the development of the model equations to predict compressive strength at different slurry weight, all possible models (logarithmic, Power, linear, exponential etc) were tested based on high multiple correlation coefficient $R^2$ and logarithmic model described best the variation of compressive strength with time and slurry weight . The compressive strength was then assumed to vary with time as shown in equation 4.

So that $CS = a+bt^{0.5}+c/t^{0.5}$ $R^2 = 0.999$ (4)

Where a, b and c are constants and CS is the compressive strength in psi, t is the compressive strength time in hrs. The constants a, b and c are assumed to be functions of slurry weight ($S_w$). The constants a, b and c were regressed against the slurry weight by multiple regression analysis using Data-fit Engineering software. The compressive strength was regressed against time to obtain equation 4. The coefficients of the equation 4 were then regressed against slurry weight to obtain the relationship between constants a, b, c and slurry weight, as shown in equations 5, 6 and 7 .Hence the combination of equations 4, 5, 6 and 7 gives the new model for predicting the compressive strength at different slurry weights.

$a = 84126.25-11167S_W^3$ $R^2 = 0.995$ (5)

$b= -8791.66+1200.551\ S_W^3$ $R^2 = 0.999$ (6)

$c= -188777+24656.6\ S_W^3$ $R^2 = 0.990$ (7)

Where a, b and c are constants in equation 3 and $S_W$ is slurry weight in kg/l

The values of constants a, b and c were then computed at different slurry weights and were used to calculate the compressive strength in equation 3 to obtain empirical compressive strength as shown in Fig 6 - Fig 8, The values obtained show good agreement with less than 1.0% deviation between experimental compressive strength and empirical compressive strength and time obtained at different and slurry weight so that for

1.96kg/l slurry weight:
$CS =43.921+247.93*t^{0.5}+-3124.24/t^{0.5}$ (8)

1.98kg/l slurry weight:
$CS=-2556.36+527.4875*t^{0.5}+2617.196/t^{0.5}$ (9)

2.0kg/l slurry weight:

$$CS = -5209 + 812.748 * t^{0.5} + 8475.8/t^{0.5} \qquad (10)$$

## Conclusions

Test results indicated that compressive strength increased with increase with temperature and slurry weight. This is in line with established previous findings that the hydration rate for cement is dependent on the cement particle size and the temperature experienced by the slurry during setting. Results calculated from the model equation showed a good agreement with experimental values with less than 1% deviation. This will help predict compressive strength development at different temperatures and slurry weights thereby saving time and rigour associated with actual laboratory pilot test.

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**Table-1: Effects of Temperature on Compressive Strength**

| **Water Type** | | **SEA** | **SEA** | **SEA** | **SEA** | **SEA** |
|---|---|---|---|---|---|---|
| Chloride Content | ppm | 17561 | 17561 | 17561 | 17561 | 17561 |
| **Test Temperature** | °F | 70 | 80 | 90 | 100 | 105 |
| **Additives** | | | | | | |
| Dyckerhoff (Cement) | KG/TON | 1000 | 1000 | 1000 | 1000 | 1000 |
| Calcium Chloride (Accelerator) | KG/TON | 5 | 5 | 5 | 5 | 5 |
| Defoamer | L/TON | 1.78 | 1.78 | 1.78 | 1.78 | 1.78 |
| Slurry Weight | KG/L | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 |
| Water Requirement | L/TON | 462.8 | 462.8 | 462.8 | 462.8 | 462.8 |
| **Compressive Strength** | | | | | | |
| 12 Hours | psi | 1090 | 1301 | 1408 | 1490 | 1520 |
| 24 Hours | psi | 2250 | 2705 | 2842 | 3100 | 3450 |

