MEASUREMENT OF CEMENT SLURRY PROPERTIES UNDER DOWNHOLE CONDITIONS

Applicant: HALLIBURTON ENERGY SERVICES, INC., Houston, TX (US)

Inventors: Merouane Khammar, The Woodlands, TX (US); Benjamin Iverson, Spring, TX (US); Thomas Singh Sodhi, New Caney, TX (US)

APPLICANT INFORMATION

App. No.: 14/371,898
PCT Filed: Sep. 6, 2013
PCT No.: PCT/US2013/058473
§ 371 (c)(1), (2) Date: Jul. 11, 2014

ABSTRACT

The present invention relates to a method for measuring a cement slurry property, such as static gel strength or yield stress, under at least one downhole condition, and apparatuses and systems for performing the same. In some embodiments, the method includes detecting a downward force exerted by a curing cement slurry under at least one downhole condition within a vessel movable along a vertical axis proportionally to the downward force. A surface substantially nonmovable along the vertical axis is disposed at least partially within the cement slurry. The method also includes determining at least one property of the cement slurry from the detected downward force.

Unhydrated cement particles
Cement gel
Capillary pores and cavities
Fig. 1

Unhydrated cement particles

Cement gel

Capillary pores and cavities

Fig. 2
MEASUREMENT OF CEMENT SLURRY PROPERTIES UNDER DOWNHOLE CONDITIONS

BACKGROUND OF THE INVENTION

[0001] Various characteristics of cement under particular downhole conditions can be valuable to know when performing subterranean cementing operations in a wellbore designed for petroleum extraction. For example, after depositing cement downhole, knowing how much curing time a particular cement mixture will likely require to reach a particular strength under the downhole conditions can help an oilfield engineer determine when it is safe to conduct other downhole operations without sacrificing the integrity of the curing cement.

SUMMARY OF THE INVENTION

[0002] In various embodiments, the present invention provides a method of measuring a cement slurry curing property under a downhole condition. The method includes detecting a downward force exerted by a curing cement slurry. The cement slurry is under at least one downhole condition. The cement slurry is within a vessel movable along a vertical axis proportionally to the downward force. A surface substantially nonmovable along the vertical axis is disposed at least partially within the cement slurry. The method also includes determining at least one property of the cement slurry from the detected downward force.

[0003] In various embodiments, the present invention provides a method of measuring a cement slurry property under a downhole condition. The method includes providing or obtaining an apparatus. The apparatus includes a vessel configured to move along a vertical axis proportionally to a downward force within the vessel. The apparatus includes a detector configured to detect a vertical position of the vessel along the vertical axis. The apparatus also includes a surface disposed at least partially within the vessel. The surface is substantially nonmovable along the vertical axis. The apparatus is configured to provide at least one downhole condition within the vessel. The method includes placing a cement slurry within the vessel. The method includes configuring at least one downhole condition within the vessel. The method includes allowing the cement slurry to at least partially cure. The method also includes determining at least one property of the cement slurry from the detected vertical position of the vessel during at least part of the curing of the cement slurry.

[0004] In various embodiments, the present invention provides an apparatus for measuring a cement slurry curing property under a downhole condition. The apparatus includes a vessel configured to move along a vertical axis proportionally to a downward force within the vessel. The apparatus includes a detector configured to detect the downward force. The apparatus includes a surface disposed at least partially within the vessel. The surface is substantially nonmovable along the vertical axis. The apparatus is configured to provide at least one downhole condition within the vessel.

[0005] In various embodiments, the present invention provides a system for measuring a cement slurry curing property under a downhole condition. The system includes an apparatus. The apparatus includes a vessel configured to move along a vertical axis proportionally to a downward force within the vessel. The apparatus includes a detector configured to detect the downward force. The apparatus includes a surface disposed at least partially within the vessel. The apparatus is configured to provide at least one downhole condition within the vessel.

[0006] Various embodiments of the present invention provide certain advantages over other methods, apparatus, and systems for measuring cement properties, at least some of which are unexpected. Various embodiments can measure the loss of cement weight due to the development of its yield strength and gel strength, and the transition time of the cement from a fluid to thickened or gelled solid and the corresponding change in properties during the transition, in a more direct and simple way compared to other methods and apparatus. In some embodiments, unlike other apparatus for determining cement properties, the apparatus includes fewer or no energized moving parts, such as motors, except for the pressure and temperature control equipment. In some examples, the present invention can provide a determination of curing properties such as gel strength and set time of cement mixtures on a surface, including surfaces with various textures to simulate materials to be cemented downhole, which is not possible with other methods and apparatus. In some embodiments, a stationary surface can be used to determine the static gel strength of a curing cement mixture over time, which is not possible with other methods and apparatus. In some embodiments, the apparatus and method can directly measure curing properties of a cement mixture over time and under downhole conditions during gas flow migration through the cement mixture, which is difficult or not possible with other methods and apparatus. In some embodiments, the apparatus and method can be more reliable, more cost-effective, and more robust than other apparatus and methods.

BRIEF DESCRIPTION OF THE FIGURES

[0007] In the drawings, which are not necessarily drawn to scale, like numerals describe substantially similar components throughout the several views. Like numerals having different letter suffixes represent different instances of substantially similar components. The drawings illustrate generally, by way of example, but not by way of limitation, various embodiments discussed in the present document.

[0008] FIG. 1a illustrates a stage of cement curing, in accordance with various embodiments.

[0009] FIG. 1b illustrates a stage of cement curing, in accordance with various embodiments.

[0010] FIG. 1c illustrates a stage of cement curing, in accordance with various embodiments.

[0011] FIG. 1d illustrates a stage of cement curing, in accordance with various embodiments.

[0012] FIG. 2 illustrates an apparatus for measuring yield stress of cement, in accordance with various embodiments.

[0013] FIG. 3 illustrates yield stress and gel strength over time, as measured by the apparatus of Example 1, in accordance with various embodiments.

