

Analyzing Cement Retrogression with Autodesk Simulation

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Abstract

The high pressure high temperature environments for oil and natural gas exploitation are characterized by extreme temperatures and pressures. Wells with depth exceeding 15,000 ft (4,570 m) are becoming common all over the world. The bottomhole temperatures in most cases exceed 230 degree F (110 degree C). To produce the oil and gas from any well economically and effectively, complete zonal isolation is indispensable. Zonal isolation implies that a particular zone may be produced or drained with the exclusion of any other zone irrespective of their proximity. Zonal isolation also aids well control and is achieved by the sheath of cement placed between the metal linear and / or casing and the wall of the wellbore. The concept of zonal isolation has become over the year a “creed” in the petroleum industry. In the process of the completion of wells, cement is usually used, the need for zonal isolation can never be more critical than in the deep HP HT wells where pressure temperature and stress conditions are extreme and intense. The cement responsible for this zonal isolation can however be compromised by several factors that come into play during the life of the well. Stresses are imposed over time, on the wellbore downhole by pressure and well bore temperature. In high pressure high temperature wells, the stress associated with the extreme temperature pressure conditions is a common cause for loss of compressive strength with accompanied increase in permeability. This is known as ‘Cement retrogression’. This paper model experimental data received via an investigation into the use of local Nigerian siliceous material as substitute for imported Silica flour. Modeling was done using Autodesk simulation

Keywords: cement retrogression, Ughelli sands, silica flour, Autodesk simulation.

1.0 Introduction

This paper is an offshoot of experiments conducted to determine if Nigerian sands rich in silica can be used as a substitute for the expensive Silica flour used by drilling companies in Nigeria. [1]

Experimental data were generated from the substitution of Ughelli sands and Benin sands into slurry preparation for the high temperature high pressure (HTHP) environments of the Niger Delta. The cements used during these experiments were API grade G cement and Ordinary Portland cement. Pressure and temperature were from 5,000 psi to 10,000 psi and 200 degrees Fahrenheit to 350 degrees Fahrenheit respectively. Curing time ranged from 30 minutes to 120 minutes

From analysis of experimental data it was determined that Benin sand were a poor materials for silica enrichment of slurries [2] and Ughelli sands held greater prospect [3] and [4].

Subsequently, it was determined to model the collected data from the investigation so that the rate of cement retrogression in the HPHT environments of the Niger Delta and the role of the indigenous Ughelli sands can be mathematically defined.

Autodesk Simulation 2012 was the software of choice; a proprietary software developed by Autodesk for the finite element analysis (FEA) of systems.

1.1 THE ENVIRONMENT

The cement in a HTHP environment resides in the annulus between the hole and the outer casing. In this position it is subjected to high temperature (>230 degrees Fahrenheit) and pressure (> 2,000 psi). This cement in HTHP environment undergoes a rapid loss of compressive strength on continuous exposure to extreme temperatures. [5] and [6]

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Usually more than half of their original strength is lost within 14 hours. Cement structures fail as a result of fatigue due to the degradation of their microstructure. X-ray diffraction studies show that calcium hydroxide and dicalcium silicate alpha-hydrate are the culprits. These hydration products appear together, and some times, singularly, depending on the temperature at which the cementing compound had been cured and the length of time of exposure. These compounds singularly or together lead to cement retrogression. Taking the schematics of a borehole (Figure 1) for illustration the cement between the casing and the annulus holds the casing in position such that the perforation is best position for recovery. With failure of the cement, the casing is displaced and this optimal positioning is lost.

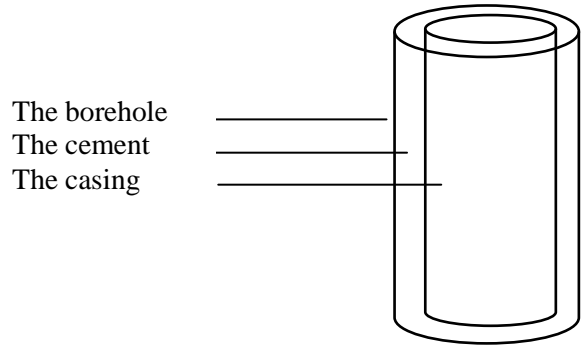


Figure 1: Schematics of a well bore

As a consequence of this HTHP, the cement retrogresses and is therefore unable to “hold” the casing in position; zonal isolation is hence compromised. Cement retrogression may be considered a chemical reaction whereby cement under high temperature and pressure breaks down

2.0 The Experimental Model

With this, a metallic box was designed, of known dimensions, with an inner metallic box which houses a heating element capable of generating heat to mimic the high temperature obtained in a HTHP environment (Figures 2, 3 and 4). This void between these two boxes was filled with the cement slurry of investigation and the contraption was there after subjected to high pressure. The full documentation of the methodology used in this experiment can be found elsewhere. [7].

