Chapter 2
Properties of Well Cement

Abstract Well cementing involves pumping a sequence of fluids into the well. Often these fluids, such as spacers and cement slurries, have non-Newtonian yield-stress rheology. After the cement slurry has been placed in the annulus, it hardens into a low-permeability annular seal. The complexity of these processes and the multitude of materials involved (drilling fluid, spacer, chemical wash, cement, casing, rocks) call for a sufficiently detailed material characterization in order to design and optimize cement jobs. A review of properties describing cements and other materials used in primary cementing is presented in this chapter. Rheological properties of washes, spacers, and cement slurries that control their flow down the well and up the annulus are discussed. Basics of non-Newtonian fluid rheology required to understand the subsequent chapters are laid out. Transition properties of cement slurry related to its solidification are reviewed. Mechanical, interfacial, hydraulic, and thermal properties of hardened cement that control e.g. response of cement to thermal stresses, vibrations, etc. are introduced, along with laboratory techniques used for their measurement (Brazilian test, uniaxial test, triaxial test, push-out test).

Keywords Cement · Properties · Rheology · Yield stress · Interface · Strength · Measurement

During a cementing job, cement undergoes a transformation from a liquid slurry being pumped down the wellbore to a solid material filling up the annular space between the casing and the borehole. While in the slurry state, the cement is characterized by rheological properties such as yield stress and plastic viscosity. These properties control the slurry flow and determine how cement displaces other fluids as it is placed behind the casing. The transition of cement from the liquid to the solid state is characterized by various properties e.g. volumetric change, rate of strength build-up or how easily formation fluids can enter the not-yet-solid cement. When hardened, cement is characterized by properties that determine how stable and permeable it is, how well it binds to the casing and the rock or how prone it is to fracturing. All of these properties need to be controlled in order to obtain a robust

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low-permeability cement sheath in the well. Therefore, we start our journey into the world of well cementing by exploring some important cement properties.

2.1 Properties of the Cement Slurry

When cement is mixed on the surface or platform and is pumped down the well, it is in the liquid state. The flow of cement slurry and the fluid displacement in the well are largely affected by the rheological properties of the fluids and by their densities. From rheological viewpoint, spacers and cement slurries are non-Newtonian fluids. They have a *yield stress*, τ_Y (Pa), which means that a shear stress in excess of a certain threshold value must be applied in order to put the slurry into motion. This implies that in a conduit, such as a well annulus, a finite pressure gradient must be applied in order for flow to commence. When the shear stress in the slurry is above the yield stress, the slurry behaves as a viscous fluid. The simplest rheological model that describes such behavior is the Bingham model. Applied to a simple shear flow, the Bingham model stipulates that the shear stress is a linear function of the shear rate when the shear stress is above the yield stress (Fig. 2.1). The slope of the shear stress versus shear rate curve is called the *plastic viscosity* of the slurry, μ_{pl} (Pa s). The Bingham model is thus a two-parameter model. This is one parameter extra as compared to a *Newtonian* fluid described by only one rheological parameter, i.e. the dynamic viscosity. Applied to a simple shear flow, the Bingham model can be represented as follows:

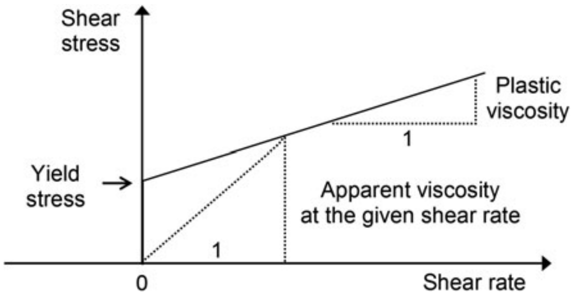
$$\tau = \tau_Y + \mu_{pl}|\dot{\gamma}| \tag{2.1}$$

where τ is the shear stress (Pa); $\dot{\gamma}$ is the shear rate (s^{-1}). If the yield stress is zero, Eq. (2.1) becomes

$$\tau = \mu_{pl}|\dot{\gamma}| \tag{2.2}$$

which is characteristic of a Newtonian fluid such as water. Newtonian fluids start flowing as soon as a non-zero shear stress is applied to them.