[0014] FIG. 4 illustrates calorimetry data for the slurry used in Example 1, in accordance with various embodiments.
DETAILED DESCRIPTION OF THE INVENTION

[0015] Reference will now be made in detail to certain embodiments of the disclosed subject matter. While the disclosed subject matter will be described in conjunction with the enumerated claims, it will be understood that the exemplified subject matter is not intended to limit the claims to the disclosed subject matter.

[0016] Values expressed in a range format should be interpreted in a flexible manner to include not only the numerical values explicitly recited as the limits of the range, but also to include all the individual numerical values or sub-ranges encompassed within that range as if each numerical value and sub-range is explicitly recited. For example, a range of “about 0.1% to about 5%” or “about 0.1% to 5%” should be interpreted to include not just about 0.1% to about 5%, but also the individual values (e.g., 1%, 2%, 3%, and 4%) and the sub-ranges (e.g., 0.1% to 0.5%, 1.1% to 2.2%, 3.3% to 4.4%) within the indicated range. The statement “about X to Y” has the same meaning as “about X to about Y,” unless indicated otherwise. Likewise, the statement “about X, Y, or about Z” has the same meaning as “about X, about Y, or about Z,” unless indicated otherwise.

[0017] In this document, the terms “a,” “an,” or “the” are used to include one or more than one unless the context clearly dictates otherwise. The term “or” is used to refer to a nonexclusive “or” unless otherwise indicated. In addition, it is to be understood that the phraseology or terminology employed herein, and not otherwise defined, is for the purpose of description only and not of limitation. Any use of section headings is intended to aid reading of the document and is not to be interpreted as limiting; information that is relevant to a section heading may occur within or outside of that particular section. Furthermore, all publications, patents, and patent documents referred to in this document are incorporated by reference herein in their entirety, as though individually incorporated by reference. In the event of inconsistencies between this document and those documents so incorporated by reference, the usage in the incorporated reference should be considered supplementary to that of this document; for irreconcilable inconsistencies, the usage in this document controls.

[0018] In the methods of manufacturing described herein, the steps can be carried out in any order without departing from the principles of the invention, except when a temporal or operational sequence is explicitly recited. Furthermore, specified steps can be carried out concurrently unless explicit claim language recites that they be carried out separately. For example, a claimed step of doing X and a claimed step of doing Y can be conducted simultaneously within a single operation, and the resulting process will fall within the literal scope of the claimed process.

[0019] The term “about” as used herein can allow for a degree of variability in a value or range, for example, within 10%, within 5%, or within 1% of a stated value or of a stated limit of a range.

[0020] The term “substantially” as used herein refers to a majority of, or mostly, as in at least about 50%, 60%, 70%, 80%, 90%, 95%, 96%, 97%, 98%, 99%, 99.5%, 99.9%, 99.99%, or at least about 99.999% or more.

[0021] The term “hydrocarbon” as used herein refers to a functional group or molecule that includes carbon and hydrogen atoms. The term can also refer to a functional group or molecule that normally includes both carbon and hydrogen atoms but wherein all the hydrogen atoms are substituted with other functional groups.

[0022] The term “solvent” as used herein refers to a liquid that can dissolve a solid, liquid, or gas. Nonlimiting examples of solvents are silicones, organic compounds, water, alcohols, ionic liquids, and supercritical fluids.

[0023] The term “room temperature” as used herein refers to a temperature of about 15°C to 28°C.

[0024] As used herein, the term “polymer” refers to a molecule having at least one repeating unit, and can include copolymers.

[0025] The term “copolymer” as used herein refers to a polymer that includes at least two different monomers. A copolymer can include any suitable number of monomers.

[0026] The term “downhole” as used herein refers to under the surface of the earth, such as a location within or fluidly connected to a wellbore.

[0027] As used herein, the term “drilling fluid” refers to fluids, slurries, or muds used in drilling operations downhole, such as the formation of the wellbore.

[0028] As used herein, the term “cementing fluid” refers to fluids or slurries used during cementing operations of a well. For example, a cementing fluid can include an aqueous mixture including at least one of cement and cement kiln dust. In another example, a cementing fluid can include a curable resinous material such as a polymer that is in an at least partially uncured state.

[0029] As used herein, the term “fluid” refers to liquids and gels, unless otherwise indicated.

[0030] As used herein, the term “subterranean material” or “subterranean formation” refers to any material under the surface of the earth, including under the surface of the bottom of the ocean. For example, a subterranean formation or material can be any section of a wellbore and any section of a subterranean petroleum- or water-producing formation or region in fluid contact with the wellbore; placing a material in a subterranean formation can include contacting the material with any section of a wellbore or with any subterranean region in fluid contact therewith. Subterranean materials can include any materials placed into the wellbore such as cement, drill shafts, liners, tubing, or screens; placing a material in a subterranean formation can include contacting with such subterranean materials. In some examples, a subterranean formation or material can be any below-ground region that can produce liquid or gaseous petroleum materials, water, or any section below-ground in fluid contact therewith. For example, a subterranean formation or material can be at least one of an area desired to be fractured, a fracture or an area surrounding a fracture, and a flow pathway or an area surrounding a flow pathway, wherein a fracture or a flow pathway can be optionally fluidly connected to a subterranean petroleum- or water-producing region, directly or through one or more fractures or flow pathways.

Method of Measuring Cement Curing Properties

[0031] The prediction of cement yield stress or gel strength development with time during the dormant period of cement hydration can help to predict cement hydrostatic pressure loss in the wellbore over time during curing and to predict the risk of gas or fluid migration. A device capable of measuring the development of cement yield stress or cement gel strength
under downhole conditions can be used to design cements that perform as desired downhole, such as with minimum risk of gas or fluid migration.

[0032] During cement placement in the wellbore, cement can be pumped as a slurry in the annulus between the formation and the casing. The pressure in the cement column is initially equal to the hydrostatic pressure of the slurry. As cement hydrates, it builds an internal structure and develops an internal supporting network. It gradually supports its weight on the walls of the formation and the casing which results in a decrease of the hydrostatic pressure. Various embodiments of the present invention can measure at least one of the shear stress, yield strength, and static gel strength during hydration in the wellbore conditions of temperature and pressure. In some embodiments, the shear stress, yield strength, or static gel strength can be used to calculate the loss of cement hydrostatic pressure over time in a wellbore.