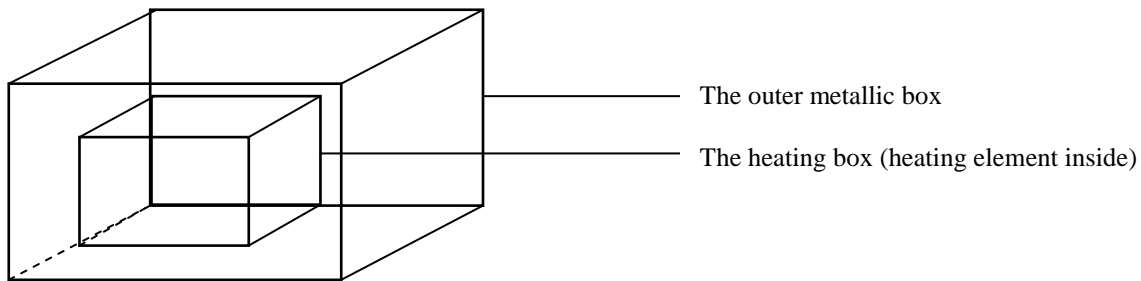


Figure 2: The relative position of the heating box and the outer metallic box

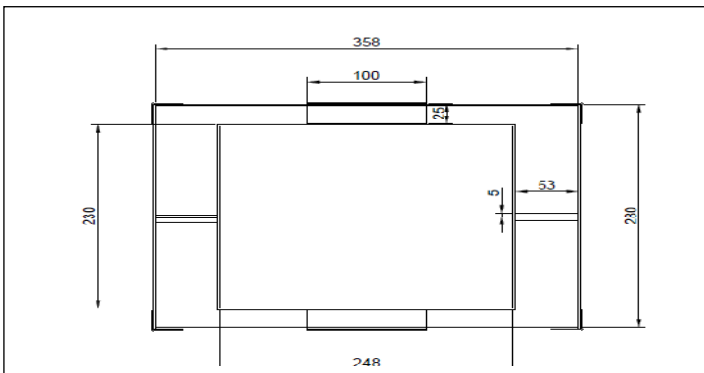


Figure 4: Dimensions of the metallic boxes

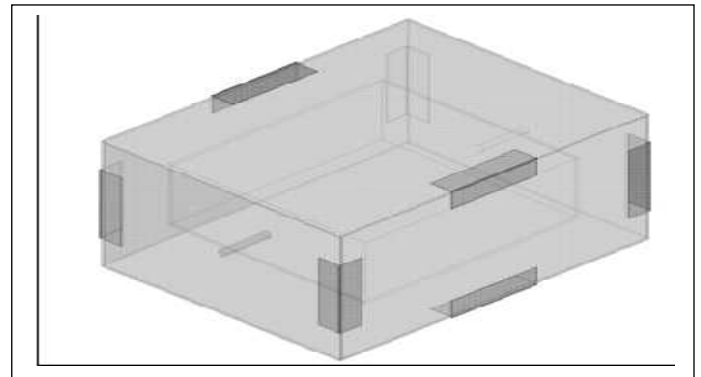


Figure 3: Representation of the boxes (drawn to scale)

