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An Experimental Study of Mechanical Properties of Class G Cement Sheath in the Niger Delta

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ABSTRACT: *There are three basic components of a wellbore system, namely: Casing, Cement sheath and Rock formation. Although the cement sheath serves multiple purposes in the wellbore, its basic function is to act as a well barrier such that wellbore integrity is maintained. As a well barrier, it prevents unintentional and uncontrollable fluid flow from one formation into another of back to the surface. However, during drilling and production operations, the cement is subjected to various stresses resulting from thermal stress, non-uniform geo-stress, compressive and tensile stresses etc. Previously the main mechanical property of cement that was measured was the compressive strength, but now focus is also shared to other properties such as flexural strength, rupture elongation percentage, young's modulus and poissons ratio. The purpose of this paper is to test experimentally the response of the cement sheath to various loads and determine its ability to resist energy/stress application. Class G cement with varying water-cement ratio (0.4, 0.5 and 0.6) were cured and tested for its mechanical properties.*

KEYWORDS – *Cement, Mechanical properties, Wellbore Integrity*

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I. INTRODUCTION

From previous research carried out, it is shown that cement-sheath has two failure criteria which are tensile failure and shear failure. The former occurs when the stress on the cement exceeds its tensile strength, while the latter occurs when its shear strength is exceeded by stress. The effect of shear and compressional stresses on cement sheath usually results in its failure. These shear and compressional stress are caused by either radial loads, high pressures present within the cement sheath or from formation tectonic movement. With an increase in the exploration of unconventional hydrocarbons, the industry delves deeper offshore, and this often comes with the risk of increased downhole temperature and pressure. In addition, the wellbore is subjected to in-situ stress that are not uniform, this emphasizes the need to ensure the mechanical integrity of the casing-cement-formation system.

During operational activities, pressure and/or temperature change generates stress which concentrate at boundaries between the casing/ cement interface or at the cement/formation interface. Hence a casing/cement/formation sheath system, the highest stress will be found at the casing/cement interface due to pressure increase.

When the cement slurry hardens, there is an increased tendency for formation fluids such as water and/or gas to invade. This is because during this hardening period, the cement loses its ability to transmit hydrostatic pressure as only fluids can do that and so there would be no deformation in the solid cement at end of its hardening. However, when cement shrinkage starts, it leads to deformation of the cement. This deformation further leads to the deformation of the casing and the formation which finally leads to damage and failure.

Whether due to shear, tensile or pressure/temperature induced stresses in the wellbore, the set cement fails by:

- Radial circumferential cracking of the cement matrix
- Breakdown of bonds in the Casing-Cement Sheath-Formation system

The service life of a well is dependent on the stress state of the casing/cement/formation system. Therefore, if the well is to perform optimally during its lifecycle, it is crucial that a stress analysis is carried out before cementing activities. This would enable the appropriate cement with good integrity be adopted to serve its purpose.

Thiercelin et al. 1998 [1] studied the failure mechanism of cement sheath theoretically and established an analytical method to calculate the stress of casing-cement sheath-formation system under temperature and pressure. Jiang Wu and Martin Knauss, 2006 [2] have analyzed casing and cement stresses under steam injection conditions in order to understand casing and cement failure mechanisms. Jessica McDaniel, Larry Watters and

Arash Shradravan, 2014 [3] carried out laboratory stress endurance testing on two different cement compositions in order to evaluate cement sheath failure resulting from cyclic stresses experienced during drilling, fracturing and production. The results were used to quantify mechanical properties needed to optimize zonal isolation

When there is a failure of the cement sheath to serve its sealing purpose, annulus pressure is generated. Sealing failure is often as a result of alternating loads induced by hydraulic fracturing and variation in the wellbore temperature.

Goodwin and Crook 1992 [4] devised a test model to determine the effects of excessive pressure or temperature changes on cement sheaths. They considered that exposure of casing to excessive temperature increases or internal test pressures caused diametrical and circumferential casing expansion. This circumferential force created a shearing force on the cement/casing interface, causing failure on the interface or radial fracturing of the cement sheath from the inner casing surface to the outer casing.