[0033] In various embodiments, the present invention provides a method of measuring a cement slurry property (e.g., at least one cement slurry property) under a downhole condition (e.g., at least one downhole condition). The method can include detecting a downward force exerted by a curing cement slurry. The cement slurry can be under at least one downhole condition within a vessel, wherein the vessel is located in any suitable location, such as above the surface (e.g., not downhole), or downhole. The vessel can be movable along a vertical axis proportionally to the downward force exerted by the curing cement slurry. A surface substantially nonmovable along the vertical axis can be disposed at least partially within the cement slurry. The method can include determining at least one property of the cement slurry from the detected downward force. The vessel can be movable along the vertical axis with respect to a fixed reference point along the vertical axis, and the surface can be nonmovable along the vertical axis with respect to the same reference point.

[0034] As the cement slurry cures, the cement slurry generates a shear stress on the surface that is substantially nonmovable along the vertical axis. The cement slurry exerts a downward force within the vessel. The downward force can include the buoyancy weight of the slurry minus the weight of the slurry that is supported on the surface by shear stress. The method can be used to measure the loss of weight of the cement slurry due to the shear stress of the cement slurry on the surface.

[0035] In some embodiments, a resilient member can provide upward resistance to the vessel proportionally to downward vertical movement of the vessel along the vertical axis caused by the downward force exerted by the cement slurry. In some embodiments, the resilient member can include a spring. The substantially nonmovable surface can be nonmovable with respect to a fixed location of the resilient member, e.g., nonmovable with respect to a portion of the resilient member that is nonmovable with respect to the fixed reference point along the vertical axis.

[0036] The downward force exerted by the cement slurry can be detected (e.g., measured) by any suitable method of detection. In some examples, the detecting of the downward force can be detected using a suitable detector. In some embodiments, the downward force can be detected by detecting (e.g., measuring) a vertical position of the vessel, such as a difference between the vertical position of the vessel when the cement slurry was fresh (e.g., time 0) and the vertical position of the vessel at a later time t. In some embodiments, the detector includes a scale or other weight-measuring device. In some embodiments, the detector includes a visual or electronic comparison between markings or reference points to determine a vertical position of the vessel and determine the corresponding downward force, e.g., using a spring below the vessel as a resilient member and measuring the vertical displacement of the vessel.

[0037] In one approach, the process of cement curing can be described in four stages as shown in FIG. 1, as described by Illston J. M., Dinwoodie J. M., Smith A. A., “Concrete, Timber and Metals”, 1979, Van Nostrand Reinhold Co. Ltd. FIG. 1 illustrates that in stage (a) after mixing to form the cement slurry, cement grains are dispersed in water. The water to cement ratio can control the spacing between cement grains. In stage (a), the cement slurry is in its most liquid-like state of the four stages described herein. FIG. 1b illustrates that in stage (b), rods of ettringite and crumpled foils of calcium silicate hydrate can form on the surface of cement grains. The water can become saturated with lime, and needle-like formations of calcium silicate hydrate can appear in the intergranular water. The rheological properties of the hydrating cement change during stage (b), and the cement slurry gels but can still flow. FIG. 1c illustrates that in stage (c), the hydration on the grains expands outwards and inwards. The hydrates in the intergranular space grow and interconnect to form a continuous solid skeletal structure with large capillary pores. In stage (c), cement slurry sets and turns into a porous hardened cement paste. FIG. 1d illustrates that in stage (d), the skeletal structure develops to a denser structure with large capillary pores remaining unfilled. At this stage, the cement slurry or hardened cement paste develops significant strength. Two general time frames can be highlighted: a pre-initial set, e.g., stages (a)-(b), and a post initial set, e.g., stages (c)-(d). In stage (a), the cement can behave as a fluid. In stage (d) the cement can behave as a solid. Stages (b) and (c) can be considered transitional stages whereby the system behaves as a fluid that has some solid characteristics (e.g., pre-initial set stage (b)) or as a solid that has some fluid characteristics (e.g., post-initial set stage (c)). In some embodiments, the approximate demarcation point between stages (b) and (c) can be discerned by the generation of a significant heat of hydration approximately between the stages.

[0038] The cement slurry property measured can be any suitable property that can be measured with the method and apparatus described herein. The cement slurry property can be any property of the cement slurry from the time of addition of water to the cement to the thickening or substantially solidification of the resulting mixture. In some embodiments, the cement slurry property can be any property of the cement that occurs during any one or more of the stages as illustrated in FIG. 1 and described herein. For example, the cement slurry property can be any cement slurry property measured from stage (a), (b), or (c), such as from the beginning, an intermediate portion, or the end of the stage, to stage (a), (b), (c), or (d), such as to the beginning, an intermediate portion, or to the end of the stage. For example, the cement slurry property measured can be any property that occurs from stage (a), such as at the beginning, an intermediate part, or the end of stage (a), to stage (c), such as to the beginning, an intermediate part, or to the end of stage (c). In another example, the cement slurry property measured can be any property that occurs from stage (a), such as at the beginning, intermediate part, or end of the stage, to stage (b), such as the beginning, intermediate part of, or end of stage (b).
The cement slurry property can be one property or more than one property. In some embodiments, the determination of the at least one property of the cement slurry includes determining at least one of a shear stress of the cement slurry on the surface, a static gel strength of the cement slurry, a yield stress of the cement slurry, a loss of weight of the cement slurry due to curing, a variation of hydrostatic pressure of the slurry over time, a setting time of the cement slurry, and a dormant time of the cement slurry. In some embodiments, the method includes determining the approximate shear stress of the cement slurry on the surface at time \( t \) by dividing a first quantity by the surface area of the surface contacted by the cement slurry. The first quantity includes the downward force exerted by the curing cement slurry at time \( 0 \) minus the downward force exerted by the curing cement slurry at time \( t \). Determining the first quantity can include multiplying a spring constant of a spring or other resilient member that provides an upward force in proportion to the downward movement of the vessel by a second quantity, wherein the second quantity includes a vertical position of the vessel at time \( 0 \) minus a vertical position of the vessel at time \( t \).

