5
Materials

The primary materials used in this research other than salt (see Chapter 3) are the steel casing and the cement, which are discussed in this chapter. Both materials are explained in detail. However, further information may be found by referring to the cited authors mentioned within this chapter.

5.1
Casing

In the drilling program, the casing insures well stability and prevents wellbore collapse. Casing design is especially important for deepwater drilling, where extreme geostatic lateral pressures exist. Therefore, the tube must be designed to resist the loading induced by the formation and cement.

The casing is a cylindrical steel pipe geometrically more stable upon hydrostatic loading. However, the formation-cement system does not necessarily load it hydrostatically, thus reducing its bearing capacity. Given that salt rock is isotropic, if the magnitude of the overburden pressure and lateral loads are the same, theoretically it will not induce non-uniform loading upon the cemented casing. However, casing eccentricity and cement defects may lead to non-uniform salt loading. Intense non-uniform lateral loading may even lead to plastic deformation in the casing. Shen (2011) says that non-uniform loading is amplified by the rate of salt creep and casing geometry and mechanical/elastic properties. Observing numerical simulation results confirmed by laboratory tests, Pattillo et al. (2003) reports that non-uniform loading can provoke unacceptable cross-sectional casing deformation, weakening the cross-sectional strength to fluid pressure differential that eventually must be undertaken.

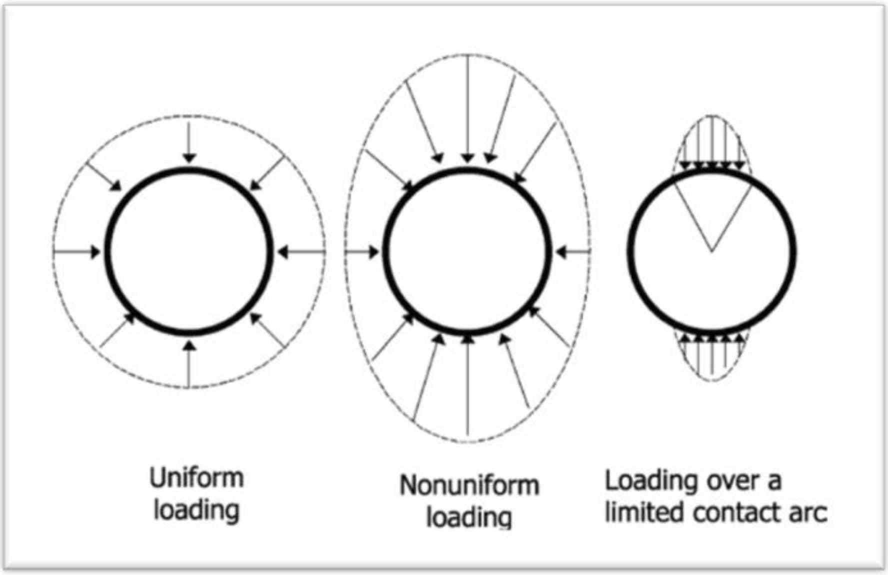

Figure 5-1: Illustration of non-uniform load configuration conventionally assumed for through-salt casing design (Willson et al., 2003).

5.1.1 Eccentricity

Positioning the casing coaxially to the wellbore cavity is another challenge faced in deepwater oil drilling. If the casing is not concentric with the borehole it is referred to as *casing eccentricity*. Eccentricity affects the quality of cement jobs, zonal isolation and good wellbore cleaning, making it an important factor to consider in drilling (Akgun et al., 2004). Centralizers as shown in Figure 5-2 are used during pipe setting to help maintain the casing centered such that the cement can be effectively and evenly distributed within the annulus. Salehabadi (2010) claims that there is also a risk of putting too many centralizers and creating a stiff drill string. This makes it difficult for the next drill pipe to fit and increases the chance of stuck pipe. Eccentricity is generally expressed as a percentage as in Eq.(5.1) by Salehabadi (2010), being a ratio of the off-centered distance δ to the difference between wellbore radius R_w and casing radius r_c.

