

Recommended Practice for Testing Well Cements

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Recommended Practice for Testing Well Cements

1 Scope

This standard specifies methods and gives recommendations for the testing of cement slurries and related materials under simulated well conditions.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API Specification 10A, *Cements and Materials for Well Cementing*

API Recommended Practice 13I, *Laboratory Testing of Drilling Fluids*

ASTM C109/C109M ¹, *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)*

ASTM C188, *Standard Test Method for Density of Hydraulic Cement*

3 Terms, Definitions, Acronyms, Abbreviations, and Symbols

3.1 Terms and Definitions

For the purposes of this document, the following definitions apply.

3.1.1

absolute volume

The volume occupied by a material, not including the intergranular space in the case of a solid.

NOTE Absolute volume corresponds to the inverse of the density.

3.1.2

additive

Material incorporated in a cement slurry to modify or enhance some desired property.

3.1.3

annulus

Space between the pipe and the wellbore wall or an outer pipe.

3.1.4

atmospheric consistometer

Device used to condition fluids prior to some tests and for determining the thickening time of arctic slurries at atmospheric pressure.

3.1.5

batch mix

Process of mixing the entire volume of cement slurry prior to placement in the wellbore.

¹ ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428, www.astm.org

3.1.6**Bearden units of consistency** B_c

Units used to express consistency of a cement slurry when determined using a pressurized consistometer. There is no correlation between Bearden units and viscosity as measured with a rheometer.

3.1.7**bottomhole circulating temperature** T_{BHC}

Pseudo-stable temperature found at the bottom of the wellbore while the well is being circulated.

3.1.8**bulk density**

Mass per unit of volume of a dry material including the air between particles.

NOTE See Annex E for further description.

3.1.9**cement****Portland cement**

Ground clinker generally consisting of hydraulic calcium silicates and aluminates and usually containing one or more of the forms of calcium sulfates as an interground additive.

NOTE Clinker: fused materials from the kiln.

3.1.10**cement blend**

Mixture of dry cement and other dry materials.

3.1.11**cement class**

Designation of classifications of well cement according to defined specifications of API 10A.

3.1.12**compatibility**

Capacity to form a fluid mixture that does not undergo undesirable chemical and/or physical reactions.

3.1.13**compressive strength**

Measured strength of a set cement sample calculated by the force required to cause it to fail in compression, expressed as a force per unit of area.

3.1.14**density****absolute density**

The mass of a material per unit of volume, not including the intergranular space in the case of a solid.

NOTE Obtain the density of a material by multiplying the relative density of the material by the density of water at 4 °C, 1000 kg/m³ (40 °F, 8.345 lbm/gal).

3.1.15**continuous-pumping squeeze cementing**

Squeeze-cementing operation that does not involve interruptions in pumping.

3.1.16
drilling fluid
mud

Fluid, generally viscosified and possibly weighted, used to remove cuttings, cool the drill bit, and prevent formation fluids from entering the wellbore during drilling or workover operations.

3.1.17
equivalent sack

Mass of the blend of fly ash or pozzolan and Portland cement that has the same absolute volume as a sack [one (1) ft³ sack = 3.59 gal] of Portland cement.

NOTE Only used in U.S. customary (USC) measurements. See also 3.1.37.

3.1.18
filtrate

Liquid that is forced out of a cement slurry during a fluid-loss test.

3.1.19
fly ash

Finely divided residue from the combustion of ground or powdered coal with pozzolanic properties.

NOTE See Annex H for further description.

3.1.20
free fluid

Colored or colorless liquid that has separated from a cement slurry when standing in a static condition.

3.1.21
freeze-thaw cycle

A prescribed cycle of exposure of a cement sample to temperatures above and below the freezing point of water or that of the cement filtrate.

3.1.22
heat-up rate

R_h

Rate of slurry temperature change from the surface slurry temperature, T_{SS} , to the predicted bottomhole circulating temperature, T_{PBHC} .