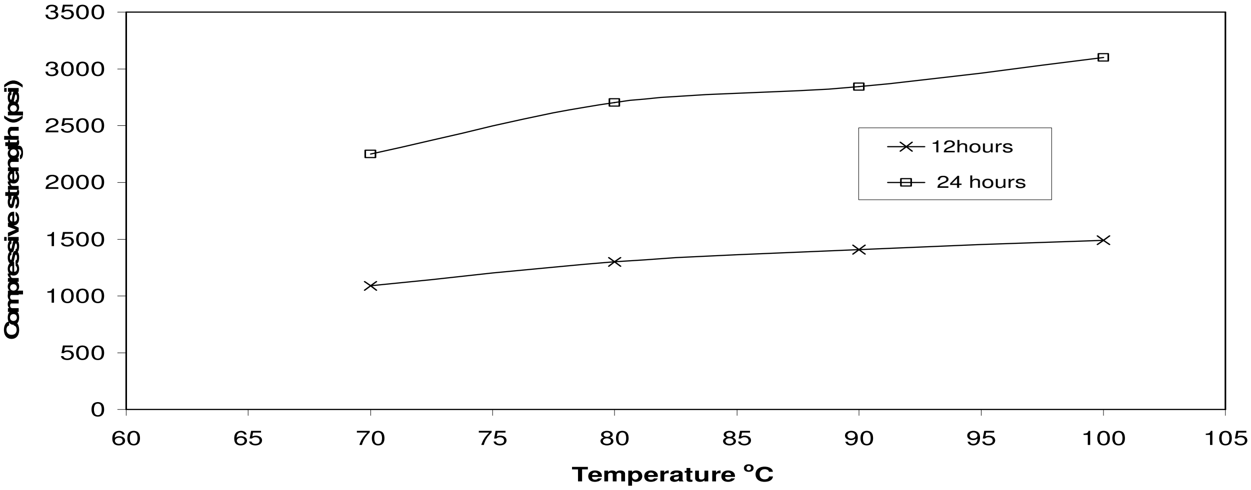


**Figure-1:Effect of temperature on compressive strength**

**Table-2: Effects of Slurry Weight on Compressive Strength**

| **Job Type** | | Grouting | Grouting | Grouting |
|---|---|---|---|---|
| BHST | °C | 13 | 13 | 13 |
| BHCT | °C | 13 | 13 | 13 |
| **ADDITIVES** | | | | |
| CEMENT | KG/MT | 1000 | 1000 | 1000 |
| **Slurry Weight** | **KG/L** | **1.96** | **1.98** | **2** |
| Water Type | | SEA | SEA | SEA |
| Water Chloride Content | ppm | 17312 | 17312 | 17312 |
| Water Requirement | L/MT | 406.3 | 391.1 | 376.6 |
| **Crush Compressive Strength** | | | | |
| 12 Hours | psi | Set, No Strength | Set, No Strength | Set, No Strength |
| 24 Hours | psi | 600 | 600 | 600 |
| 48 Hours | psi | 600 | 700 | 950 |
| 72 Hours | psi | 1750 | 2250 | 2500 |
| 1 Week (168 Hours) | psi | 3000 | 4500 | 6000 |

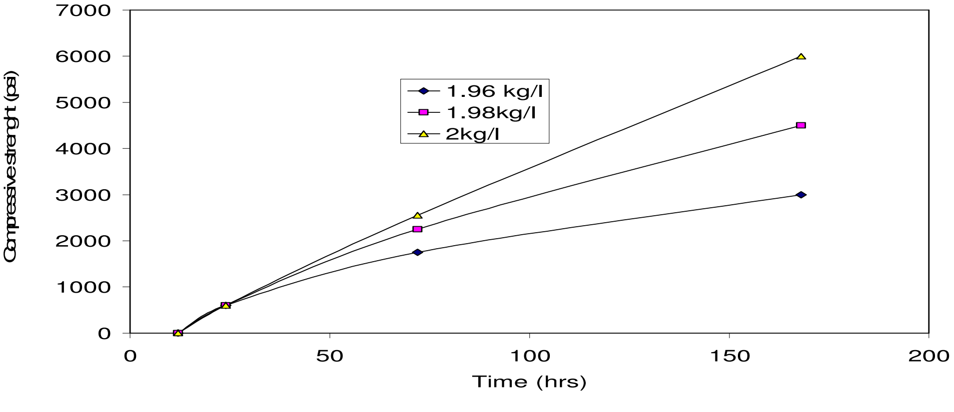
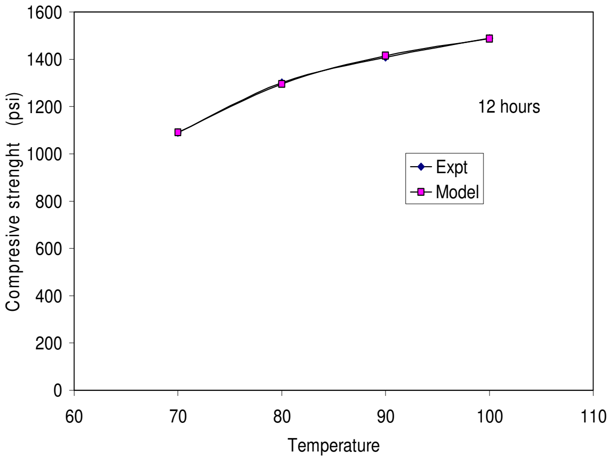
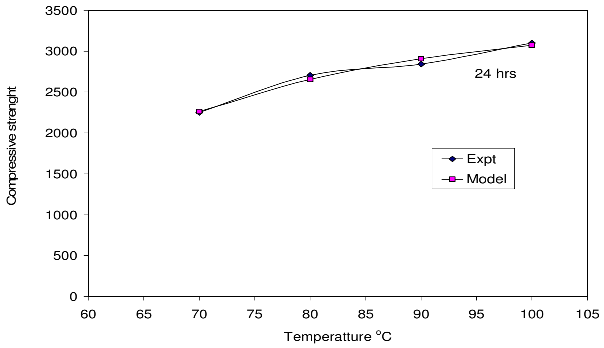