In some embodiments, the determining the at least one property of the cement slurry includes determining the yield stress of the cement slurry. As used herein, yield stress refers to the amount of shear stress required to cause a cement slurry to undergo plastic deformation or yield, wherein yielding occurs when the applied shear stress exceeds the yield strength. In some embodiments, the determination of the at least one property of the cement slurry includes determining the static gel strength of the slurry. As used herein, static gel strength refers to the yield stress of the cement slurry after the slurry has been undisturbed for a period of time, such as 1 s, 5 s, 10 s, 20 s, 30 s, 40 s, 50 s, 60 s, 1.5 min, 2 min, 3 min, 4 min, 5 min, 6 min, 7 min, 8 min, 9 min, 10 min, 15 min, 20 min, 30 min, 40 min, 50 min, 60 min, 1.5 h, 2 h, 3 h, 4 h, 5 h, 10 h, 15 h, 20 h, 1 d, 1.5 d, 2 d or more. The static gel strength can be determined while substantially no agitation occurs within the cement slurry, such as substantially no agitation adjacent to the surface contacting the slurry, for a suitable period of time.

The at least one downhole condition can be established within the vessel in any suitable way. In some embodiments, a compartment encloses the vessel within an interior region of the compartment. The compartment can be configured to provide the at least one downhole condition within the vessel. For example, the interior of the compartment can include the at least one downhole condition. The interior of the compartment can include any suitable material, such as a gas or a liquid. The interior of the compartment can include an aqueous liquid, such as substantially pure water, or a solution of water and a salt, or a mixture of an aqueous liquid and another liquid. In some embodiments, the interior of the compartment can include an organic solvent, such as any suitable organic solvent, such as ethylene glycol, diethylene glycol methyl ether, diethylene glycol dimethyl ether, dimethyl formamide, diethylene glycol methyl ether, ethylene glycol butyl ether, diethylene glycol butyl ether, propylene carbonate, limonene, a \( C_6-C_{10} \) fatty acid, \( C_7-C_{10} \) alkyl ester, 2-butoxy ethanol, butyl acetate, furfuryl acetate, dimethyl sulfoxide, dimethyl formamide, or a combination thereof.

In some embodiments, the compartment encloses at least part of a detector that detects the downward force exerted by the cement slurry within the interior of the compartment. The vessel can be movable along the vertical axis with respect to the interior of the compartment. The compartment can enclose some or substantially all of the surface within the interior of the compartment. The surface can be substantially rigidly attached to the interior of the compartment, such that the vessel is movable along the vertical axis, while the surface is held substantially stationary by the rigid connection to the compartment.

In some embodiments, the compartment encloses substantially all of the detector within the interior of the compartment. For example, the compartment can enclose some or all of a spring or other resilient member that provides an upward force proportionally to the downward vertical movement of the vessel. A detector that measures the vertical position of the vessel can be located within the compartment, outside of the compartment, or a combination thereof. In some examples, the vertical position of the vessel can be read manually or automatically from inside or outside the compartment, for example with a scale printed on the compartment or other location with a pointer or other indicator that shows the vertical position of the vessel, or an electronic sensor within or outside the compartment can measure the vertical position of the vessel and output this information to a suitable receiver.

The downhole condition can be any suitable downhole condition that is consistent with the method and apparatus described herein. The downhole condition can be one downhole condition or more than one downhole condition. In some embodiments, the downhole condition is at least one of temperature, pressure, agitation (e.g., shear history, agitation over time, conditioning of the slurry, and the like), and liquid environment of the slurry. A downhole condition including the liquid environment of the slurry can be a liquid contacting at least part of or substantially all of the exterior of the slurry during the curing of the slurry. In some embodiments, a liquid environment can be absent, and the slurry can directly contact the interior of the compartment. In other embodiments, a liquid such as at least one of an aqueous liquid, an oil, and an organic solvent can form a liquid environment for the slurry and can be disposed at least partially between the slurry and the container, or in some embodiments within the slurry. In some embodiments, the downhole condition is temperature and pressure. The pressure of the environment within the compartment, such as a gas or liquid environment, can be controlled using any suitable means, to generate a downhole pressure within the interior of the compartment and the vessel. The downhole pressure can be any suitable downhole pressure. In some embodiments, the downhole pressure can be about 14 psi to about 100,000 psi, or about 5,425 psi to about 30,000 psi, or about 14 psi or less, or about 15 psi, 20, 30, 40, 50, 75, 100, 150, 200, 250, 300, 400, 500, 600, 700, 800, 900, 1,000, 1,500, 2,000, 3,000, 4,000, 5,000, 6,000, 7,000, 8,000, 9,000, 10,000, 15,000, 20,000, 25,000, 50,000, 75,000 psi, or about 100,000 psi or more. The temperature of the environment within the compartment, such as a gas or liquid environment, can be controlled using any suitable means, to generate a downhole temperature within the interior of the compartment and the vessel. The temperature can be any suitable downhole temperature, such as about 30°C to about 600°C, or about 150°C to about 500°C, or about 30°C or less, or about 40°C, 50°C, 60°C, 70°C, 80°C, 90°C, 100°C, 125°C, 150°C, 175°C, 200°C, 225°C, 250°C, 275°C, 300°C, 325°C, 350°C, 375°C, 400°C, 425°C, 450°C, 475°C, 500°C, or about 600°C or more. The amount of agitation within the vessel can be controlled using any suitable means to generate a downhole agitation condition within
the vessel. The agitation can include applying any type of shearing force to the cement slurry, and can include, for example, at least one of vibrating, shaking, and stirring.

[0045] In some embodiments, the method includes injecting gas into a suitable location within the vessel, such as a lower portion or the bottom portion, to measure the effect on one or more curing properties of the cement slurry over time. The measurement can include analyzing the effect of the gas flow on the shear stress of the cement on the plate via detecting changes in the downward force of the cement slurry by methods described herein.