3.1.23
hesitation-pumping squeeze cementing

Squeeze-cementing operation involving alternate pumping and non-pumping periods.

3.1.24
load frame

Frame to place a compressive or tensile load on a set cement sample for determining material properties (e.g. compressive strength or tensile strength).

3.1.25
mix fluid

Mix water containing solid, liquid, or both types of additives.

3.1.26
mix water

Fresh water, brine, or seawater without solid or liquid (or both) additives.

3.1.27**nonaqueous fluid****NAF**

NAF is a nonaqueous drilling fluid or well circulating fluid. Common NAF systems are diesel, mineral oil, synthetic-fluid-based invert emulsions, or other non-water-based fluids.

NOTE Nonaqueous drilling fluids are also named using symbol NADF.

3.1.28**plug cementing**

Process of placing a volume of cement in a well to form a plug across the wellbore.

3.1.29**pozzolan**

Siliceous or siliceous and aluminous material that, in itself, possess little or no cementitious value but, in finely divided form and in the presence of moisture, reacts with calcium hydroxide to form a cementitious material.

NOTE See Annex H for further description.

3.1.30**preflush**

Fluid that is not viscosified nor densified with insoluble, solid weighting agents.

3.1.31**pressure-down rate**

R_{pd}

Rate at which pressure is reduced from the bottomhole pressure, p_{BH} , to the pressure at the top-of-cement column, p_{TOC} , during a thickening-time test.

3.1.32**pressure-up rate**

R_{pu}

Rate at which pressure is increased from the starting pressure, p_S , to the bottomhole pressure, p_{BH} , during a thickening-time test.

3.1.33**pressurized consistometer**

Device used to measure the thickening time of a cement slurry and also to condition fluids prior to some tests under temperature and pressure.

3.1.34**pressurized curing chamber**

Apparatus used for curing a sample of cement under temperature and pressure.

3.1.35**pressurized fluid density balance**

Beam-type balance used to measure fluid density under pressure to minimize the effects of air entrained in the fluid.

3.1.36**relative density****specific gravity**

SG

Ratio of the mass of a solid or a liquid substance to the mass of an equal volume of a standard substance at a reference temperature.

NOTE The standard substance is usually water; the reference temperature is usually 4 °C (40 °F).

3.1.37

sack

A unit of measure of cement that occupies a bulk volume of 1 ft³ (3.59 gal).

NOTE 1 Normally 94 lbm for Portland cement.

NOTE 2 Only used in USC measurements.

3.1.38

sedimentation

Separation and settling of solids in a cement slurry.

3.1.39

slurry container

Container used to hold the slurry in a consistometer for conditioning or testing.

3.1.40

slurry stability test

Test to determine the degree of sedimentation and/or free-fluid development in a cement slurry.

3.1.41

sonic strength

Strength of a cement sample obtained by measuring the velocity of sound through the cement and computing the strength using a correlation to compressive strength measurements.

3.1.42

spacer

Viscosified fluid that may be densified with insoluble, solid weighting agents and used to separate drilling fluids and cement slurries during cementing operations.

3.1.43

squeeze cementing

Remedial process in which cement slurry is forced under pressure into a specific portion of the well such as a fracture or opening with the intent to form a bridge of dehydrated cement slurry.

3.1.44

starting pressure

p_s

Initial pressure applied to the cement slurry at the beginning of the thickening-time test.

3.1.45

static fluid-loss test

Test to determine filtrate lost from a cement slurry when placed against a 45 µm (U.S. No. 325) screen at 6900 kPa (1000 lbf/in.²) differential pressure.

3.1.46

stirred fluid-loss apparatus

Apparatus specially designed to allow for conditioning of the cement slurry within the same cell used to perform a static fluid-loss test.