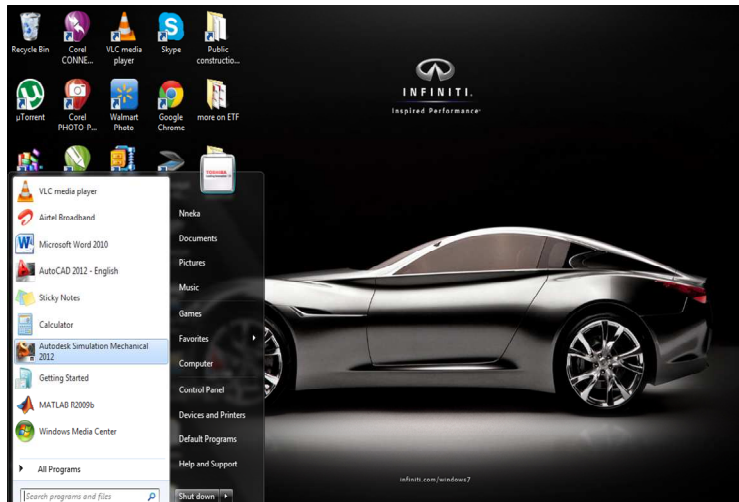


Figure 5: Starting Autodesk Simulation from the

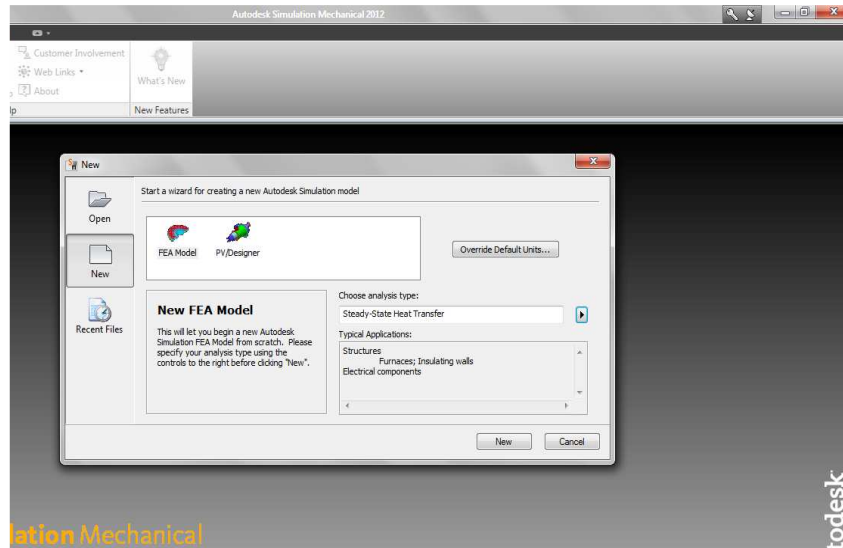


Figure 6: Starting a new project

Table 1: Tables of dimension and their measurement units

S/N	Dimension	Units
1	Length	Inches,
2	Time	Seconds, minutes
3	Pressure	Psi
4	Temperature	Degree Fahrenheit

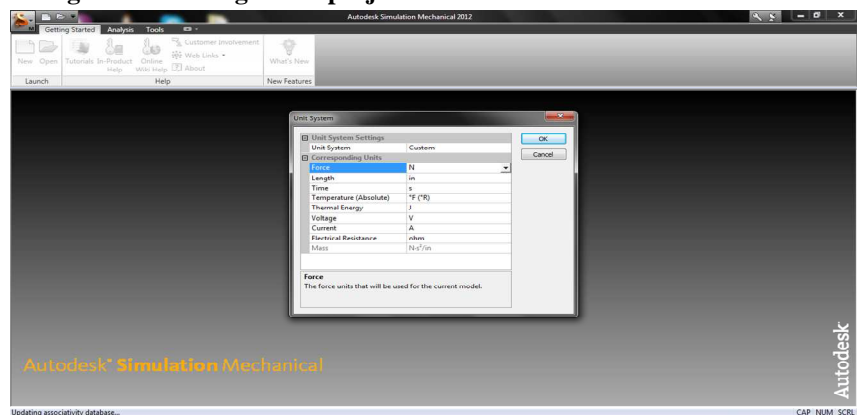


Figure 7: Define the measurement system to be used in the project

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A model of the mould and heating box was used. They were drawn to scale using a Computer aided design (CAD) application, Autodesk 2012. The CAD drawing of the mould and heating box from the Autodesk software, AutoCAD 2012 were Imported to Autodesk simulation 2012 (Figure 8) and meshed in Autodesk simulation (Figure 9) to enable FEA of the systems. The mesh represents a grid of nodes and elements that represents the model.