[0046] The surface nonmovable along the vertical axis can be any suitable surface. The surface can be a sphere, a conical section, an irregular shape, or a plate. The surface can have any suitable texture. In some embodiments, the surface can have a texture that simulates a downhole surface that is desired to be cemented, such as a rock surface, a casing, a hardened resin, gravel pack, or any suitable downhole surface.

[0047] The cement slurry used in methods of the present invention can be any suitable cement slurry. The cement slurry can include an aqueous mixture including at least one of cement and cement kiln dust. The cement kiln dust can be any suitable cement kiln dust. Cement kiln dust can be formed during the manufacture of cement and can be partially calcined kiln feed which is removed from the gas stream and collected in a dust collector during manufacturing process.

Cement kiln dust can be advantageously utilized in a cost-effective manner since kiln dust is often regarded as a low value waste product of the cement industry. Some embodiments of the cement slurry can include cement kiln dust but no cement, cement kiln dust and cement, or cement but no cement kiln dust. The cement can be any suitable cement. The cement can be a hydraulic cement. A variety of cements can be utilized in accordance with the present invention, for example, those including calcium, aluminum, silicon, oxygen, iron, or sulfur, which can set and harden by reaction with water. For example, the cement can be Portland cement, pozzolana cement, gypsum cement, high alumina content cement, slag cement, silica cement, or a combination thereof. In some embodiments, the Portland cements that are suitable for use in the present invention are classified as Classes A, C, H, and G cements according to the American Petroleum Institute, API Specification for Materials and Testing for Well Cements, API Specification 10, Fifth Ed., Jul. 1, 1990. A cement can be generally included in the cement slurry in an amount sufficient to provide the desired compressive strength, density, or cost. In some embodiments, the hydraulic cement can be present in the cement slurry in an amount in the range of from 0 wt % to about 100 wt %, about 0 wt % to about 95 wt %, about 20 wt % to about 95 wt %, about 50 wt % to about 90 wt %, or about 1 wt %, 2, 3, 4, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 96, 97, 98 wt %, or about 99 wt % or more of the slurry. A cement kiln dust can be present in an amount of at least about 0.01 wt %, or about 5 wt % to about 80 wt %, or about 10 wt % to about 50 wt %.

[0048] The cement slurry can include at least one of water, brine, and salt water, in any suitable proportion, such as in an amount of 1 wt %, 2, 3, 4, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 96, 97, 98 wt %, or about 99 wt % or more of the slurry. The cement slurry can include any suitable cement additive, such as fly ash, metakaolin, shale, a zeolite; a set retarding additive; a surfactant, a gas, an accelerator, a weight reducing additive, a heavy-weight additive, a lost-circulation material, a filtration control additive, a dispersant, a crystalline silica compound, amorphous silica, a salt, a fiber, a hydratable clay, microspheres, pozzolan lime, a thixotropic additive, or a combination thereof. The cement additive can be present in any suitable proportion, such as about 0.000, 1 wt % or less, or about 0.005, 0.001, 0.005, 0.01, 0.05, 0.1, 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, or about 70 wt % or more.

[0049] In some embodiments, the composition can include any suitable amount of any suitable material used in a downhole fluid. For example, the composition can include aqueous base, oil, organic solvent, synthetic fluid oil phase, aqueous solution, alcohol or polyol, cellulose, starch, alkalinity control agents, density control agents, density modifiers, emulsifiers, dispersants, polymeric stabilizers, crosslinking agents, polyacrylamide, a polymer or combination of polymers, antioxidants, heat stabilizers, foam control agents, solvents, diluents, plasticizer, filler or inorganic particle, pigment, dye, precipitating agent, rheology modifier, oil-wetting agents, breakers, crosslinkers, rheology modifiers, curing accelerators, curing retarders, pH modifiers, chelating agents, scale inhibitors, enzymes, resin, water control materials, oxidizers, markers, or a combination thereof.

Apparatus for Measuring Cement Slurry Properties Under Downhole Conditions.

[0050] In various embodiments, the present invention provides an apparatus for measuring a property (e.g., at least one property) of a cement slurry under a downhole condition (e.g., at least one downhole condition). The apparatus can be any suitable apparatus that can carry out the method described herein. In some embodiments, the apparatus includes a vessel configured to move along a vertical axis proportionally to a downward force within the vessel. The apparatus can include a detector configured to detect the downward force. The apparatus can include a surface disposed at least partially within the vessel. The surface can be substantially nonmovable along the vertical axis. The apparatus can be configured to provide at least one downhole condition within the vessel.

[0051] The detector can be configured to detect the downward force within the vessel by detecting the vertical position of the vessel along the vertical axis, such as a change in the vertical position over time. The downward force within the vessel can be exerted by contents that can be placed in vessel, e.g., a cement slurry.

[0052] The apparatus can include a compartment that encloses the vessel within an interior of the compartment. The compartment can be configured to provide the at least one downhole condition within the vessel. The compartment can enclose at least part of the detector within the interior of the compartment. The surface can be secured to the interior of the compartment. The surface can be substantially nonmovable along the vertical axis with respect to the interior of the compartment.

[0053] FIG. 2 illustrates an apparatus for measuring yield stress of cement, in accordance with various embodiments. The apparatus (100) includes a compartment (110) encapsulating a vessel (120), wherein the vessel (120) is movable along a vertical axis, and wherein the downward movement of the vessel (120) can be detected by a spring or scale (130). The vessel (120) is filled with a cement slurry (140). The compartment (110) can be pressurized with water (150) at a desired pressure to simulate a downhole pressure condition.
within the vessel (120). The temperature within the vessel (120) can be controlled by circulating water (150) or another suitable fluid at a desired temperature around the vessel (120) within the compartment (110), to simulate a downhole temperature. In other embodiments, the temperature within the vessel (120) can be controlled by using a heater with a temperature controller. A thin plate (160) is rigidly bound to the frame of the compartment (110), such that it is nonmovable along the vertical axis. The surface of the thin plate (160) can be covered with a desired texture to mimic the tuckiness of a formation or the texture of a steel casing. The plate (160) is at least partially immersed in the cement slurry (140) in the vessel (120). As the cement (140) hydrates and builds its internal structure, it supports partially its weight on the surfaces of the plate (160), causing the force exerted on the spring to decrease, causing the vertical position, x, of the vessel to change (170) over time.