Fig. 2.1 Shear stress versus shear rate (*solid line*) in a simple shear flow of a Bingham fluid



The rheological parameters of the Bingham model, i.e. τ_Y and μ_{pl}, can be measured in a standard rheometric test performed in a rotational viscometer or a rheometer.[1] Different designs of these devices are available. For instance, shear can be applied to a slurry sample placed in the gap between two coaxial cylinders: the static inner cylinder and the rotating outer one. Torque as a function of rotations per minute (rpm) is then used to derive the plastic viscosity and the yield stress of the slurry. Oilwell cement slurries and spacers typically have yield stress on the order of 1–100 Pa, while their plastic viscosity is on the order of 0.01–0.1 Pa s. It should be noted that both τ_Y and μ_{pl} depend on temperature and, to a lesser extent, on pressure. For this reason, rheological measurements should ideally be performed in the range of pressures and temperatures that the fluid will be exposed to as it flows down the well and up the annulus.

Even though the linear model given by Eq. (2.1) only approximately describes the rheological behavior of real yield-stress fluids such as cement, it does capture one essential property of the slurry, namely the existence of a yield stress. As we will see later, this property is crucial for analysis of cement flow in the annulus.

If a more accurate description of cement flow is needed, the assumption of linear dependence of the shear stress on the shear rate above the yield stress should be relaxed. More realistic modelling of yield-stress rheology can then be achieved with e.g. the Herschel-Bulkley model [2] given by

$$\tau = \tau_Y + C|\dot{\gamma}|^n \tag{2.3}$$

where C is the consistency index; n is the flow behavior index. The consistency index determines the magnitude of the viscous forces at a given shear rate, while the non-dimensional flow behavior index determines whether the fluid becomes less or more viscous as the shear rate increases. If $n > 1$, the fluid thickens (becomes more viscous and difficult to flow) at higher shear rates. If $n < 1$, the fluid exhibits a shear-thinning behavior (becomes less viscous as the shear rate increases). The Bingham model is a specific case of the Herschel-Bulkley model, with $n = 1$. Better representations of cement slurry behavior are obtained using flow behavior indices lower than 1.

The Herschel-Bulkley model is a three-parameter model, and this increases both the complexity of slurry flow calculations and the computing time. In practice, the Bingham model is therefore still often used in the industry to represent the rheology of cement slurries, spacers, and drilling fluids.[2]

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[1]A rheometer is a more versatile instrument than a viscometer and enables application of oscillatory movement and measurement of viscoelastic properties, in addition to the shear stress versus shear rate curve. The typical shear rate range of a rheometer (10^{-6}–10^{5} s^{-1}) is larger than of a typical viscometer (10^{-1}–10^{3} s^{-1}). See e.g. [1].

[2]Most fluids used in drilling and cementing have yield-stress rheology. Exceptions are water and air, sometimes used as drilling fluids, and Newtonian washes sometimes used to clean the annulus before pumping spacer and cement in a cementing job.

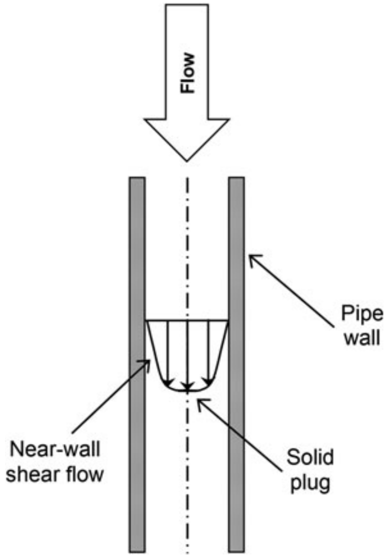

Fig. 2.2 Schematic illustration of fluid velocity profile in a pipe (e.g. flow of cement down the casing). The fluid has non-zero yield stress

The existence of yield stress has significant implications for fluid flow in pipes and annuli. In particular, the shear stress is lower than the yield stress around the axis of the pipe. As a result, a hard core moving as a solid plug rather than a liquid develops around the axis of the pipe. The fluid thus flows as a liquid near the walls, where the shear stress is above the yield stress, and moves as a solid plug near the axis (Fig. 2.2). This can be compared to toothpaste flowing as a plug out of the tube. A similar flow pattern develops in an annulus, where the fluid flows as a liquid near the walls and moves as a plug in the middle of the conduit.