3.1.47**thickening time**

Time elapsed from the initial application of pressure and temperature while stirring to the time at which the slurry reaches a consistency deemed sufficient to make it unpumpable (e.g. 70 B_c or 100 B_c) under the test conditions.

3.1.48**transit time**

TT

Transit time (sometimes referred to as compressional sonic slowness) is a measurement of sonic velocity that starts when the transmitter is fired and ends when a determined amplitude peak from the waveform arrives at the receiver.

NOTE 1 Transit time is typically expressed in microseconds per inch.

NOTE 2 Transit time is a measurement of sonic velocity and shall not be confused with travel time. Some apparatus may report a travel time through the cement sample and this time shall be converted into transit time by dividing it by the distance between the two sonic sensors.

3.1.49**well-simulation test**

Test with parameters designed and/or modified to simulate anticipated conditions found in the wellbore.

3.2 Symbols, Acronyms, and Abbreviations**3.2.1 Symbols**

For the purposes of this document, the symbols given in Table 1 apply. This list is not exhaustive.

Table 1—Symbols

Symbol	Meaning	Units
B_c	consistency	Bearden units
$c_{ad.sol}$	solid additive concentration	percent by weight of cement
E	mixing energy	kilojoules
E/m	mass mixing energy	kilojoules per kilogram
$d_{rel,i}$	relative density (specific gravity) of cement segment (i)	dimensionless
h_{TOCTVD}	top-of-cement true vertical depth	meters (feet)
h_{TVD}	true vertical depth	meters (feet)
k	consistency index	$\text{Pa} \cdot \text{s}^n$ ($\text{lbf} \cdot \text{s}^n / 100 \text{ ft}^2$)
m	mass	kilograms (pounds-mass)
$m_{ad.liq}$	liquid additive mass (volume $V_{ad.liq}$)	kilograms per metric ton of cement (pounds-mass per sack of cement)
$m_{ad.liq,600}$	liquid additive mass for 600 mL of slurry	grams
$m_{ad.sol}$	solid additive mass concentration	kilograms per metric ton of cement (pounds-mass per sack of cement)
$m_{ad.sol,600}$	solid additive mass for 600 mL of slurry	grams
$m_{air,i}$	mass of cement segment (i) in air	grams

Symbol	Meaning	Units
$m_{\text{bld,sk-eq}}$	mass weight of 1 equivalent sack (3.59 gal) of blend	pounds-mass
m_c	mass of 1 metric ton or 1 sack of cement	1000 kilograms or normally 94 pounds-mass
$m_{\text{cmt,sk}}$	mass weight of 1 sack (3.59 gal) of cement	pounds-mass
$m_{c,600}$	cement mass for 600 mL of slurry	grams
m_{dw}	mass of distilled water	grams
m_{lfm}	mass of 100 mL of loosely filled material	grams
$m_{\text{poz,sk}}$	mass weight of 1 sack (3.59 gal) of pozzolan	pounds-mass
m_s	slurry mass	kilograms per metric ton of cement (pounds-mass per sack of cement)
$m_{s,600}$	mass of 600 mL of slurry	grams
m_w	mix water mass	kilograms per metric ton of cement (pounds-mass per sack of cement)
$m_{w,600}$	mix water mass for 600 mL of slurry	grams
$m_{\text{water},i}$	mass of cement segment (i) in water	grams
n	flow behavior index	dimensionless
n_s	total number of sedimentation test sample segment	dimensionless
p_{BH}	bottomhole pressure ^a	kilopascals (pounds-force per square inch)
p_{FSQ}	final bottomhole squeeze-cementing pressure	kilopascals (pounds-force per square inch)
p_s	starting pressure	kilopascals (pounds-force per square inch)
p_{SQ}	maximum surface squeeze-cementing pressure	kilopascals (pounds-force per square inch)
p_{TOC}	top-of-cement pressure	kilopascals (pounds-force per square inch)
q	pump rate	cubic meters per minute (barrels per minute or cubic feet per minute)
R_h	temperature heat-up rate	degrees Celsius per minute (degrees Fahrenheit per minute)
R_{pd}	rate of pressure decrease	kilopascals per minute (pounds-force per square inch and minute)
R_{pu}	rate of pressure increase	kilopascals per minute (pounds-force per square inch and minute)
R_{PSQ}	rate of pressure increase to apply the squeeze-cementing pressure	kilopascals per minute (pounds-force per square inch and minute)
$R_{\Delta T}$	rate of temperature change to top of cement circulating temperature (T_{TOCC}) (heat-up or cooldown)	degrees Celsius per minute (degrees Fahrenheit per minute)
T	torque	gram-centimeters
TT	transit time (acoustic slowness)	microseconds per inch
T_{BHC}	bottomhole circulating temperature	degrees Celsius (degrees Fahrenheit)
T_{BHS}	bottomhole static temperature	degrees Celsius (degrees Fahrenheit)
T_{PBHC}	predicted bottomhole circulating temperature	degrees Celsius (degrees Fahrenheit)
T_{PSP}	predicted bottomhole squeeze-cementing or plug-cementing temperature	degrees Celsius (degrees Fahrenheit)
T_{SS}	slurry surface temperature	degrees Celsius (degrees Fahrenheit)