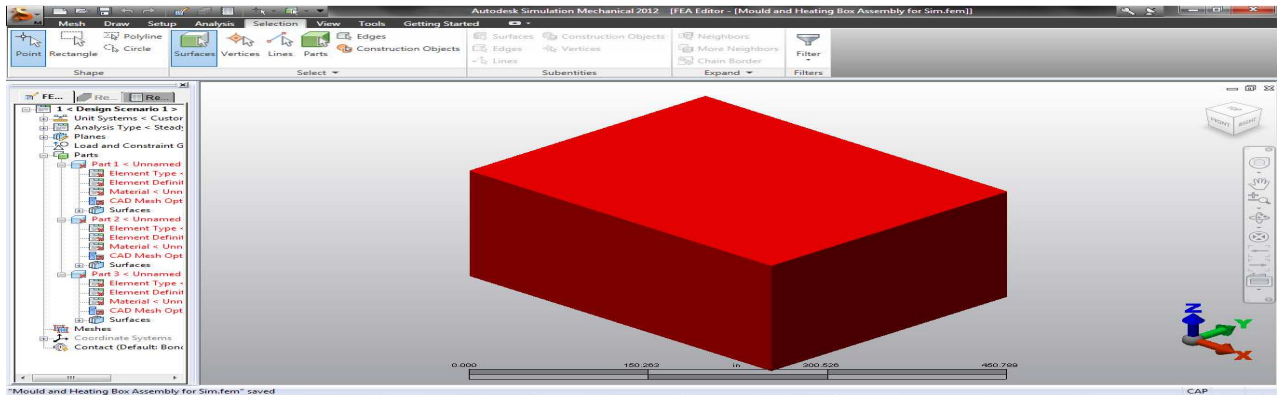


Figure 8: The Model in Auto CAD

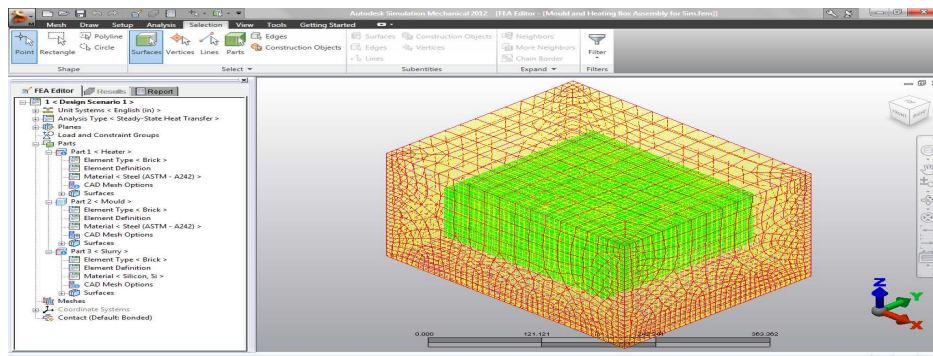


Figure 9: The Model after importation into Autodesk simulation

A Thermal analysis of the model was undertaken by selecting:

Analysis Type > Thermal > steady state heat transfer from the menu

A linear steady-state heat transfer model was adopted. It was assumed that the effects of radiation and convection can be safely ignored and only the effects of conduction on heat transfer were considered.

An equation expressing the heat flow by conduction is:

$$q = kA \frac{\Delta T}{L} \dots\dots\dots (1)$$

Where

- q = heat flow
- k = thermal conductivity (a constant) entered as a material property. Isotropic materials fall under this category.
- A = cross section area of an element face
- $\frac{\Delta T}{L}$ = the temperature gradient in the direction normal to the area, A..... (2)

The

heate
r was setup as the source of heat in the simulation. The heat source is the coil inside the heater and the sink is the harden cement slurry.

Setup > heat source > heater

3.1 The Loads and the Constraints

The heater is placed at a constant temperature of 350 degree Fahrenheit. The temperature of the heater is modeled as a constant temperature to mimic the effect of the geothermal heat expected at the depth of the earth.

The harden cement slurry is modeled as a sink. It is expected to be receptive of the “geothermal heat” (from the heater).

This temperature effects the harden slurry (part 3 in the simulation, Figure 8 and Figure 9) and is modeled using the “Internal heat generation” menu which is applied to a part that will either act as a heat source or heat sink throughout the analysis. The internal heat generation is specified on a per volume basis.

The volume of cement slurry is calculated thus using data from the Table 2.