The width of the solid plug (core) across the conduit is a function of the pressure gradient along the direction of flow. As the pressure gradient decreases, the solid core expands, until it occupies the entire width of the conduit. In annular flow, this happens when the pressure gradient is equal to [3]:

$$\left|\frac{\mathrm{d}P}{\mathrm{d}x}\right| = \frac{2\tau_{\mathrm{Y}}}{R_o - R_i} \tag{2.4}$$

where R_i and R_o are the inner and outer radii of the annulus, respectively (m); x points in the direction of flow. Equation (2.4) assumes that the inner and outer pipes are concentric, and neither of them is moving. Applying rotating or reciprocating motion to one of the pipes, e.g. the inner, increases the total shear rate in the fluid and thereby facilitates the flow. The threshold pressure gradient may thereby drop below the value given by Eq. (2.4). This is the principle behind improving the quality of well cementing by casing rotation or reciprocation.

In addition to the yield stress and plastic viscosity, viscous properties of a non-Newtonian fluid are sometimes characterized by *apparent viscosity*. This is what is found by a single viscosity measurement at a constant speed in a viscometer. For a Newtonian fluid, the apparent viscosity is constant (and equal to the dynamic viscosity), but for non-Newtonian fluids the apparent viscosity depends on the shear rate. As a consequence, reporting the apparent viscosity without specifying the shear rate is of limited value. The apparent viscosity is not a material property and is simply the slope of a straight line in the shear stress versus shear rate plot joining the origin with a given point on the rheogram (Fig. 2.1). The apparent viscosity thus describes the flow properties of the fluid at a given shear rate.

The yield stress introduced above characterizes the rheology of a yield-stress fluid as it flows. If the fluid is at rest, its yield stress usually increases over time. *Gel strength* values for cement are typically measured 10 s and 10 min after the fluid was brought to rest. The 10-s gel strength of a "typical" oilwell cement is on the order of 10 Pa. The gel strength builds up because colloidal particles develop a structure as the slurry rests. This is a reversible process, and the structures can be broken if the slurry is again subject to shear. In addition, over a longer time, chemical reactions in cement slurry result in irreversible strength build-up until the slurry solidifies. As pointed out in Ref. [4], ten minutes is too short a time to be representative of static periods that drilling fluid or spacer may experience in the well.

Static *stability* is an important slurry quality that describes how well the slurry maintains homogeneous density while at rest. Solid particles in the slurry tend to settle down, and this can cause a heterogeneous pressure gradient in the annulus whereby the density and the pressure gradient are largest at the bottom of the interval. This may promote the influx of formation fluids into the slurry in the upper parts of the cemented interval where the slurry density is low. If the formation fluid is gas, such influx may create gas channels in the not-yet-hardened cement, which will persist after the cement has hardened.

In laboratory experiments, the static stability of a cement slurry can be evaluated by examining the density distribution in a cement sample that was left to harden in a vertical sedimentation tube. The difference between the density measured at the bottom and at the top of the cement sample divided by the average density provides a quantitative measure of the slurry stability. Slurry segregation may also involve accumulation of *free fluid* (water) in the upper part of the cement column. Free fluid can be measured by placing a sample into a graduated tube [4]. Slurry segregation in horizontal wells may have a particularly detrimental effect on the results of a cement job by creating a channel that runs in the upper part of the cemented annulus [5].

In addition to rheological properties, *density* is an important property of a slurry. Depending on composition, the density of well cement slurries may range from as low as 720 kg/m^3 (foamed cements) to as high as 2400 kg/m^3 (high-density systems). In Chap. 3, we will see how the density and rheological properties of different fluids affect the flow and displacement in the annulus during a primary cementing job.

2.2 From Slurry to Solid: Cement Hardening

Cement powder is mixed with water at the rig site, and the slurry is pumped down the casing. After reaching bottomhole, the cement enters the annulus behind the casing, and pumping continues until an annular cement sheath of a required height is created. Cement is then left in the annulus to harden. The hardening is due to hydration of cement which starts immediately or some time after the cement slurry has been mixed.