Symbol	Meaning	Units
T_{TOCC}	top-of-cement circulating temperature	degrees Celsius (degrees Fahrenheit)
T_{TOCS}	top-of-cement static temperature	degrees Celsius (degrees Fahrenheit)
t	elapsed time	minutes
t_a	time to displace the leading edge of the cement slurry from bottom of the casing to the top of the annular column	minutes
t_{cd}	cooldown time	minutes
t_d	time to displace the leading edge of cement slurry from the surface to the bottom of the wellbore	minutes
t_{mix}	mixing time	seconds
t_{sq}	time to apply squeeze-cementing pressure to cement slurry after bottomhole placement	minutes
V_F	volume of free fluid	milliliters
V_M	volume at a receiver specific mark	milliliters
V_a	annular volume of cement	cubic meters (barrels or cubic feet)
$V_{ad.liq}$	liquid additive volume concentration	liters per metric ton of cement (gallons per sack) of cement
$V_{ad.sol}$	solid additive volume (mass $m_{ad.sol}$)	liters per metric ton of cement (gallons per sack of cement)
V_c	volume of 1 metric ton of cement or for 1 sack of cement	liters per metric ton of cement (gallons per sack of cement)
V_{fp}	final packed volume	milliliters
V_{mix}	volume of mixed cement slurry	milliliters
$V_{mix,SI}$	volume of mixed cement slurry	cubic meters
V_p	volume of the pipe	cubic meters (barrels)
V_s	slurry yield (surface conditions)	liters per metric ton of cement (cubic feet per sack of cement)
$V_{s,dh}$	slurry yield at downhole conditions	liters per metric ton of cement (cubic feet per sack of cement)
V_{sl}	initial volume of cement slurry	milliliters
V_t	volume of filtrate collected at the time nitrogen blows through	milliliters
V_w	mix water volume	liters per metric ton of cement (gallons per sack of cement)
V_{30}	volume of filtrate collected at 30 min	milliliters
Z	acoustic impedance	megarayls
ΔT_p	pseudo-temperature gradient ^b	degrees Celsius per 100 meters (degrees Fahrenheit per 100 feet)
$\Delta \rho_{sc,i}$	density variance of the set cement segment (i)	percent
γ	shear rate	reciprocal seconds (s^{-1})
μ_p	plastic viscosity	pascal-seconds (centipoises)
$v_{ad.abs}$	solid additive absolute volume	gallons per pound