Figure 5-2: Centralizer used to keep the Casing concentric with the borehole. (Deepwater Horizon Study Group, 2011).

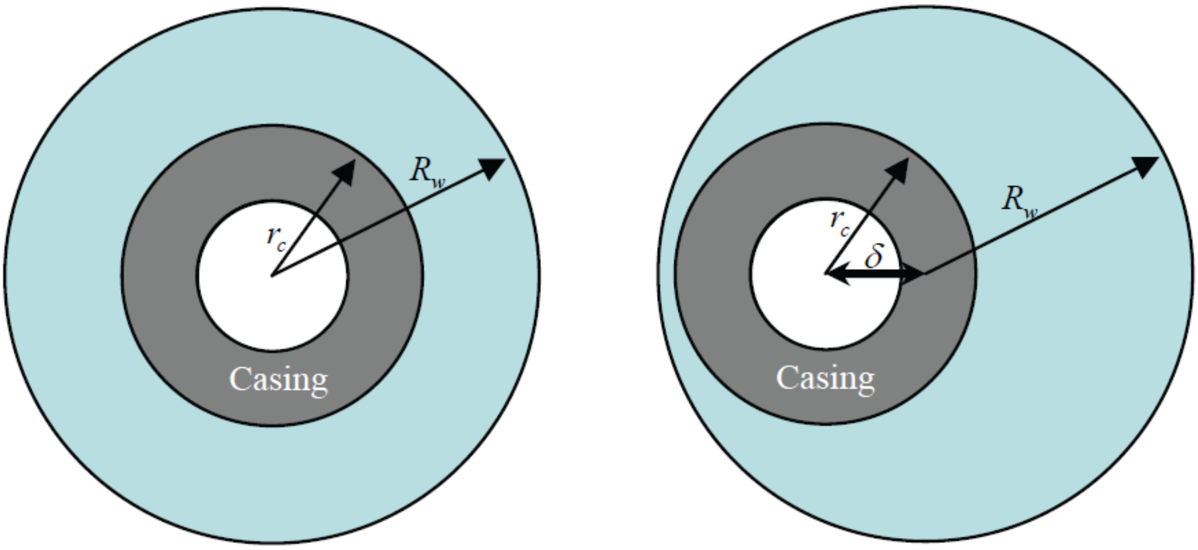

Figure 5-3: Left: Concentric casing. Right: Eccentric casing (Salehabadi, 2010).

$$Eccentricity\% = \frac{\delta}{(R_w - r_c)} \cdot 100 \tag{5.1}$$

Where

δ = difference between center of the wellbore and the casing;

R_w = Radius of the wellbore; and

R_c = Radius of the casing.

5.1.2
Ovalization

Due to mobile formations, tectonic activity or extreme loading conditions, casing ovalization may occur. Experiments have shown that intense ovalization may not only reduce casing drift but also lead to a reduction in the tube's resistance to common loading conditions, namely pressure differential (Pattillo et al., 2004). Ovalization can be expressed as the maximum measured diameter difference divided by the mean diameter (1995, 2004), given by

$$O_v = \frac{OD_{max} - OD_{min}}{\left(\frac{OD_{max} + OD_{min}}{2}\right)} \times 100 \qquad (5.1)$$

Where

OD_{max} = Maximum outer diameter;

OD_{min} = Minimum outer diameter; and

O_v = Percent ovality

In his work, Poiate et al. (2006) used the following expression for ovalization:

$$O_v = \frac{OD_{max} - OD_{min}}{OD_{max} + OD_{min}} \times 100 \qquad (5.2)$$

It is worth noting that several other equations may be used to describe ovalization. It is also conjectured that considerable ovalization may have an effect upon an existing cement defect in highly mobile salt layers.