System for Measuring Cement Slurry Properties Under Downhole Conditions.

[0054] In various embodiments, the present invention provides a system for measuring a cement slurry property under a downhole condition. The system can include any suitable system that includes the apparatus described herein or that can carry out the method described herein. For example, the system can include an apparatus that includes a vessel configured to move along a vertical axis proportionally to a downward force within the vessel. The apparatus can include a detector configured to detect the downward force. The apparatus can include a surface disposed at least partially within the vessel, wherein the surface is substantially nonmovable along the vertical axis. The apparatus can be configured to provide at least one downhole condition within the vessel. The system can also include a cement slurry within the vessel, wherein the surface is at least partially immersed in the slurry. The cement slurry can be any suitable cement slurry.

Examples

[0055] The present invention can be better understood by reference to the following Examples which are offered by way of illustration. The present invention is not limited to the Examples given herein.

Example 1a

Apparatus

[0056] The apparatus used in this Example included a thin brass plate covered with sand paper and rigidly bound to a metallic frame. The plate was partially immersed in a beaker containing fresh cement slurry. The variation of the apparent weight of the cement paste with time was recorded using a balance connected to a computer.

[0057] The cement slurry used in the Example contained 762.3 g of Texas L high class H, 22.9 g of calcium chloride, 350.7 g of water, and 4.6 g of D-Air 3000™ defoamer.

Example 1b

Derivation of Yield Stress

[0058] During the curing of the cement slurry, the force applied by the apparent weight of the cement on the spring F(t) represents the difference between the actual buoyancy weight of the slurry F(t=0)−ρ_{slurry}V_{slurry}g and the weight supported on the plate by the shear stress 2S·τ(t), where S is the surface area of one side of the plate. The variation in the vertical position of the vessel due to the variation of the cement weight applied on the spring/scale can be used to calculate the shear stress applied on the surface of the plate as:

$$\tau(t) = \frac{F(t) - F(t_0)}{2S}$$.

[0059] The apparent weight of the cement on the spring F(t) can be obtained by measuring the time dependent spring deformation Δx(t): F(t)−kΔx(t), where k is the spring constant and Δx(t) is the spring deformation at time t. The spring deformation Δx(t) can be measured, for example, using a linear variable differential transducer (LVDT). The shear stress acting on the plate surface can be calculated by combining the equation for shear stress with the equation for spring deformation:

$$\tau(t) = \frac{k(Δx(t) - Δx(t_0))}{2S}.$$

Example 1c

Measurement of Yield Stress

[0060] A comparison between experimental yield stress measurements obtained using the thin plate experiment and the MACS 2 measurements is shown in FIG. 3. FIG. 3 illustrates yield stress/gel strength development versus time. The dashed line (−−−−) represents measurement obtained using a MACS 2 (performed at 31.7° C. shifted by 5 min to account for the time of filling and loading the can in the MACS 2), dotted lines(••) represent measurement obtained using a MACS 2 (performed at 25.1° C. and without D-Air 3000™ defoamer in the cement slurry, shifted by 5 min to account for the time of filling and loading the can in the MACS 2), and the continuous line (−) represents measurement using the thin-plate apparatus of the present Example at room temperature (about 25° C.).

[0061] Reasonable agreement between the different measurements was observed up to about 40 min after mixing. At this time, the slope of the plot yield stress versus time changes and the MACS 2 results begin to diverge from those of the thin-plate apparatus. Up to 40 min after mixing, the cement is viscoplastic and is in a dormant period. Measured mass loss can be attributed to the cement slurry developing yield strength and supporting part of its weight on the plate surface. At this stage the material is thought to build structure and cohesion. After 40 min, the dormant period ends, the formation of hydrates is accelerated and the exothermic reactions are initiated, as shown in FIG. 4. Yield stress/gel strength measurements with the proposed technique appear to be in agreement with the MACS 2 results in the dormant period, before the initiation of exothermic reaction and cement setting.

[0062] The terms and expressions which have been employed are used as terms of description and not of limitation, and there is no intention in the use of such terms and expressions of excluding any equivalents of the features...
shown and described or portions thereof, but it is recognized that various modifications are possible within the scope of the invention claimed. Thus, it should be understood that although the present invention has been specifically disclosed by specific embodiments and optional features, modification and variation of the concepts herein disclosed may be resorted to by those of ordinary skill in the art, and that such modifications and variations are considered to be within the scope of this invention as defined by the appended claims.

Additional Embodiments

[0063] The present invention provides for the following exemplary embodiments, the numbering of which is not to be construed as designating levels of importance:

[0064] Embodiment 1 provides a method of measuring a cement slurry property under a downhole condition, the method comprising: detecting a downward force exerted by a curing cement slurry under at least one downhole condition within a vessel movable along a vertical axis proportionally to the downward force, a surface substantially nonmovable along the vertical axis being disposed at least partially within the cement slurry; and determining at least one property of the cement slurry from the detected downward force.

[0065] Embodiment 2 provides the method of Embodiment 1, wherein the downward force comprises a buoyancy weight of the slurry minus a weight of the slurry supported on the surface by shear stress.

[0066] Embodiment 3 provides the method of any one of Embodiments 1-2, wherein the method measures a loss of weight of the cement slurry due to a shear stress of the cement slurry on the surface.

[0067] Embodiment 4 provides the method of any one of Embodiments 1-3, wherein detecting the downward force comprises detecting a vertical position of the vessel.

[0068] Embodiment 5 provides the method of any one of Embodiments 1-4, wherein the determining the at least one property comprises determining at least one of a shear stress of the cement slurry on the surface, a static gel strength of the cement slurry, a yield stress of the cement slurry, a loss of weight of the cement slurry due to curing, a variation of hydrostatic pressure of the slurry over time, a setting time of the cement slurry, and a dormant time of the cement slurry.