Symbol	Meaning	Units
$V_{c,abs}$	cement absolute volume	gallons per pound
ρ_{LAB}	loose apparent bulk density	kilograms per cubic meter (pounds-mass per cubic feet)
ρ_{PAB}	packed apparent bulk density	kilograms per cubic meter (pounds-mass per cubic feet)
$\rho_{ad,liq}$	density of liquid additive	kilograms per liter (pounds-mass per gallon)
$\rho_{ad,sol}$	density of solid additive	kilograms per liter (pounds-mass per gallon)
ρ_{af}	density of annular fluid	kilograms per liter (pounds-mass per gallon)
ρ_{bulk}	average bulk density	kilograms per cubic meter (pounds-mass per cubic feet)
ρ_c	density of cement	kilograms per liter (pounds per gallon)
ρ_{dw}	density of distilled water	grams per milliliter
$\rho_{s,m}$	density of slurry measured after mixing	kilograms per liter (pounds-mass per gallon)
ρ_s	density of slurry	kilograms per liter (pounds-mass per gallon)
$\rho_{s,dh}$	density of slurry at downhole conditions	kilograms per liter (pounds-mass per gallon)
ρ_{set}	density of the set cement	kilograms per liter (pounds-mass per gallon)
$\rho_{set,i}$	density of set cement segment (<i>i</i>)	kilograms per liter (pounds-mass per gallon)
ρ_w	density of mix water	kilograms per liter (pounds-mass per gallon)
τ	shear stress	pascals (pounds-force per 100 square feet)
τ_y	yield stress	pascals (pounds-force per 100 square feet)
ω	rotational speed of the blender	revolutions per minute
ω_{rev}	rotational speed of the cement-mixing device	revolutions per minute
Φ_{cmt}	ratio of cement in the pozzolan/cement blend	percent
Φ_{poz}	ratio of pozzolan in the pozzolan/cement blend	percent
ϕ	fluid volume fraction	percent
^a Hydrostatic pressure at the bottom of the well, calculated using the true vertical depth and the fluid densities in the wellbore. ^b Gradient in °C/100 m (°F/100 ft), calculated from the difference between the maximum recorded bottomhole static temperature and 27 °C (80 °F).		

3.2.2 Acronyms and Abbreviations

BWOB	by weight of blend
BWOC	by weight of cement
BWOW	by weight of water
CAS	Chemical Abstracts Service [division of ACS (American Chemical Society)]
ECD	equivalent circulating density
HPHT	high pressure, high temperature
LWS	lightweight cement slurry
NAF	nonaqueous fluid

PPE	personal protective equipment
SG	relative density (specific gravity)
SSST	spacer surfactant screening test
TOC	top of cement

4 Sampling

4.1 General

Samples of cement, cement blend, solid and liquid additives, and mix water may be required to test a cement slurry in accordance with this standard. Some commonly used sampling techniques are described in this section. Sample volumes should be sufficient to perform the desired testing. When extracting multiple samples of the same blend or additive, composite sample creation and testing may be considered.

4.2 Sampling Cement at a Field Location

Multiple samples shall be extracted using a suitable device (see Figure 1). A composite of the samples shall be prepared, packaged, and labeled (see 4.7).