The slurry resides in the annulus between the mould and the heater, therefore the volume would be (the volume of the mould) – (the volume of the heater)

Table 2: Dimensions of Mould and Heater boxes

		Length	Height	Width
Mould				
	Internal dimension	12.0	6.02	11.0
Heater				
	External dimension	9.60	3.52	8.88

- All measurements in inches

The experiments were conducted over a wide range of temperatures, pressures and compositions; temperature of 200 - 350 degrees F and pressures range of 5,000 psi to 10,000 psi. These data are from the Table 3. The model was checked in order to validate the robustness of the model

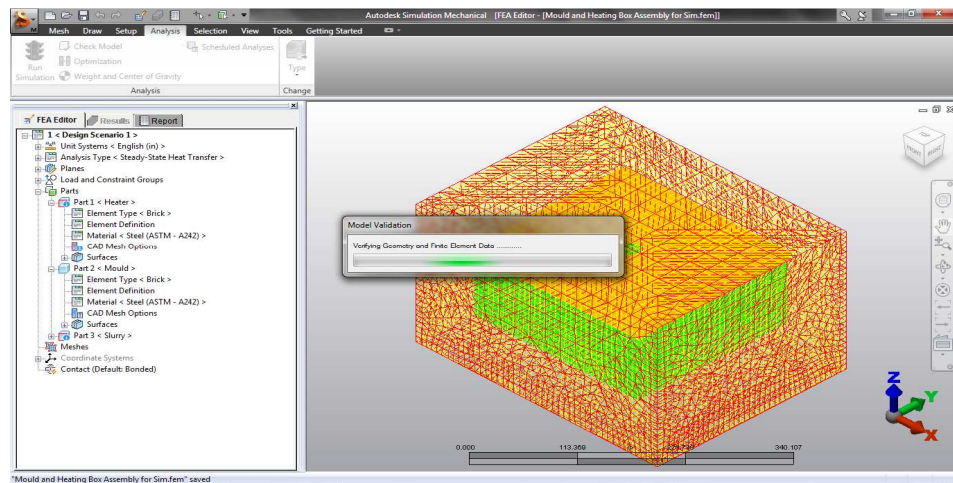


Figure 10: Validation of Entries

4.0 Conclusion

The cement in HT HP environment was observed to be under stress due to the temperature pressure condition at depth.

Factors that were observed to affect temperature rise includes the following, namely:

1. Cement type
2. Aggregate and additives
3. Ambient Temperature
4. Placement Techniques

A study of the completed simulated model (Figure 11) showed the effects of the thermal expansion. Cement hydration is a very exothermic process, leading to a rise in temperature, if the surface temperature is allowed to deviate greatly from that of the core, thermal cracking will develop. General equations were used to estimate the temperature rise and thermal stress developed. The outer surface cools faster than the core of the section. By thermal expansion/contraction, the temperature differential induces thermal (tensile) stresses at the surface. It was assumed that the thickness of the cement sheath around the wellbore and the temperature raise due cement hydration is insufficient to lead to thermal expansion (and cracking).

Cement hydration produces a rise in internal temperature, but other factors must be examined, such as heat flow to or from the environment. In this case there is a heat flow from the environment to the cement at depth due to the geothermal heat at depth. The temperature at depth was estimated to be all three direction and only one degree of freedom is defined for these elements; the temperature.