The distribution and magnitude of cement sheath stress is affected by how the wellbore temperature and pressure varies during different operations such as hydraulic fracturing, Enhanced oil recovery schemes, acid treatment etc. If the stress is excessive, damage of the cement sheath occurs. Yong Li, Shuoqiong et al. 2010 [5] worked on the analysis of the cement stress considering variation of wellbore temperature and pressure during production process. He concluded that an increase of the casing temperature brings tensile effect on the

cement sheath.

Modelling of wellbore stresses is now used to determine the suitability of a cement design for expected wellbore induced stress. However, during the modelling, it is necessary that the mechanical parameters of the cement sheath be defined. This is because it helps to know the ability of the cement to withstand the expected stresses downhole.

Two vital parameters to be measured are: The tensile

Tensile Strength: this is the defined as the maximum stress a material can withstand while being stretched or pulled just before it yields in a flexural test. Hence it is a measure of the force that is required to deform the material. If the material withstands more force, then it is regarded as being more flexible.

: When a material reaches a certain stress value, it begins to deform. If the stress is

expressed as the ratio of longitudinal stress to the longitudinal strain. It is a measure of the interatomic bond

used to predict when a structure would deform.

material is stiffer and more susceptible to failure. Therefore, to withstand the stresses inherent of the wellbore, the cement sheath should be more **flexible** and **resilient**. This can be achieved with an increased ratio between

Various methods can be used to reduce to improve Cement Flexibility:

- Slurry Density reduction: An extender is a chemical additive or inert material used to decrease the density or increase the yield of a cement slurry (glossary.oilfireld.slb.com). If extenders such as sodium silicate and bentonite that accommodate additional water are used in the cement slurry, this could possibly increase the flexibility of the set cement.
- Foamed cement is an alternate solution. First introduced in the 1980s, is a method to considerably reduce density of cement by mixing the cement slurries with foaming agents and gas (which is usually Nitrogen) to as low as 8ppg (958.6 kg/m^3) while at the same time maintaining good strength properties of the cement. The desired foam quality is usually 18-38 % foam quality.
- Elastomeric composites/Flexible particles
- Fibers added to the cement matrix to improve flexural strength

Jessica et al. 2014 [3] developed a correlation between the Applied Energy vs. Energy Resistance correlation. The resulting model may allow engineers the ability to develop a cement design that will withstand the predicted stresses for the life of the well. This will require detailed stress analysis prediction for the life of the well and specialized cement testing such as tensile strength, anelastic strain, flexural

applications.

II. EQUIPMENT AND PROCESS

The cement compositions used for this study was obtained from an operational service company in the Niger Delta. The cement slurry formula used for production section of the well had its water cement ratio varied and its mechanical properties investigated in the civil engineering lab, Rivers state University of Science and technology.

The cement slurry was mixed at room temperature and left to cure for a period of 24 hours after which the tests were carried out.

Table 1: Cement slurry composition

Cement System	System 1	System 2	System 3
Density (ppg)	14.19	14.89	15.75
Water-cement ratio	0.6	0.5	0.4
Cement Type	Class G	Class G	Class G
Seawater %bwoc	0.4	0.4	0.4
Antifoam %bwoc	0.0044	0.0044	0.0044
Gasblok %bwoc	0.04	0.04	0.04
Dispersant %bwoc	0.01	0.01	0.01
Retarder %bwoc	0.18	0.18	0.18

The tests carried out on the cement systems include:

Table 2: Mechanical properties and reasons for measure

S/N	PROPERTY MEASURED	REASON
1	Drying Shrinkage (Cement Shrinkage Test)	Cement shrinkage during cement hydration leads to reduction 100.85 531.26 0.48 0.48001 ref8001

Fig 2: Curing mould

2.1 Cement Shrinkage Test (Reference: ASTM C157)

ASTM C157 is a standard test method for length change of hardened hydraulic-cement mortar and concrete. It is a test used to measure the strain (length change) in concrete due to shrinkage.