4.3 Sampling Cement Blends at a Blending Facility

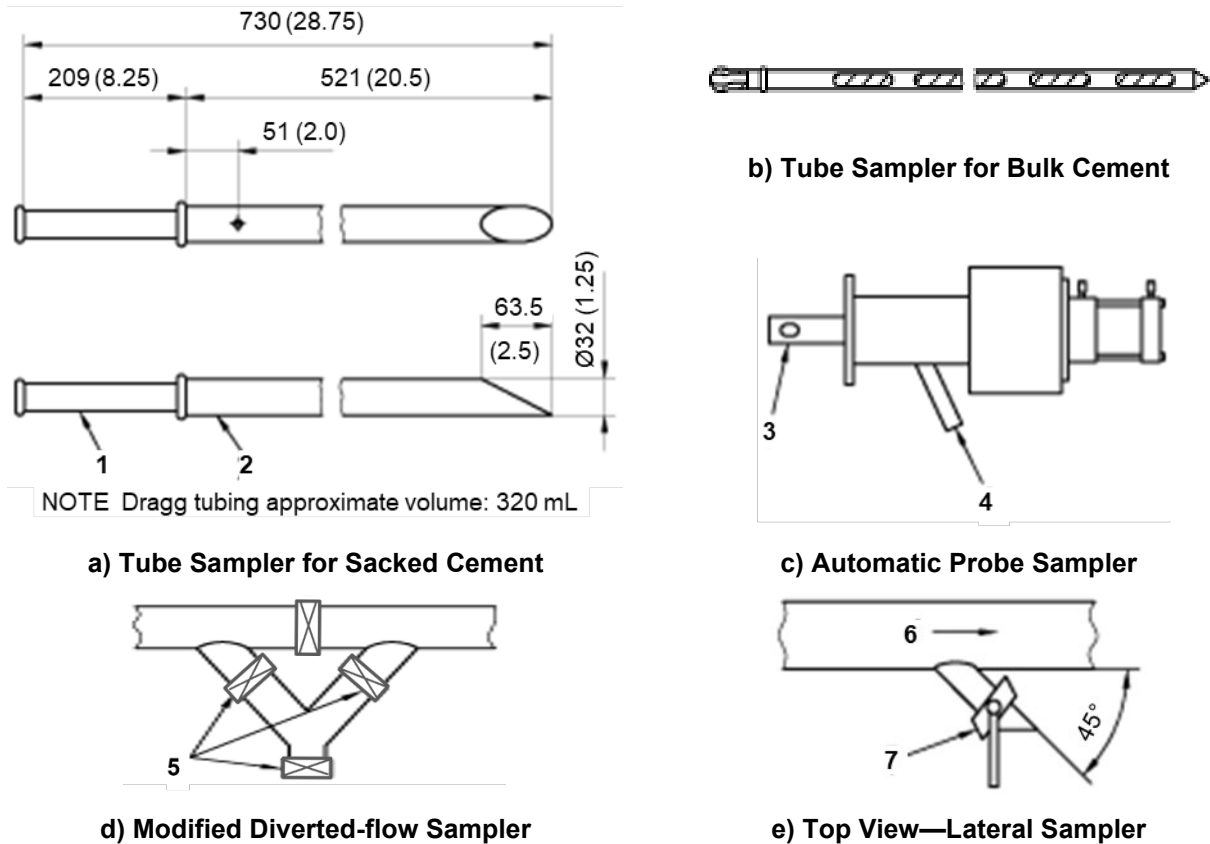
Cement blends may be sampled from the weigh batch mixer (scale tank), bulk transport, or extracted from the flow lines during transfer. The cement and dry additives shall be thoroughly blended prior to sampling. Samples extracted from a flow line during a transfer are preferred and may be taken from a properly installed sample valve, diverted flow sampler, or automatic in-line sampling device [see Figures 1 c), 1 d), and 1 e)] using a procedure designed to give a representative sample of the blend being transferred. The samples shall be prepared, packaged, and labeled (see 4.7).

NOTE Weigh batch mixers (scale tank) are devices or systems for the weighing and blending of cement with dry additives for a cementing operation.

4.4 Sampling Dry Cement Additives

Dry cement additive samples may be extracted from a bulk container or sack. Multiple samples should be extracted from the center of the source using a suitable sampling device [see Figure 1 a) or Figure 1 b)]. A composite of the samples from the same lot shall be prepared, packaged, and labeled (see 4.7).

Dimensions in millimeters (inches) unless otherwise indicated.