**Figure-2: Effect of slurry weight on compressive strength**



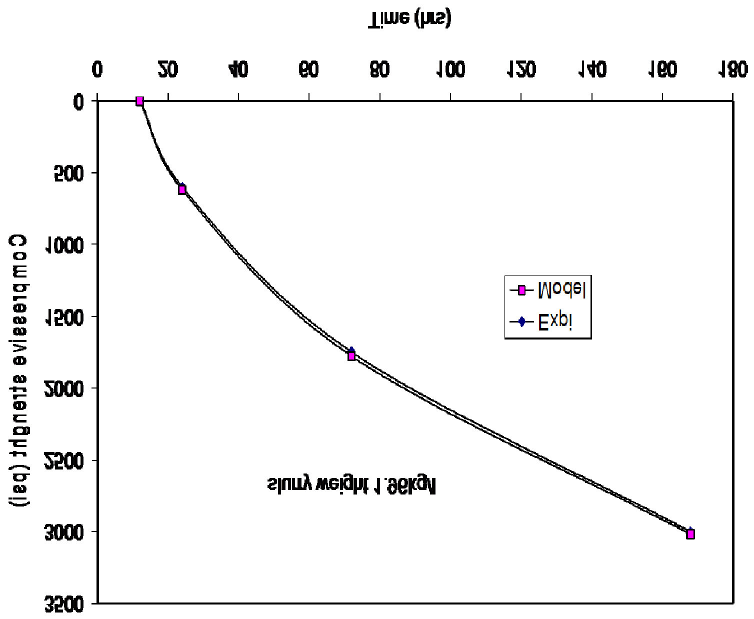
| Temperature $^oF$ | Expt | Model |
|---|---|---|
| 70 | 1090 | 1091.376 |
| 80 | 1301 | 1295.485 |
| 90 | 1408 | 1415.119 |
| 100 | 1490 | 1487.02 |

**Figure-3:comparison between experimental compressive strength and empirical compressive strength at different temperature for compressive time of 12hrs**



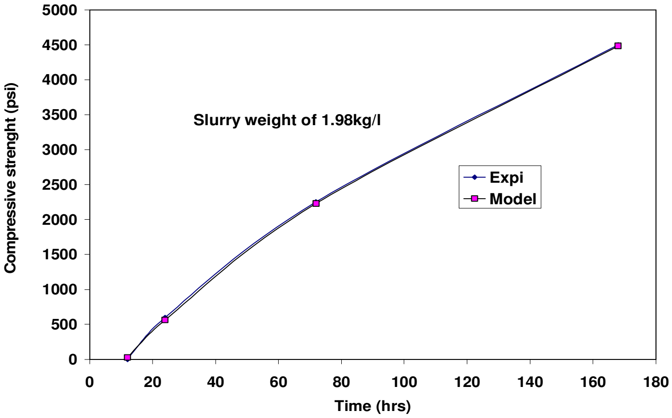
| Temperature $^oF$ | Expt | Model |
|---|---|---|
| 70 | 2250 | 2262.401 |
| 80 | 2705 | 2655.298 |
| 90 | 2842 | 2906.161 |
| 100 | 3100 | 3073.14 |

**Figure-4:comparison between experimental compressive strength and empirical compressive strength at different temperature for compressive time of 24hrs**



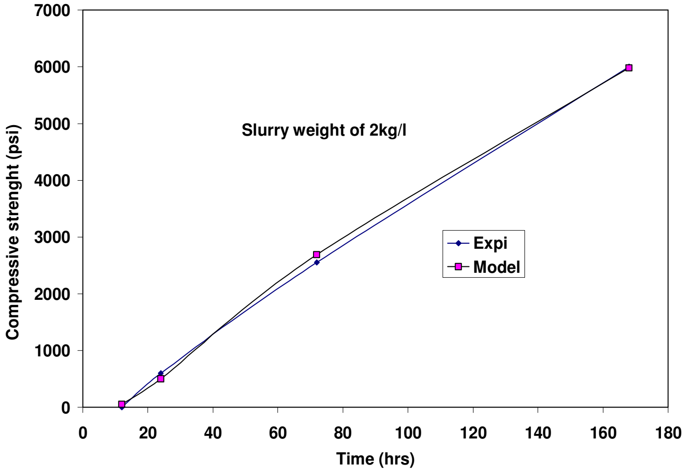
| Compressive time (hrs) | Expt | Model |
|---|---|---|
| 12 | 0 | 26.42971 |
| 24 | 600 | 562.0233 |
| 72 | 2250 | 2227.959 |
| 168 | 4500 | 4482.58 |

**Figure-5: Comparison between experimental compressive strength and empirical compressive strength and time at slurry weight of 1.96kg/l**



| **Compressive time (hrs)** | **Expt** | **Model** |
|---|---|---|
| 12 | 0 | 26.42971 |
| 24 | 600 | 562.0233 |
| 72 | 2250 | 2227.959 |
| 168 | 4500 | 4482.58 |

**Figure-6: Comparison between experimental compressive strength and empirical compressive strength and time at slurry weight of 1.98kg/l**



| **Compressive time (hrs)** | **Expt** | **Model** |
|---|---|---|
| 12 | 0 | 53.19437 |
| 24 | 600 | 502.7512 |
| 72 | 2550 | 2686.278 |
| 168 | 6000 | 5979.34 |

**Fig 7: Comparison between experimental compressive strength and empirical compressive strength and time at slurry weight of 2.0kg/l**