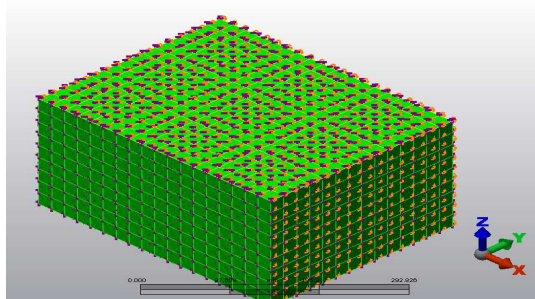


Figure 11: The completed Autodesk Simulation model

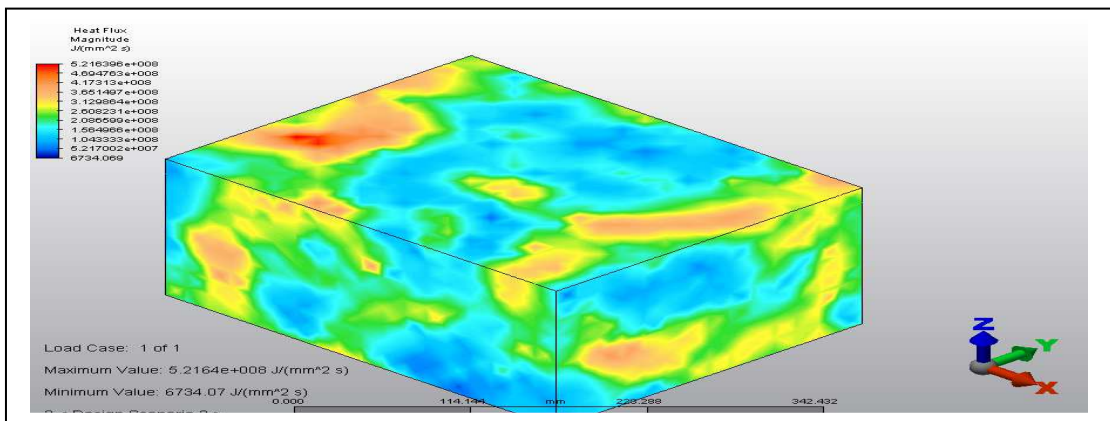


Figure 12: Heat flux

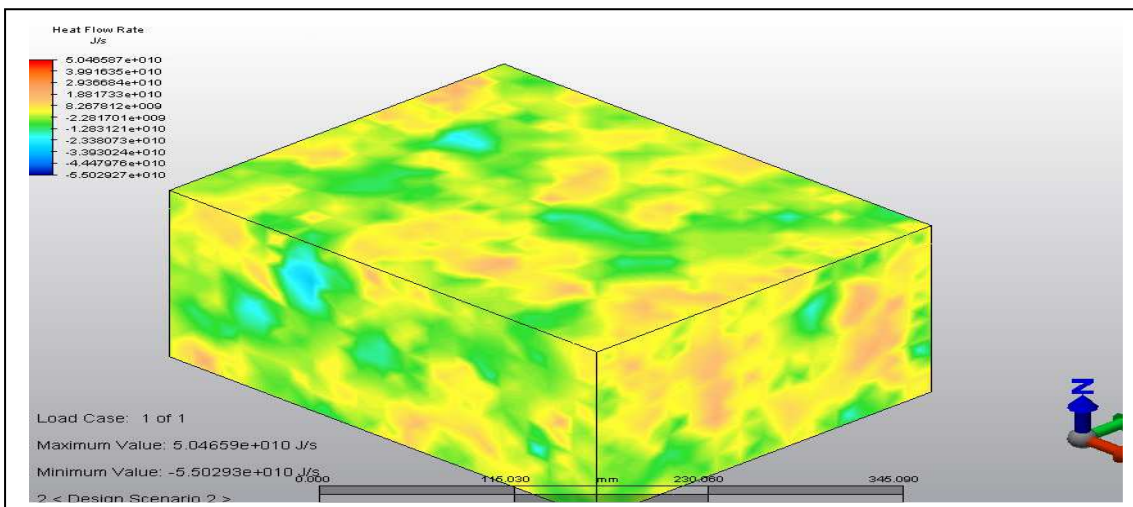


Figure 13: The heat flow rate

The value of the heat rate through a face is affected by the heat flow. A positive value indicates that heat is flowing out of the element ; a negative value indicates that heat is flowing into the element through the face.

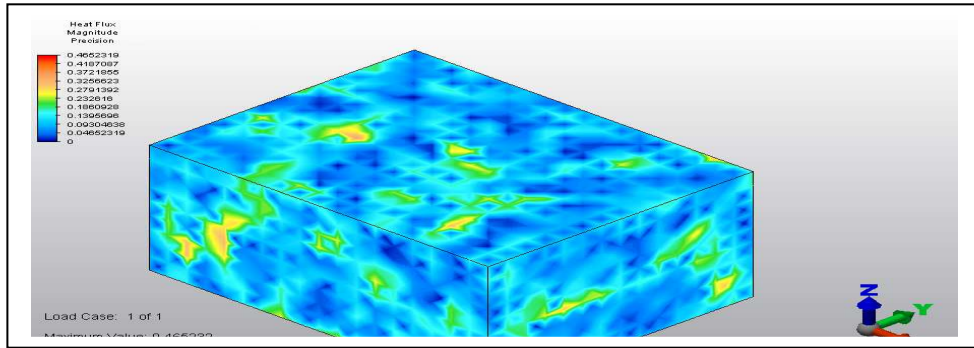


Figure14: Heat flux precision

Figure 12, 13, and 14 show the results of the thermal analysis of the cement slurries. They reveal the change in the heat flux, the heat flow rates through the different faces and the precision of the heat flux for the simulation, respectively. Mathematical modelling with Microsoft Excel (Figure 15 to Figure 19) reveals a complex relation between experimental pressure and the compressive strength of the cement slurries. Trend line analysis showed that the relationship between the compressive strength of the cement slurries at elevated pressure is most likely to have an exponential function.