[0069] Embodiment 6 provides the method of any one of Embodiments 1-5, wherein the determining comprises determining the approximate shear stress of the cement slurry on the surface at time t comprising dividing a first quantity by a surface area of the surface contacted by the cement slurry, wherein the first quantity comprises the downward force exerted by the curing cement slurry at time 0 minus the downward force exerted by the curing cement slurry at time t.

[0070] Embodiment 7 provides the method of Embodiment 6, wherein determining the first quantity comprises multiplying a spring constant by a second quantity, wherein the second quantity comprises a vertical position of the vessel at time 0 minus a vertical position of the vessel at time t.

[0071] Embodiment 8 provides the method of any one of Embodiments 1-7, wherein the determining comprises determining a yield stress of the cement slurry.

[0072] Embodiment 9 provides the method of any one of Embodiments 1-8, wherein the determining comprises determining a static gel strength of the cement slurry.

[0073] Embodiment 10 provides the method of any one of Embodiments 1-9, wherein the vessel is located above the surface.

[0074] Embodiment 11 provides the method of any one of Embodiments 1-10, wherein a compartment encloses the vessel within an interior of the compartment, wherein the compartment is configured to provide the at least one downhole condition within the vessel.

[0075] Embodiment 12 provides the method of Embodiment 11, wherein the interior of the compartment comprises the at least one downhole condition.

[0076] Embodiment 13 provides the method of any one of Embodiments 11-12, wherein the interior of the compartment comprises a liquid.

[0077] Embodiment 14 provides the method of any one of Embodiments 11-13, wherein the interior of the compartment comprises an aqueous liquid.

[0078] Embodiment 15 provides the method of any one of Embodiments 11-14, wherein the interior of the compartment comprises water.

[0079] Embodiment 16 provides the method of any one of Embodiments 11-15, wherein the compartment encloses at least part of a detector within the interior of the compartment, wherein the detector detects the downward force.

[0080] Embodiment 17 provides the method of Embodiment 16, wherein the compartment encloses substantially all of the detector within the interior of the compartment.

[0081] Embodiment 18 provides the method of any one of Embodiments 11-17, wherein the vessel is movable along the vertical axis with respect to the interior of the compartment.

[0082] Embodiment 19 provides the method of any one of Embodiments 11-18, wherein the compartment encloses at least part of the surface within the vessel.

[0083] Embodiment 20 provides the method of any one of Embodiments 11-19, wherein the compartment encloses substantially all of the surface within the vessel.

[0084] Embodiment 21 provides the method of any one of Embodiments 11-20, wherein the surface is secured to the interior of the compartment and the surface is substantially nonmovable along the vertical axis with respect to the interior of the compartment.

[0085] Embodiment 22 provides the method of any one of Embodiments 11-21, wherein the downhole condition comprises at least one of temperature, pressure, agitation, and liquid environment of the slurry.

[0086] Embodiment 23 provides the method of Embodiment 22, wherein the downhole condition comprises temperature and pressure.

[0087] Embodiment 24 provides the method of any one of Embodiments 22-23, wherein the temperature is about 300°C to about 600°C.

[0088] Embodiment 25 provides the method of any one of Embodiments 22-24, wherein the temperature is about 150°C to about 500°C.

[0089] Embodiment 26 provides the method of any one of Embodiments 22-25, wherein the pressure is about 14 psi to about 100,000 psi.

[0090] Embodiment 27 provides the method of any one of Embodiments 22-26, wherein the pressure is about 5,000 psi to about 30,000 psi.

[0091] Embodiment 28 provides the method of any one of Embodiments 22-27, wherein the agitation comprises shearing.

[0092] Embodiment 29 provides the method of any one of Embodiments 22-28, wherein the agitation comprises at least one of vibrating, shaking, and stirring.
Embodiment 30 provides the method of any one of Embodiments 1-29, wherein the surface comprises a plate.

Embodiment 31 provides the method of any one of Embodiments 1-30, wherein the surface comprises a textured surface.

Embodiment 32 provides the method of any one of Embodiments 1-31, wherein the detecting of the downward force comprises using a detector.

Embodiment 33 provides the method of Embodiment 32, wherein the detector comprises a scale.

Embodiment 34 provides the method of any one of Embodiments 32-33, wherein a resilient member provides upward resistance proportional to downward vertical movement of the vessel along the vertical axis.

Embodiment 35 provides the method of any one of Embodiments 32-34, wherein the resilient member comprises a spring.

Embodiment 36 provides the method of any one of Embodiments 1-35, wherein the cement slurry comprises Portland cement, pozzolana cement, gypsum cement, high alumina content cement, slag cement, silica cement, or a combination thereof.

Embodiment 37 provides the method of any one of Embodiments 1-36, wherein the cement slurry comprises at least one of water, brine, and salt water.

Embodiment 38 provides the method of any one of Embodiments 1-37, wherein the cement slurry comprises fly ash, metakaolin, shale, a zeolite, a set retarding additive, a surfactant, a gas, an accelerator, a weight reducing additive, a heavy-weight additive, a lost-circulation material, a filtration control additive, a dispersant, a crystalline silica compound, an amorphous silica, a salt, a fiber, a hydratable clay, microspheres, possalum lime, a thixotropic additive, or a combination thereof.

Embodiment 39 provides a method of measuring a cement slurry property under a downhole condition, the method comprising: providing or obtaining an apparatus comprising a vessel configured to move along a vertical axis proportionally to a downward force within the vessel; a detector configured to detect a vertical position of the vessel along the vertical axis; and a surface disposed at least partially within the vessel, wherein the surface is substantially nonmovable along the vertical axis; wherein the apparatus is configured to provide at least one downhole condition within the vessel; placing a cement slurry within the vessel; configuring at least one downhole condition within the vessel; allowing the cement slurry to at least partially cure; and determining at least one property of the cement slurry from the detected vertical position of the vessel during at last part of the curing of the cement slurry.