Hydration involves changes to both the structure and the properties of cement. In particular, the density of hydration products is higher than that of the original unhydrated phases. In the absence of an extra water supply, this causes neat cement to shrink. Examples of shrinkage-induced reduction of cement bulk volume in the range of 0.5–5 % have been reported [4]. As a result of chemical shrinkage, i.e. shrinkage due to hydration, porosity and pore pressure decrease as setting proceeds [6]. If an external water supply is available, the decline of pore pressure leads to water being sucked into the cement's pore space. Water availability reduces the bulk shrinkage of cement and may even cause bulk expansion. In addition to the decline in porosity and pore pressure, shrinkage may cause fracture growth in cement. It may also lead to the development of a microannulus between the cement and the formation, which is one of the mechanisms behind well leakage [7].

Porosity is defined as the ratio of the pore volume to the total (bulk) volume of the material. If a porous material contains a connected pore system, applying a pressure gradient will put the fluid in the pore space into motion. Flow of a Newtonian fluid through a porous medium, such as a cement slurry undergoing solidification, can be described by Darcy's law. The total discharge Q (m^3/s) can then be calculated as follows:

$$Q = -\frac{kA}{\mu}\frac{dP}{dx} \tag{2.5}$$

where x points in the direction of flow; A is the cross-section area normal to flow (m^2); P is the pore pressure (Pa); μ is the dynamic viscosity of the pore fluid (Pa s). The coefficient k (m^2) in Eq. (2.5) is called the *absolute permeability*. During cement hydration, decreasing porosity results in a significant reduction of permeability [8]. The permeability of a cement slurry is on the order of 1 D, while the permeability of hardened cement is on the order of 1–10 μD. Rapid decline of permeability during setting is mentioned as a key quality of good well cement [6]. It is, however, not easy to measure the exact slurry permeability. Conventional steady-state permeability measurements with water as the flowing fluid show poor reproducibility and significant scatter for cement slurries. Using gas as the flowing fluid encourages cement drying, shrinkage and fracturing [6]. A transient method has been proposed based on analyzing the pore pressure decline in cement during hydration [6].

As cement slurry hydrates, its *tensile strength* and *shear strength* gradually build up. *Tensile strength* (Pa) is defined as the maximum tensile stress that a material can withstand without breaking apart. Tensile strength of a cement slurry undergoing solidification can be measured in laboratory conditions by injecting water at some location inside the slurry [8]. Water is injected at a constant flow rate, and the injection pressure is measured over time. The pressure increases up until a fracture is formed in the slurry. This peak pressure is then used as an estimate of the slurry's tensile strength. Values of the tensile strength as high as 0.5 MPa have been reported for cement slurries [8]. *Shear strength* (Pa) is the maximum shear stress that the slurry can withstand without failing or starting to flow. The shear strength is initially equal to the yield stress of the slurry (i.e. on the order of 1–10 Pa) and gradually increases as the slurry sets.

The pressure that the cement slurry exerts in the annulus is an important factor controlling fluid influx from the formation during cement setting. Laboratory experiments demonstrate that pressure reduction in a slurry column during setting can be quite substantial [9]. Shear stresses between the slurry and the casing or rock (the wall friction) reduce the hydrostatic pressure that the slurry exerts. These stresses are limited by the yield stress of the slurry. Therefore, build-up of cement shear strength reduces the pressure since higher shear stresses can be sustained at the walls. Moreover, the cement pressure can further be reduced if fluid is lost from the slurry into the permeable rock.[3] As the cement hardening proceeds, shrinkage may also causes reduction in the slurry pressure.

Given the detrimental effects of shrinkage, such as fracture development and reduction in the cement column pressure, efforts have been made in the industry to develop well cements that do not shrink or might even expand during setting. This has led to the development of a series of products (*expanding cements*) in which various additives counteract shrinkage. This is achieved either by chemical interaction with Portland cement constituents so as to produce expansion during hydration, or by adding materials that expand themselves and thereby compensate for shrinkage [10]. Other types of shrinkage than chemical shrinkage also exist, e.g. *carbonation shrinkage* if cement reacts with CO_2, or *desiccation shrinkage* if cement dries out.

Cement hydration is an *exothermic reaction*, i.e. heat is released as hydration proceeds. The heat release makes the temperature of cement increase during setting. This causes the casing diameter to be slightly larger than it otherwise would be during cement setting. When the temperature falls back to its regular value, a microannulus can be formed between the cement and the casing. The heat release during hydration also has a detrimental effect when cementing permafrost intervals as it may cause melting of the formation. This may lead to poor bonding and induce subsidence in the near-well region. The heat release is, however, the basis of an evaluation technique for the quality of well cementing, namely the temperature log.