Table 3: Trend lines

S/N	Trend line	Figure	R ²
1	Exponential	15	0.987
2	Linear	16	0.970
3	Log	17	0.852
4	Poly	18	0.985
5	Power	19	0.910

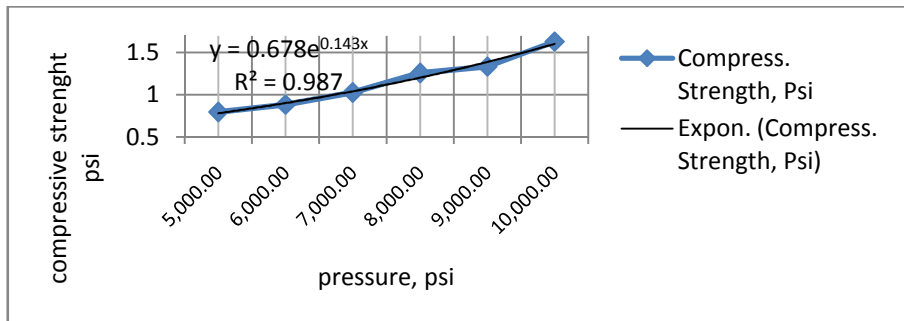


Figure 15: The Change in Compressive Strength with Pressure at Constant Composition and Temperature

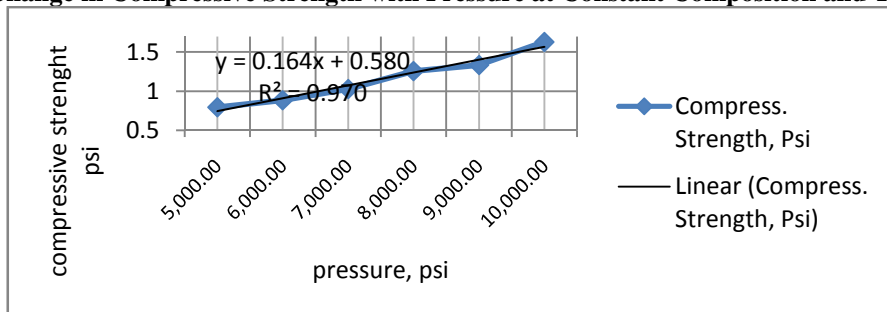


Figure 16: The Change in Compressive Strength with Pressure at Constant Composition and Temperature

One of the worst fit came from a logarithmic regression trend with $R^2 = 0.852$ (Figure 17)

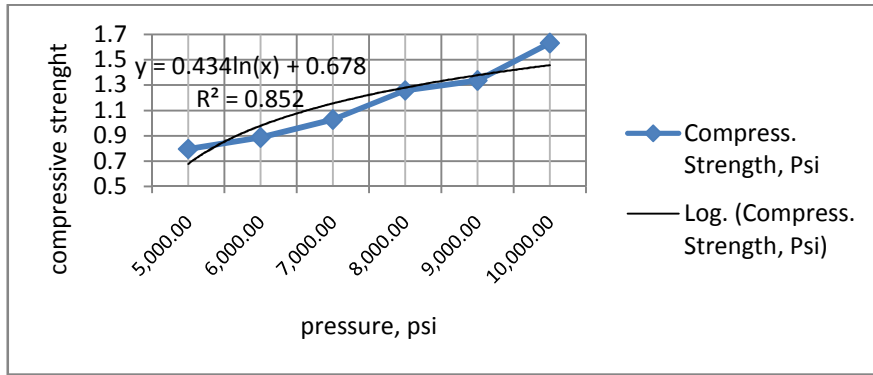


Figure 17: The Change in Compressive Strength with Pressure at Constant Composition and Temperature

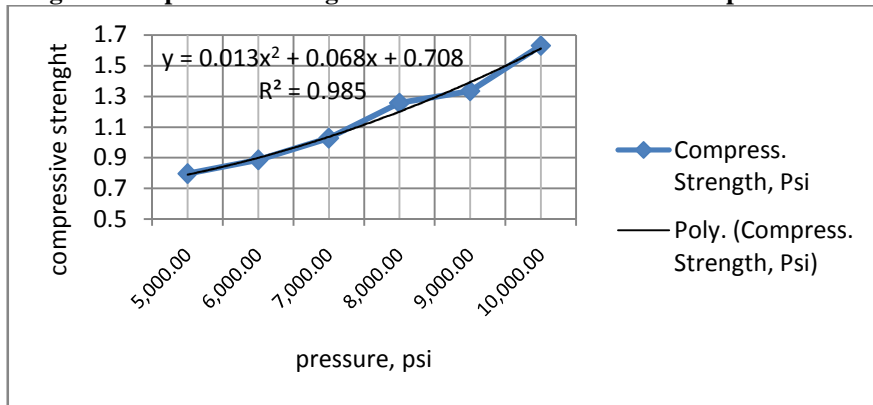


Figure 18: The Change in Compressive Strength with Pressure at Constant Composition and Temperature