From the result below, the cement system with the highest water-cement ratio (0.6) exhibited the highest shrinkage due to presence of excess water in the slurry. When the shrinkage is higher, the capillary pore system builds up fast and the shrinkage stress weakens the cement. As would be observed in the subsequent mechanical tests, the cement slurry with the highest water-cement ratio had the lowest mechanical strength.

Table 3: Shrinkage values for respective cement samples

IDENTIFICATION	WATER-CEMENT RATIO	SHRINKAGE (με)
0.4 WC-01	0.4	-234
0.4 WC-01		-244
0.5 WC-01	0.5	-256
0.5 WC-01		-252
0.6 WC-01	0.6	-269
0.6 WC-01		-273

2.2 Split cylinder tensile test (Reference: BS 1881)

BS 1881 is a method for determining the tensile splitting test of hardened cement. It is important to measure this property as cement is susceptible to tensile cracking under various types of applied load. Few studies have suggested that if this ratio is l

to failure.

Tensile Strength (N/m^2): $\delta = \frac{2p}{\pi dl}$ .... (1)

Table 4: Tensile strength values for respective cement samples

W/C ratio	Age (hrs)	Length of Beam (m)	Diameter of Beam (m)	Applied Load (KN)	Tensile Strength (N/m^2)	Tensile Strength (psi)
0.4	24	0.1	0.2	40	1.27 x 10^6	185
0.5	24	0.1	0.2	40	1.27 x 10^6	185
0.6	24	0.1	0.2	30	0.96 x 10^6	139

2.3 Crush Test

This mechanical test measures the maximum amount of compressive load a material can bear before fracturing. As observed in table 5, the cement system with the lowest water-cement ratio had the highest compressive strength. A denser cement results in higher strength because it has less voids and porosity.

Crush Strength (N/m^2): $\sigma = \frac{p}{lb}$ .... (2)

Table 5: Crush strength values for respective cement samples

W/C ratio	Age (hrs)	Length of Beam (m)	Breadth of Beam (m)	Applied Load (KN)	Crush Strength (N/m^2)	Crush Strength (psi)
0.4	24	0.1	0.1	140	14 x 10^6	2031
0.5	24	0.1	0.1	120	12 x 10^6	1740
0.6	24	0.1	0.1	100	10 x 10^6	1450

2.4 Modulus of Elasticity Test-form (Reference: BS 1881-121:1983)

BS 1881-121:1983 is a test used to determine the static modulus of elasticity in compression of

when a load is applied to it. The higher the elastic modulus, the stiffer the material. From table 6, the cement system with a water-cement ratio of 0.4 had the highest modulus and so is the stiffest. Therefore, it would be more resistant to fatigue and cyclic forces as compared to the more ductile cement system with a ratio of 0.6. Before cement bears load, damage already exists due to its heterogeneous components and the failure process is caused by development and evolution of the already existing cracks. As seen above in the stress-strain graphs, non-linearity is exhibited, and this is probably due to the micro-cracks existing in the cement systems.

Table 6: Stress Strain values for cement sample with water-cement ratio of 0.4

Stress	1.0	2.0	3.0	4.0	5.0	5.8
Strain	2.0	3.2	4.4	5.6	6.7	7.2

Modulus of Elasticity $= \frac{\text{Stress}}{\text{Stress}} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{4-2}{(5.6-3.3)\times 10^{-4}} = 8.7\text{kN/mm}^2 = 8.7\text{ GPa}$