[3]Laboratory data about fluid-loss properties of a slurry are obtained in filter-press experiments.

Such logs can be performed after the cement job has been completed, in order to find the *top of cement*, i.e. the height of the cement sheath set in the annulus.

2.3 Properties of Hardened Cement

During the life of a well, the annular cement sheath can be exposed to a variety of forces such as heating/cooling cycles, mechanical stresses, vibrations, formation fluid influx or reactive flows. Properties of hardened cement affect its sealing capacity, and understanding them is therefore crucial for maintaining well integrity. Properties of solid cement can be subdivided into mechanical, interfacial, hydraulic, and thermal.

Mechanical properties characterize the response of cement to mechanical loads and deformations. These can further be subdivided into *elastic properties* and *strength properties*. We have already come across strength properties of cement slurries in Sect. 2.2 (tensile and shear strength).

(i) *Elastic properties*. The most commonly used elastic properties are *Young's modulus* and *Poisson's ratio*. Both of these parameters can be obtained from stress-strain curves recorded in a uniaxial compressive test. In this test, a cylindrical cement specimen is loaded by applying compressive load at its top and bottom faces (Fig. 2.3). The specimen geometry with the height-to-diameter ratio of 2–3 is most common in rock mechanics since it reduces the effect of friction between the specimen and the loading platens on the test results. However, in cement testing, using cubic specimens is not uncommon [4]. In a uniaxial test, Young's modulus is

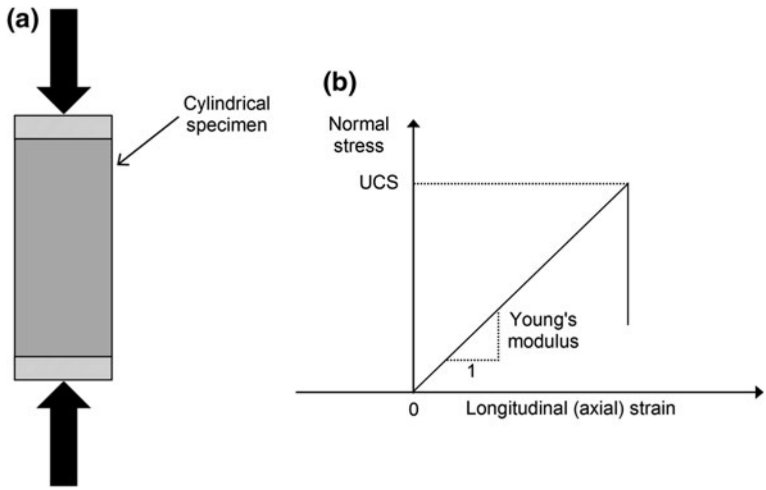

Fig. 2.3 Schematic illustration of a uniaxial compressive test (**a**) and stress-strain *curve* obtained in a such test (**b**). UCS is unconfined compressive strength

the slope of the axial stress versus axial strain curve. Poisson's ratio is the ratio of the transverse strain to the axial strain.

The elastic parameters evaluated from stress-strain curves are called *static moduli*. Alternatively, both parameters can be evaluated from the velocities of longitudinal and shear acoustic waves propagating through cement. Moduli obtained in this way are called *dynamic moduli*. The dynamic Young's modulus is higher than the static modulus. The static Young's modulus is typically on the order of 1–10 GPa for oilwell cements, while Poisson's ratio is on the order of 0.1–0.25.

The perfectly linear stress-strain curve shown in Fig. 2.3 is an idealization. Real curves are nonlinear, and Young's modulus can be estimated as the slope of the curve at the stress equal to 50 % of peak stress (stress at failure). Inelastic deformation of cement grains, irreversible slip at grain boundaries, closing of microcracks and intergranular pores, and generation of new microcracks may all contribute to inelastic deformation of cement during loading.

(ii) *Strength properties*. When the stress in the uniaxial test reaches a certain value, the specimen breaks down. The stress value at which this happens is called the *unconfined compressive strength* (UCS). It describes the ability of cement to carry load under compression. UCS is on the order of megapascals or tens of MPa for oilwell cements, depending on their structure and composition. It should be remembered, however, that cement set in the annulus is, in general, in a triaxial stress state. *Triaxial tests* can be used for a more detailed characterization of cement strength in compressive conditions. In a triaxial test, stresses are applied not only at the top and bottom, but also on the side surface of a cylindrical specimen. The stress applied on the side surface is known as the *confining stress*. Confining and axial stresses on the specimen are first increased simultaneously to the same level. Then, the confining stress is held constant while the axial stress is increased to failure. Several tests at different confining stresses are usually performed to fully characterize cement in triaxial conditions.