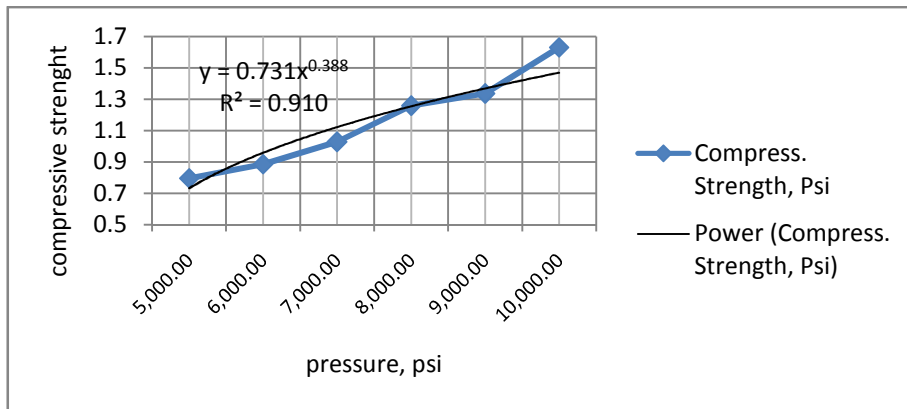


Figure 19: The Change in Compressive Strength with Pressure at Constant Composition and Temperature

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Table 4: Experimental Data from Investigation Involving Ughelli Sands, API Grade G Cement And Silica Flour

S/N	Lab temp ,deg F	Curing time ,minutes	Silica flour, dry wt. gram	Ughelli sands, dry wt ,gram	API grade G cement, dry wt, gram	Water temp ,deg F	Water Vol, ml	Exp. Temp. deg F	Exp. Pressure, Psi	Max. Load ,KN	Compress. Strength, Psi
19	75.2	30	4,680.00	3,900.00	18,720.00	71.6	1,200	350	5,000.00	6.2	0.7958
20	75.2	30	4,680.00	3,900.00	18,720.00	71.6	1,200	350	6,000.00	6.9	0.8857
21	75.2	30	4,680.00	3,900.00	18,720.00	71.6	1,200	350	7,000.00	8	1.0269
22	75.2	30	4,680.00	3,900.00	18,720.00	71.6	1,200	350	8,000.00	9.8	1.2579
23	75.2	30	4,680.00	3,900.00	18,720.00	71.6	1,200	350	9,000.00	10.4	1.3349
24	75.2	30	4,680.00	3,900.00	18,720.00	71.6	1,200	350	10,000.00	12.7	1.6302
43	77	60	2,080.00	5,770.00	18,900.00	71.6	1,200	350	5,000.00	5.8	0.7445
44	77	60	2,080.00	5,770.00	18,900.00	71.6	1,200	350	6,000.00	5.8	0.7445
45	77	60	2,080.00	5,770.00	18,900.00	71.6	1,200	350	7,000.00	6.2	0.7958
46	75.2	60	2,080.00	5,770.00	18,900.00	71.6	1,200	350	8,000.00	6.4	0.8215
47	77	60	2,080.00	5,770.00	18,900.00	71.6	1,200	350	9,000.00	6.5	0.8343
48	77	60	2,080.00	5,770.00	18,900.00	71.6	1,200	350	10,000.00	6.5	0.8343
67	77	60	6,500.00	1,300.00	18,200.00	71.6	1,200	350	5,000.00	6.8	0.8728
68	77	60	6,500.00	1,300.00	18,200.00	71.6	1,200	350	6,000.00	7.0	0.8985
69	77	60	6,500.00	1,300.00	18,200.00	71.6	1,200	350	7,000.00	7.2	0.9242
70	75.2	60	6,500.00	1,300.00	18,200.00	71.6	1,200	350	8,000.00	7.5	0.9627
71	75.2	60	6,500.00	1,300.00	18,200.00	71.6	1,200	350	9,000.00	8.3	1.0654
72	75.2	60	6,500.00	1,300.00	18,200.00	71.6	1,200	350	10,000.00	8.6	1.1039

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