Key

- | | |
|-------------------------|------------------|
| 1 handle | 5 valve |
| 2 dragg tubing | 6 flow direction |
| 3 sample tube, extended | 7 valve |
| 4 product discharge | |

Figure 1—Commonly Used Sampling Devices

4.5 Sampling Liquid Cement Additives

Most liquid additives are solutions or suspensions of dry materials. Storage can allow separation of the active ingredients; thus, the active ingredients may float to the top of the container, be suspended as a phase layer, or settle to the bottom. For these reasons, liquid additives shall be thoroughly mixed prior to sampling. The sample shall be extracted from the center of the container using a clean, dry sampling device. A composite of the samples from the same lot shall be prepared, packaged, and labeled (see 4.7).

4.6 Sampling Mix Water

The mix water shall be sampled from the source or from the tank in which it is stored just prior to mixing. The sample shall be extracted in such a way as to avoid contamination. The sample shall be packaged and labeled (see 4.7).

4.7 Shipping and Storage

Test samples shall be packaged promptly in unused, clean, airtight, moisture-proof containers suitable for shipping and long-term storage. The containers shall be lined with metal, plastic, or other heavy-walled material to assure sample integrity and meet transportation regulations. Resealable plastic bags may be used provided the bag is placed in a protective container prior to shipping to prevent puncturing and to contain all material that may leak out during shipping. Aluminum or aluminum alloy containers, ordinary cloth sacks, cans, used bottles, or jars shall not be used. Shipping in glass containers is not recommended unless required due to sample reactivity with other container types.

The contents of each blend container shall be clearly labeled and identified with the type of material, lot number, source, and date of sampling. Shipping containers shall also be labeled. The lids of containers shall not be marked since the lids can be readily interchanged and leading to confusion. Any required regulatory identification or documentation shall be enclosed or securely attached to the container. All hazardous material samples shall be packaged and labeled in accordance with all regulatory requirements.

4.8 Sample Preparation Prior to Testing

Upon arrival at the testing location, the samples shall be closely examined to ensure they have remained sealed during shipment and are not contaminated.

If the sample was not shipped in a leak-proof container, the sample shall be transferred into a suitable, leak-proof container. The container shall be properly labeled, dated, and stored in a dry place where room temperatures remain fairly constant. Repackaging shall be indicated. At the time of testing, each sample shall be examined for quality and thoroughly blended just prior to slurry preparation. If the sample container is not leak-proof, contamination of the sample or weathering of hygroscopic materials is possible. Test results interpretation should take this into consideration. Check the sample specific gravity for comparison to the manufacturer's provided data. For blend samples, check the specific gravity against a lab-prepared sample of known component percentages.

Shelf life(s) for all samples shall be provided by the supplier or manufacturer. If unknown, use of any cement additive that has been stored for longer than 1 year is not recommended.

4.9 Sample Disposal

Sample disposal shall comply with all regulatory requirements.

5 Preparation of Slurry

5.1 General

The preparation of cement slurries varies from that of classical solid/liquid mixtures due to the reactive nature of cement. Shear rate and time at shear are important factors in the mixing of cement slurries. Varying these parameters has been shown to affect slurry performance properties.

The procedure described in this section is recommended for the laboratory preparation of slurries that require no special mixing conditions. If large slurry volumes are needed for a test series, use the alternative method for slurry preparation given in Annex A. Annex G (informative) describes alternative procedures to prepare lightweight cement slurries with hollow microspheres or cement slurries with excess foaming tendencies requiring de-airing.

5.2 Apparatus

5.2.1 General

Calibration of apparatuses used for the preparation of cement slurries shall follow Annex B.

5.2.2 Balances

Balances shall conform to requirements specified in Annex B.