The material strength in triaxial stress state is commonly described using one of the so-called failure criteria. A *failure criterion* defines a combination of stresses at which the material fails. In stress space, the failure criterion defines a surface (the *failure surface*). Several failure criteria have been proposed for hardened cement, differing in their degree of detail and complexity. Higher accuracy usually increases the number of parameters that need to be determined from triaxial tests. One of the simplest criteria routinely used for cement, concrete, and some rocks is the *Mohr-Coulomb failure criterion*. In terms of principal stresses ($\sigma_1 \geq \sigma_3$), it can be expressed as follows:

$$\sigma_1 = \sigma_{\mathrm{UCS}} + \tan^2\left(\frac{\pi}{4} + \frac{\varphi}{2}\right)\sigma_3 \tag{2.6}$$

where σ_1 and σ_3 are the maximum and minimum principal stresses (Pa; positive in compression); σ_{UCS} is the unconfined compressive strength (Pa); φ is the *angle of*

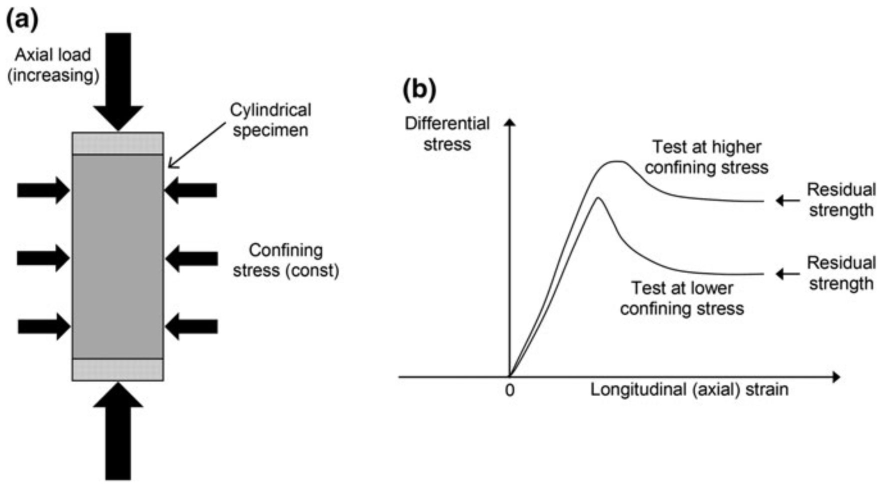

Fig. 2.4 Schematic illustration of a triaxial compressive test (**a**) and stress-strain curves obtained in such a test (**b**). Differential stress is axial minus confining stress. Higher confining results in more ductile (less brittle) behavior

internal friction (°). Hence, the Mohr-Coulomb criterion makes use of two constitutive parameters,σ_{UCS} and φ, meaning that a minimum of two triaxial tests (or a triaxial test and a uniaxial test) are required in order to characterize cement with this criterion. As evident from Eq. (2.6), the Mohr-Coulomb criterion does not account for a possible effect of the intermediate principal stress, σ_2, on cement failure. More elaborate failure criteria may include σ_2. Poromechanical models of well cements, based on Biot theory of poroelasticity/poroelastoplasticity, have been introduced recently [11].

According to Eq. (2.6), confining stress increases the triaxial strength. It also makes the mechanical response of cement more ductile: as the confining stress increases, the post-failure part of the stress-strain curve becomes less steep, and the residual strength increases (Fig. 2.4).