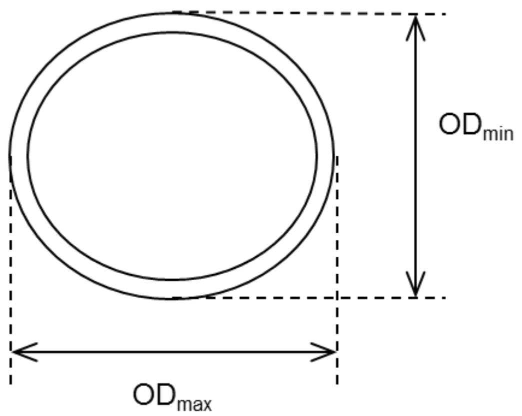

Figure 5-4: Ovality is measured by the outer diameter (OD).

5.2 Cement

Wet cement (also referred to as *slurry* or *sealant*) displaces the drilling fluid which fills the spacing left between the casing and the formation to provide stability, protection and zonal isolation for the steel casing. Zonal isolation refers to the prevention of any fluids that may leak from the formation into the annular space outside the casing. This is avoided by filling the entire annulus with competent slurry. Although there does exist the alternative of increasing the casing thickness, cementing is far more economical, especially since the steel casing alone may make up nearly 18 percent of the total cost of the drilling program (Bourgoyne, 1986). Cement is always used in deepwater offshore wells and is important especially for salt formations due to the high loading conditions.

5.2.1 Cement Composition

Casings are cemented using portland-based slurries. Such a sealant is ideal since it can be easily pumped through the casing and hardens in a timely manner. Portland cement comes in a powdered form and is mixed with water to produce the slurry. It is made up of four main chemical components: lime, iron, silica, and alumina.

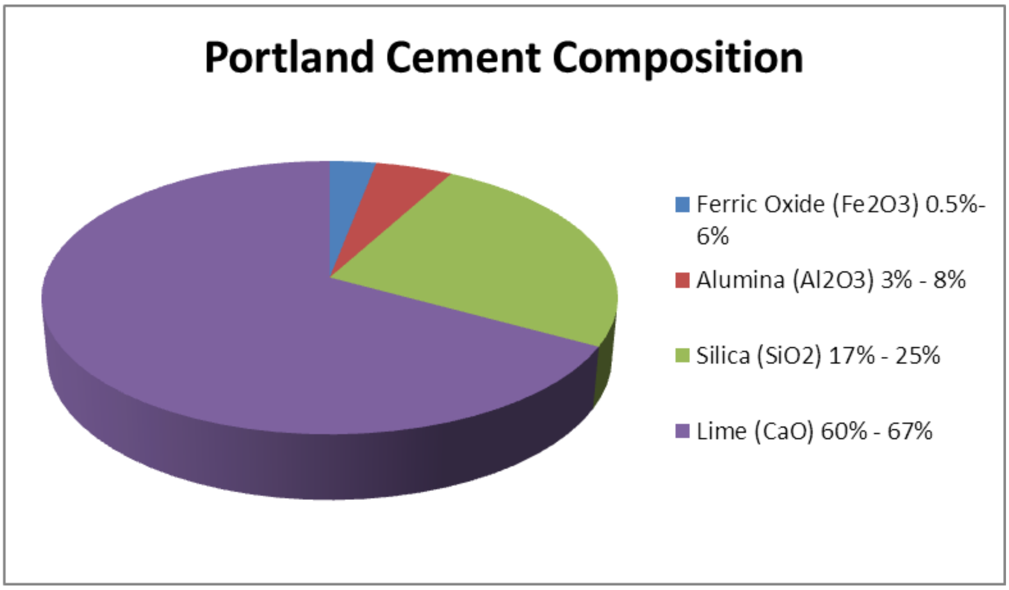

Figure 5-5: Portland cement composition (Melo, 2009 modified).

Figure 5-6: Cement powder by Aalborg Portland. (http://www.aalborgwhite.com/default.aspx?m=2&i=62).