Embodiment 40 provides an apparatus for measuring a property of a cement slurry under a downhole condition, the apparatus comprising: a vessel configured to move along a vertical axis proportionally to a downward force within the vessel; a detector configured to detect the downward force; and a surface disposed at least partially within the vessel, wherein the surface is substantially nonmovable along the vertical axis; wherein the apparatus is configured to provide at least one downhole condition within the vessel.

Embodiment 41 provides the apparatus of Embodiment 40, wherein the detector is configured to detect a vertical position of the vessel along the vertical axis.

Embodiment 42 provides the apparatus of any one of Embodiments 40-41, wherein a compartment encloses the vessel within an interior of the compartment, wherein the compartment is configured to provide at least one downhole condition within the vessel.

Embodiment 43 provides the apparatus of Embodiment 42, wherein the compartment encloses at least part of the detector within the interior of the compartment.

Embodiment 44 provides the apparatus of any one of Embodiments 42-43, wherein the surface is secured to the interior of the compartment and the surface is substantially nonmovable along the vertical axis with respect to the interior of the compartment.

Embodiment 45 provides the apparatus of any one of Embodiments 40-44, wherein the downward force within the vessel is exerted by contents of the vessel.

Embodiment 46 provides the apparatus of Embodiment 45, wherein the contents comprise a cement slurry.

Embodiment 47 provides a system for measuring a cement slurry property under a downhole condition, the system comprising: an apparatus comprising a vessel configured to move along a vertical axis proportionally to a downward force within the vessel; a detector configured to detect the downward force; and a surface disposed at least partially within the vessel, wherein the surface is substantially nonmovable along the vertical axis; wherein the apparatus is configured to provide at least one downhole condition within the vessel; a cement slurry within the vessel, wherein the surface is at least partially immersed in the slurry.

Embodiment 48 provides the apparatus, method, or system of any one or any combination of Embodiments 1-17 optionally configured such that all elements or options recited are available to use or select from.

1. A method of measuring a cement slurry property under a downhole condition, the method comprising:
   - detecting a downward force exerted by a curing cement slurry under at least one downhole condition within a vessel movable along a vertical axis proportionally to the downward force, a surface substantially nonmovable along the vertical axis being disposed at least partially within the cement slurry; and determining at least one property of the cement slurry from the detected downward force.

2. The method of claim 1, wherein the downward force comprises a buoyancy weight of the slurry minus a weight of the slurry supported on the surface by shear stress.

3. (canceled)

4. The method of claim 1, wherein determining the downward force comprises detecting a vertical position of the vessel.

5. The method of claim 1, wherein determining the at least one property comprises determining at least one of a shear stress of the cement slurry on the surface, a static gel strength of the cement slurry, a yield stress of the cement slurry, a loss of weight of the cement slurry due to curing, a variation of hydrostatic pressure of the slurry over time, a setting time of the cement slurry, and a dormant time of the cement slurry.

6. The method of claim 1, wherein determining comprises determining the approximate shear stress of the cement slurry on the surface at time $t$ comprising dividing a first quantity by a surface area of the surface contacted by the cement slurry, wherein the first quantity comprises the downward force exerted by the curing cement slurry at time $t$ minus the downward force exerted by the curing cement slurry at time $t$. 
7. The method of claim 6, wherein determining the first quantity comprises multiplying a spring constant by a second quantity, wherein the second quantity comprises a vertical position of the vessel at time 0 minus a vertical position of the vessel at time t.

8-10. (canceled)

11. The method of claim 1, wherein a compartment encloses the vessel within an interior of the compartment, wherein the compartment is configured to provide the at least one downhole condition within the vessel.

12-15. (canceled)

16. The method of claim 11, wherein the compartment encloses at least part of a detector within the interior of the compartment, wherein the detector detects the downward force.

17. (canceled)

18. The method of claim 11, wherein the vessel is movable along the vertical axis with respect to the interior of the compartment.

19. The method of claim 11, wherein the compartment encloses at least part of the surface within the vessel.

20. (canceled)

21. The method of claim 11, wherein the surface is secured to the interior of the compartment and the surface is substantially nonmovable along the vertical axis with respect to the interior of the compartment.

22. The method of claim 1, wherein the downhole condition comprises at least one of temperature, pressure, agitation, and liquid environment of the slurry.

23-28. (canceled)

29. The method of claim 22, wherein the agitation comprises at least one of shearing, vibrating, shaking, and stirring.

30. (canceled)

31. The method of claim 1, wherein the surface comprises a textured surface.

32. The method of claim 1, wherein the detecting of the downward force comprises using a detector.

33. The method of claim 32, wherein the detector comprises a scale.

34. The method of claim 32, wherein a resilient member provides upward resistance proportional to downward vertical movement of the vessel along the vertical axis.

35. (canceled)

36. The method of claim 1, wherein the cement slurry comprises Portland cement, pozzolana cement, gypsum cement, high alumina content cement, slag cement, silica cement, or a combination thereof.

37-38. (canceled)

39. A method of measuring a cement slurry property under a downhole condition, the method comprising:
   providing or obtaining an apparatus comprising:
   a vessel configured to move along a vertical axis proportionally to a downward force within the vessel;
   a detector configured to detect a vertical position of the vessel along the vertical axis; and
e a surface disposed at least partially within the vessel,
   wherein the surface is substantially nonmovable along the vertical axis;
   wherein the apparatus is configured to provide at least one downhole condition within the vessel;
   placing a cement slurry within the vessel;
   configuring at least one downhole condition within the vessel;
   allowing the cement slurry to at least partially cure; and
   determining at least one property of the cement slurry from the detected vertical position of the vessel during at least part of the curing of the cement slurry.

40. An apparatus for measuring a property of a cement slurry under a downhole condition, the apparatus comprising:
   a vessel configured to move along a vertical axis proportionally to a downward force within the vessel;
   a detector configured to detect the downward force; and
   a surface disposed at least partially within the vessel,
   wherein the surface is substantially nonmovable along the vertical axis;
   wherein the apparatus is configured to provide at least one downhole condition within the vessel.

41-47. (canceled)