The Mohr-Coulomb criterion describes failure in compression. It needs to be supplemented with a tensile failure criterion to completely describe the strength of cement. This is usually done by specifying the *tensile strength*, i.e. the maximum magnitude of a tensile stress that the material can sustain without breaking apart. This can be measured in a direct tension test, in which a cylindrical specimen is pulled in opposite directions at its ends (imagine the reverse of the uniaxial compressive test shown in Fig. 2.3). It turns out, however, that performing a direct tension test is more cumbersome and may require specially shaped specimens (e.g. “dog bone” shape). An alternative often employed in testing of brittle materials is the so-called Brazilian test (Fig. 2.5). *Brazilian test* is an indirect tensile test in which a specimen shaped as a circular cylinder is loaded in compression along the straight lines on its curved side surface. This creates a nonuniform stress state even if the material is perfectly homogeneous. In particular, tensile stress normal to the

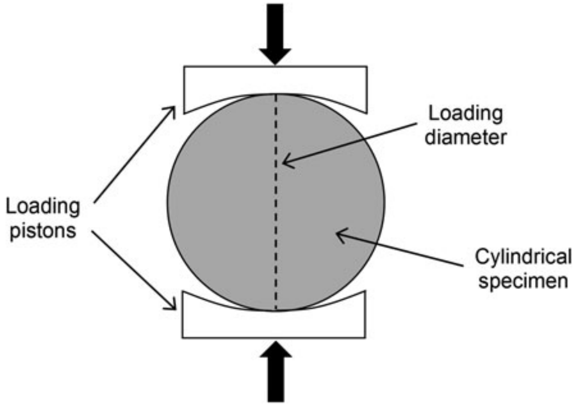

Fig. 2.5 Schematic illustration of Brazilian test. The *dashed line* indicates the loading diameter

loading diameter is produced along a significant part of that diameter. The tensile stress is largest near the cylinder's axis and tends to split the cylinder into two halves. Compressive load is increased during the test up until the specimen breaks down. The maximum load, F_m, recorded during the test is then used to obtain the tensile strength of the material, T_0 [12]:

$$T_0 = \frac{2F_m}{\pi DL} \tag{2.7}$$

where D and L are the diameter and length of the cylinder (m).

Compressive and tensile strength values are important characteristics of cement's load-bearing capacity. For instance, fracture nucleation and propagation in cement when the casing diameter increases as a result of casing pressurization is controlled by the cement's tensile strength, amongst other parameters. It should, however, be remembered that annular cement can be subject to complicated stress paths and loading/unloading cycles during its lifetime. Annular cement is confined between the casing and the formation, and its deformation is therefore strongly influenced by deformations of the casing and the rock. The coupled deformation of casing, cement and rock can be studied in specially-designed laboratory tests such as the one described in [13]. In this test, a complex structural test of a casing-cement-rock assembly was performed. The assembly was composed of a central core (a cylinder representing the casing), a cement sheath around it, and an outer metal hollow cylinder representing the formation. The cement sheath could be loaded/unloaded and brought to failure by expanding/contracting the core. Permeability measurements of cement were performed during the test. It should be noted that these kinds of tests are not standardized. Therefore, it can be difficult to compare results obtained with such specially-designed tests in different laboratories.

An important aspect of cement's mechanical behavior is that cement is a brittle material, i.e. it fails with very little preceding plastic deformation. Similarly to other brittle materials, such as crystalline rocks or consolidated sandstones, cement has much larger compressive strength (UCS) than tensile strength (often by an order of magnitude). Brittleness of cement is often estimated indirectly by means of its Young's modulus. Lower Young's modulus indicates a less brittle cement. Low Young's modulus improves the ability to deform without stresses becoming so high that they would exceed the strength of cement. Unfortunately, lowering the Young's modulus by means of additives may degrade other properties of cement, in particular strength. Improving mechanical stability of solid cement by changing its composition is therefore an optimization exercise.

Interfacial properties In addition to failure in the bulk cement, there are other mechanisms that control cement failure in wells. In particular, interfaces between cement and casing, and between cement and rock are known as potential weak spots. Local lack of bonding can be discovered by performing a cement bond log after the cement job is finished. However, even when bonding is good, the *interface bonding strength* can be lower than the bulk cement strength. The bonding strength can be estimated by means of laboratory tests, e.g. push-out experiments [14–16]. The setup is schematically shown in Fig. 2.6. It includes a compound specimen with a steel pipe or a rock cylinder in the middle and cement around it. During the test, the steel pipe or rock is pushed downwards so as to induce failure at the cement interface. The interfacial bonding strength is calculated as the peak load divided by the area of contact between the steel (rock) and the surrounding cement. The shear bond strength evaluated this way is typically on the order of 0.1–1.0 MPa.