There are eight different types of portland cement listed in Table 5-1 that adhere to the requirements provided by the American Society of Testing and Materials (ASTM). Type I is the typical portland cement used in construction. Type II has a lower heat of hydration compared to Type I and is desired for use in moderate exposure to sulfate attack. Some construction projects may need to use cement that gains strength quickly, and in such case, early strength cement Type III is more suitable. Type IV has low heat of hydration and is ideal for concrete dams. However, MacGregor (2004) states that today, builders tend to use Types I and II cement combined together with fly ash instead of Type IV. Similar to Type II, Type V is a sulfate-resistant cement and is most applicable for footings, basement walls, sewers and other soils containing sulfates. Some concretes have *air entraining* which allows for tiny air bubbles to exist within the cement and remains in the set concrete. This reduces the risk of cracking due to freezing and thawing while also improving the cement’s workability. The drawback to air entraining is that it reduces the cement’s compressive strength (MacGregor et al., 2005).

ASTM Cement Type	Description
Type I	Normal
Type IA	Normal, air entraining
Type II	Moderate resistance to sulfate attack
Type IIA	Moderate resistance, air entraining
Type III	High early strength
Type IIIA	High early strength, air entraining
Type IV	Low heat of hydration
Type V	High resistance to sulfate attack

Table 5-1: Types of portland cement given by ASTM International (Allen, 2004 modified).

Oil well cements commonly adhere to the standards and requirements provided by the American Petroleum Institute (API) and, like ASTM International, is recognized worldwide. API also has eight different types or *classes* of portland cement that are termed alphabetically from A to H as displayed in Table 5-2. The API classes are designed to suit well depth, pressure and temperature. The most employed for deepwater wells are classes G and H mainly because of low cost and their ability to meeting design needs by using additives. In view of the descriptions in Table 5-1 and Table 5-2, the ASTM cement types I, II, and III are comparable to API classes A, B and C. Bourgoyne (1986) indicates that oil wells are not restricted to the application of API class portland cement, hence the use of ASTM construction type cements are also permitted. Deep wells require cement with relatively slow strength gain (Melo, 2009). Some formations make it challenging to cement, namely salt rock. Due to the creep behavior in salt rock, it is paramount to use strong cement with retarding agents. Low plastic viscosity is desirable for slurries in evaporite zones such as salt rock in order to improve pumpability.

Class A: Ordinary use. Ideal if no special properties are required. Depths from surface to 6,000-ft (1830m). Similar to ASTM Type I.
Class B: Moderate to high sulfate resistance; depths from surface to 6,000-ft (1830-m). Similar to ASTM Type II.
Class C: High early strength; available in ordinary, moderate and high sulfate- resistant types. Depths from surface to 6,000-ft (1830-m). Similar to ASTM Type III.
Class D: Conditions of moderately high temperatures and pressures. Available in both moderate and high sulfate-resistant types. Depths from 6,000- to 10,000-ft (1830 to 3050-m).
Class E: Conditions of high temperatures and pressures. Available from moderate to high sulfate-resistant types. Depths from 10,000- to 14,000-ft. (3050-m to 4270-m).
Class F: Conditions of extremely high temperatures and pressures. Available in both moderate and high sulfate-resistant types. Depths from 10,000- to 16,000-ft (3050- to 4880-m).
Class G: Basic cement . Can be used as manufactured or with accelerators and retarders to cover a wide range of well depths and temperatures. No additions other than calcium sulfate or water, or both, shall be interground or blended with the clinker during manufacture of Class G cement. Available in moderate and high sulfate-resistant types. Depths fom surface to 8,000-ft (2400-m) .
Class H: Basic cement. Can be used as manufactured *and* with accelerators and retarders to cover a wide range of well depths and temperatures. No additions other than calcium sulfate or water, or both, shall be interground or blended with the clinker during manufacture of Class G cement. Available in moderate and high sulfate-resistant types. Depths fom surface to 8,000-ft (2400-m) .

Table 5-2: API cement classes (Bourgoyne, 1986 modified).