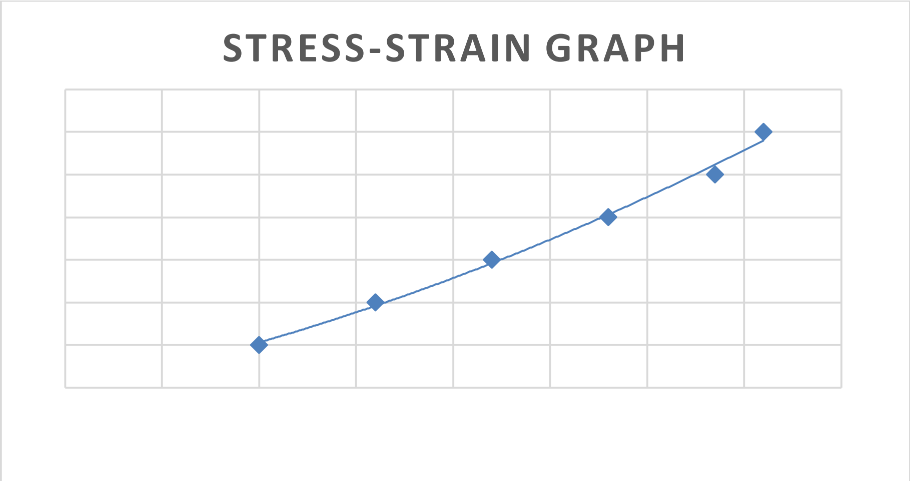

Chart 1: Stress vs Strain for cement sample with water-cement ratio of 0.4

Table 7: Stress Strain values for cement sample with water-cement ratio of 0.5

Stress	1.0	2.0	3.0	4.0	5.0	6.0
Strain	2.0	3.4	4.7	5.9	7.1	7.5

Modulus of Elasticity $= \frac{\text{Stress}}{\text{Stress}} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{5-2}{(7.1-3.4)\times 10^{-4}} = 8.11\text{kN/mm}^2 = 8.11\text{ GPa}$

Table 10: Values of flexural strength for respective cement samples

W/C ratio	Age (hrs)	Length (m)	Breadth (m)	Depth (m)	Applied Load (KN)	Flexural Strength (N/m^2)	Flexural Strength (psi)
0.4	24	0.5	0.1	0.1	11.78	5.89×10^6	854
0.5	24	0.5	0.1	0.1	11.39	5.70×10^6	827
0.6	24	0.5	0.1	0.1	10.80	5.40×10^6	783

III. CONCLUSION

This paper has investigated the mechanical properties of the typical Class G used in the Niger Delta wells in Nigeria. The following properties were investigated

- Shrinkage: The cement sheath with the lowest water-cement ratio (0.4) exhibited the highest shrinkage and is more susceptible to weakening than the cement sheath with a water-cement ratio of 0.5 or 0.6 (all specimens containing the same percentage of additives). Refer to TABLE 3.
- Tensile strength: The cement sheath with the lowest water-cement ratio (0.4) exhibited the highest tensile strength of 185 psi and would be able to withstand tensile stresses better than the cement sheath with a water-cement ratio of 0.5 or 0.6 (all specimens containing the same percentage of additives). Refer to TABLE 4.
- Crush strength: The cement sheath with the lowest water-cement ratio (0.4) exhibited the highest crush strength of 2031psi and would be able to withstand compressive stresses better than the cement sheath with a water-cement ratio of 0.5 or 0.6 (all specimens containing the same percentage of additives). Refer to TABLE 5.
- Modulus of Elasticity: The cement sheath with the lowest water-cement ratio (0.4) exhibited the highest modulus of 8.7 Gpa, hence it is the stiffest and would not be able to withstand fatigue and cyclic forces better than the more ductile cement sheath with a water-cement ratio of 0.5 or 0.6 (all specimens containing the same percentage of additives). Refer to TABLE 9.
- Flexural Strength: Modulus of Elasticity: The cement sheath with the lowest water-cement ratio (0.4) exhibited the highest flexural strength of 854 psi, hence it is the stiffest and would not be able to withstand fatigue and cyclic forces better than the more flexible cement sheath with a water-cement ratio of 0.5 or 0.6 (all specimens containing the same percentage of additives). Refer to TABLE 10.

In conclusion, a lower water-cement ratio would result in better resistance to tensile and compressive forces but

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