The interfacial bonding strength evaluated in a push-out test is the shear strength. During the lifetime of a well, tensile stresses acting in the cement in the radial direction can be induced as we will see in Chaps. 5 and 6. Such stresses are likely to promote *tensile* failure at the interface. Development of a commonly-accepted test for tensile interface strength is still an outstanding task.

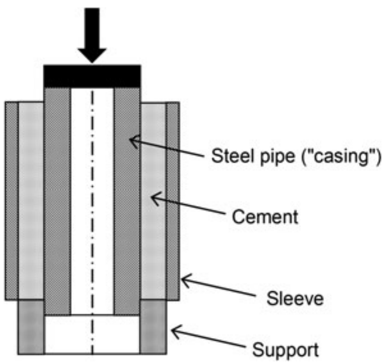

Fig. 2.6 Principle of push-out testing for interfacial bond strength

In addition to the bonding strength, *hydraulic bonding* properties of an interface can provide a valuable estimate of the bond quality with respect to possible leakage. Laboratory tests have been designed that quantify hydraulic bonding by applying fluid pressure at the interface in a compound cement-steel or cement-rock specimen [4].

It should be noted that the terms "interface failure" and "interface strength" may suggest that the cement-steel or cement-rock systems fail at the very interface. Experiments show, however, that interface failure is a much more complex phenomenon. In particular, as we will see in Chap. 4, a so-called *interfacial transition zone* (*ITZ*) forms in cement along cement-steel interfaces. The strength of cement in this zone is lower than in the bulk cement or at the very wall. As a result, fractures often develop not at the very contact between cement and steel, but inside the ITZ, i.e. at some distance from the wall [17].

Hydraulic properties Mechanical properties determine one important function of cement, namely its resistance to mechanical loads. Hydraulic properties determine the other, i.e. the ability to create a leak along the well or the rate with which the cement sheath will be chemically degraded. Leakage along the annulus may create communication between geological horizons or even bring formation fluids to the surface. The leakage can, in particular, be due to microannulus, gas channels, and fractures in cement. If cement is free of these flaws, the leakage capacity is determined by cement's *permeability*, the parameter introduced in Sect. 2.2. Permeability of currently used well cements is considered sufficiently low to prevent leakage if the cement remains intact. We will see in later chapters how microannuli, fractures, and gas channels develop in cemented wells. We will see, in particular, how imperfect slurry flow and displacement may produce gas channels and how the mechanical properties introduced above control the formation of fractures during a well's life.

Thermal properties One of the mechanisms of fracture development in well cement is linked to heating and cooling. In this case, in addition to mechanical properties, thermal properties of cement play a crucial role, in particular the *coefficient of thermal expansion* and the contrast between casing, cement and formation with regard to it. A sample of some "typical" values of this parameter for steel, cement and sandstone is given in Table 2.1. Other thermal properties include the *thermal conductivity* and the *specific heat capacity*.

Table 2.1 Example values of the coefficient of thermal expansion for steel, cement and rocks

Material	Coefficient of thermal expansion ($\times 10^{-6}$ K^{-1})
Steel	10–16
Cement	10–12
Sandstone	10–12

2.4 Summary and Discussion

Well cementing involves pumping a sequence of fluids into the well. At least some of these fluids, such as spacers and cement slurries, have non-Newtonian yield-stress rheology. After the cement slurry has been placed in the annulus, it hardens into a low-permeability annular seal. The complexity of all these processes and the multitude of materials involved (drilling fluid, spacer, chemical wash, cement, casing, rocks) call for a sufficiently detailed material characterization in order to design and optimize cement jobs. A review of cement properties presented in this chapter shows that these properties can largely be grouped into three classes:

- rheological properties of washes, spacers, and cement slurries that control their flow down the well and up the annulus;
- transition properties of cement slurry related to its solidification;
- mechanical, interfacial, hydraulic, and thermal properties of hardened cement that control e.g. response of the cement to thermal stresses, vibrations, etc.

Well-established testing procedures can be used to obtain some of these parameters. They are described in e.g. API Recommended Practices[4] and ASTM Standards.[5] Measurements of other parameters, such as the gel strength, are standardized to a much lesser extent.

In later chapters, we will see how the material properties introduced in this chapter affect the quality of cement jobs and the performance of an annular cement sheath during a well's lifetime from drilling to plugging and abandonment.

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