5.2.2
The Cementing Process

After drilling, the casing is placed along with centralizers being used to help center it with the borehole as mentioned in Chapter 5.1.1. Mud circulation is used to clear away debris that could potentially be obstructive within the annulus. The slurry is then pumped down through the casing and flows upward through the annulus as displayed in Figure 5-7. This way, the existing drilling mud in the annulus is displaced by the slurry using the best techniques and procedures to avoid cement voids or channels from developing. Crew members check for lost returns by monitoring the lift pressure and verifying that the total volume

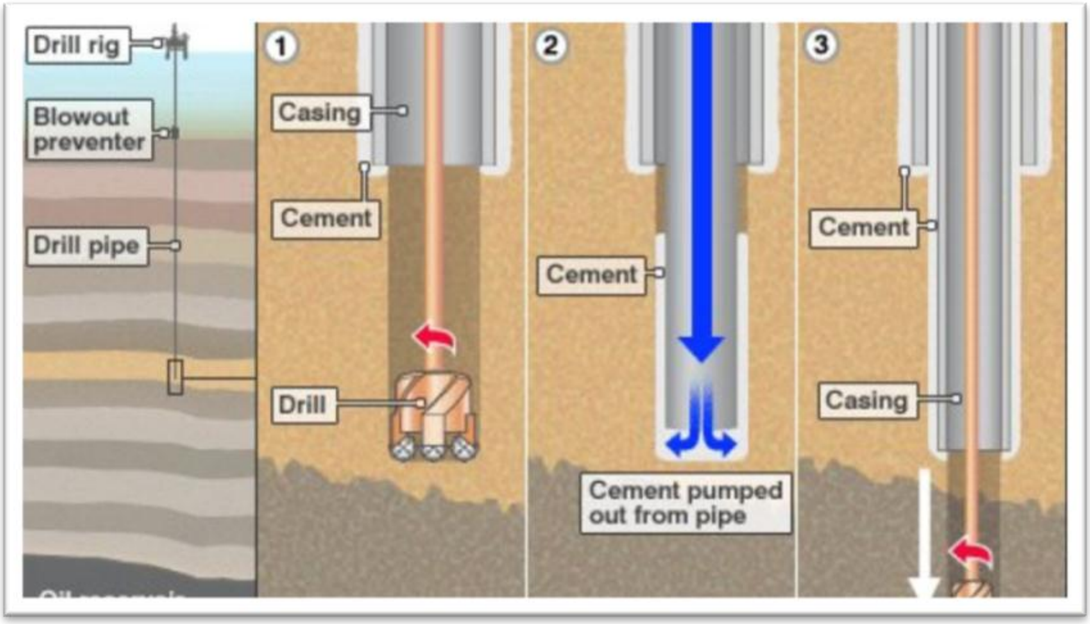

Figure 5-7: Simplified cement pumping process. (http://blow-out.info?p=26).

of pumped cement matches with the cement volume pumped out of the cement tanks (Chief Counsel Report, 2011). Once the cement is set, it is to act as an impervious continuous solid that prevents gases or liquids from flowing up or down. Figure 5-8 also illustrates the drilling stages: the surface casing is installed, followed by cementing; the next casing string has a smaller diameter and fits inside the previous casing while leaving room for cementing. This process is repeated until the production casing is set.

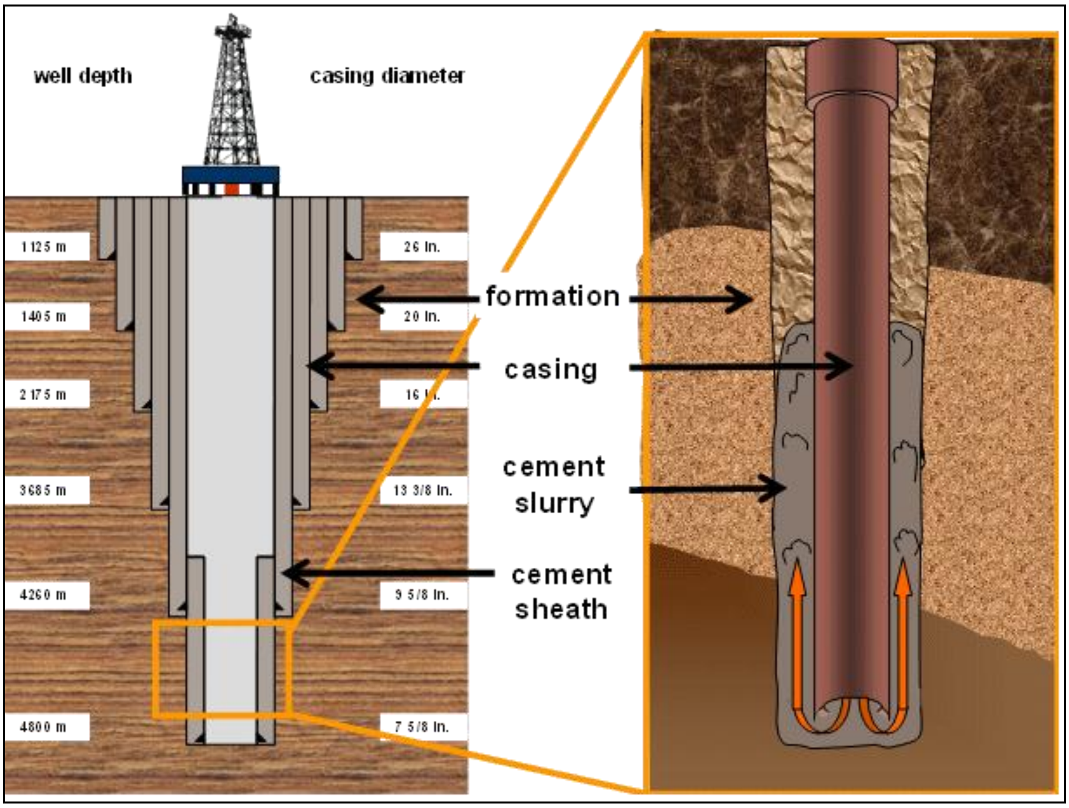

Figure 5-8: Cement is pumped through the casing and flows upwards due to uplift pressure (http://www.bauchemie-tum.de/master-framework/index.php?p=Tief&i=13&m=1&lang=en).

5.2.3 Cement Strength

The strength of cement is commonly determined by the same procedure used for concrete. It is measured in terms of unconfined compressive strength (UCS), where laboratory tests are performed on cylindrical specimens. These specimens are tested in compliance with API Specification 10A. The cement specimen increases in strength slowly over time as portrayed in Figure 5-9. Class G cement after 7 days of curing achieves a compressive strength of approximately 49.78 MPa (Souza et al., 2011). The lower the porosity of the cement, the greater its strength (Dowling, 1999).

Figure 5-9: Typical unconfined compression test performed for cement (Souza et al., 2011).

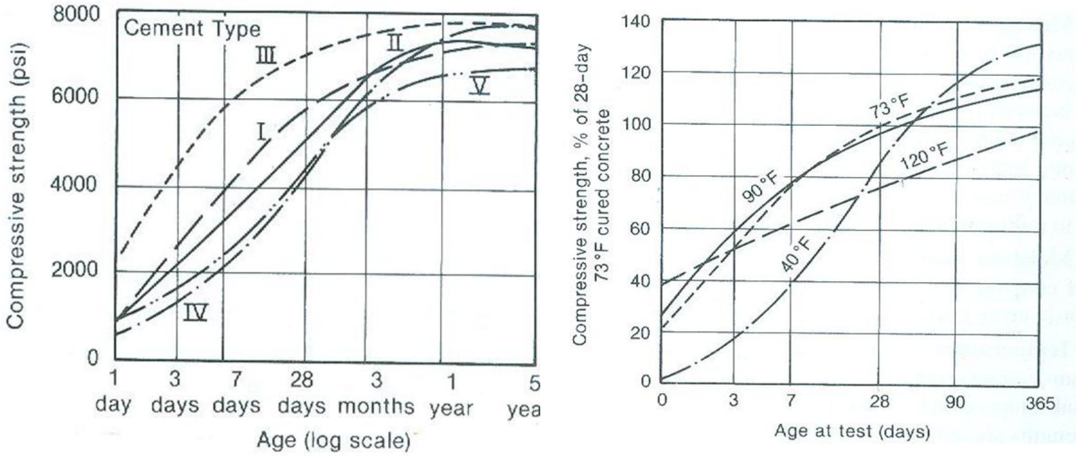

Figure 5-10: Left: Strength gain of concrete—moist cured, w/c = 0.49 (Gonnerman et al., 1951). Right: Temperature effects on Type I 28-day concrete, w/c = 0.41, air content=4.5%. (Macgregor et al., 2005).

The strength is greatly controlled by the water/cement ratio (w/c)—the lower the ratio, the lower its porosity. The water content in cement can be calculated by using the following equation:

$$\boldsymbol{percent\ mix} = \frac{\boldsymbol{water\ weight}}{\boldsymbol{cement\ weight}} \cdot 100 \qquad (5.3$$

where percent mix is essentially a weight percent of the water content. For a Class G cement with no additives, it is desired to attain a ratio of 0.44 (Bourgoyne, 1986).

5.2.4 Mechanical Behavior of Cement

The cement's mechanical behavior may vary depending upon whether it is a "weak" cement or a "competent" cement, since some experts model drilling cement as a ductile material while others model it as a brittle material. Competent cements have a high Young's modulus and a low Poisson's ratio while weak cements have a low Young's modulus and high Poisson's ratio. In his work, Bosma (1999) compares the ductile behavior in different types of slurries. Fleckenstein (2000) also presents two sample cement properties that are on opposite ends of the hardness spectrum shown in Table 5-3.

Competent Cement	Weak Cement
Compressive strength: 65.5 MPa	Compressive strength: 6.89 MPa
Young's modulus: 16,547 MPa	Young's modulus: 4,757 MPa
Poisson's ratio: 0.11	Poisson's ratio: 0.42

Table 5-3: Mechanical properties for a competent cement and soft cement sample (Fleckenstein, 2000).

Ductile behavior in cement is a result of the microcracking that occurs as it sets over time. The time-dependent cracking is one form of explaining cement's creep behavior. Other factors are said to influence creep behavior. For instance, the remaining water molecules that did not partake in the chemical bonding reaction are compressed and consequently, "squeezed" out from the voids in the manner of a viscous flow (Dowling, 1999). Today, the creep mechanism in cement is still not purely understood. Its ductile behavior can be modeled by using the von Mises yield criterion (Berger, 2004). The discrepancy with using a yield criterion is that it assumes the cohesive strength c to be zero, which does not seem realistic. For brittle cements, the Mohr-Coulomb failure criterion can be used (Fourmaintraux, 2005) in combination with a tensile strength criterion; usually the Mode I failure criterion is used. Oil well cement can fail by either tension or compression.

Cement is weaker in tensile stress, and according to Jo (2008), its tensile strength is about one tenth of its compressive strength. Yet depending on the loading induced by the formation, failure may be governed by compression.

5.2.5 Difficulty with Deepwater Oil Well Cementing

The displaced cement at thousands of meters below the rig cannot be monitored or inspected for cracks, voids or channels. This may only be determined by monitoring signs of lost returns as well as the uplift pressure. Although a void may not be present, an intact, weak area within the annulus may occur. Such cases cause extreme loading over a small surface arc as depicted in Figure 5-1. Moreover, casing eccentricity can cause the cement to be unevenly distributed and to experience poor cementation, degrading the defected zone. In this work, the terms "defected cement zone" and "poorly-cemented region" are interchangeable. Therefore, the drilling team must take precaution in their decision making in order to foresee and prevent poor cement jobs while adhering to the necessary steps within the guidelines.

5.2.6 Chapter Summary:

- It is important to account for casing ovality in oil well simulations.
- Casing eccentricity and cement defects cause non-uniform loading induced by salt formation.
- Cement defects create the risk of contaminants, formation fluids, and even petroleum ascending through its openings in the annular and causing dangerous scenarios for the drill rig.