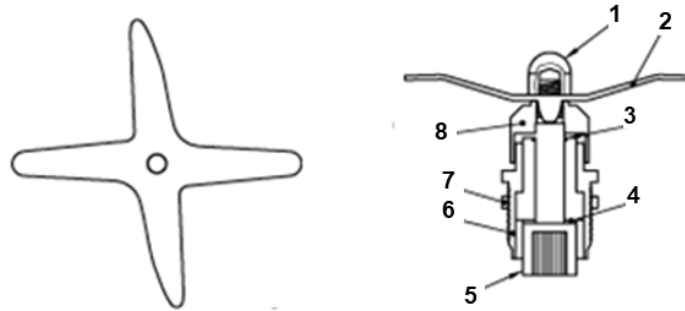
5.2.3 Mixing Device

The mixing device for the preparation of well cement slurries shall be a 1-L (1-qt) size, bottom-drive, blade-type mixer with a timing device able to measure mixing times and preset times of 15 s (optional) and 35 s. The mixing device shall be able to mix cement slurry at $4000 \text{ r/min} \pm 250 \text{ r/min}$ rotational speed and at $12,000 \text{ r/min} \pm 500 \text{ r/min}$ rotational speed.

An example of a mixing device in common use for preparation of slurries is shown in Figure 2. The blender container and the blender blade (see Figure 3, Key 2) shall be constructed of durable, corrosion-resistant material. The mixing-blade assembly (see Figure 3) shall be constructed in such manner that the blade can be removed for weighing and changing. The blade shall be mounted with its sharp edge on the leading-edge rotation. According to Annex B, the mixing blade shall be weighed initially and replaced with an unused blade if observed blade deformation has occurred or after blade has lost 10 % of its mass. If the mixing device leaks at any time during the mixing procedure, the contents shall be discarded, the leak repaired, and the procedure restarted.



Figure 2—Example of a Typical Cement-mixing Device

**Key**

- | | |
|--|---------------------|
| 1 cap nut | 5 socket head shaft |
| 2 blade (installed with tapered edge down) | 6 bearing holder |
| 3 O-ring | 7 hexagonal nut |
| 4 thrust washer | 8 bearing cap |

Figure 3—Common Blade Assembly**5.2.4 Pressurized Consistometer or Atmospheric Consistometer**

Any pressurized consistometer as referenced in Section 9 or Annex C, or alternatively an atmospheric consistometer as referenced in API 10A, may be used for cement slurry conditioning.

5.2.5 Temperature-measuring Device

A thermometer or a thermocouple with a minimum range from $-20\text{ }^{\circ}\text{C}$ to $105\text{ }^{\circ}\text{C}$, or $0\text{ }^{\circ}\text{F}$ to $220\text{ }^{\circ}\text{F}$, with minimum scale divisions not exceeding $1\text{ }^{\circ}\text{C}$ ($2\text{ }^{\circ}\text{F}$) may be used in an atmospheric consistometer.

A thermocouple with a range of $-20\text{ }^{\circ}\text{C}$ up to at least $205\text{ }^{\circ}\text{C}$, or $0\text{ }^{\circ}\text{F}$ to at least $400\text{ }^{\circ}\text{F}$, or above the range limitation of the equipment shall be used in a pressurized consistometer.

5.2.6 Timer

A stopwatch or electric timer with time indicated in minutes and seconds shall be used. Timers incorporated into mixing devices shall meet Annex B requirements.

5.3 Procedure**5.3.1 Density Determination of Components****5.3.1.1 General**

The density of different batches of cement can vary due to natural variations in the composition of the raw materials used in the manufacturing process. Portland cement density may vary from 3100 kg/m^3 to 3250 kg/m^3 (25.87 lbm/ft^3 to 27.12 lbm/ft^3). This can result in variation in slurry densities by as much as 34 kg/m^3 (0.28 lbm/gal) for slurries with constant water-to-solids ratios. The density of mix water can also vary, depending on the source, resulting in slurry density inconsistencies. Determination of the density of all components of the slurry shall be necessary to properly calculate the required amounts for slurry preparation.

5.3.1.2 Density of Cement and Dry Additives

The density of the cement and any dry additives can be determined by the use of a gas pycnometer (also known as stereopycnometer). Alternatively, a Le Chatelier flask as outlined in ASTM C188 may be used for determining the density of these materials.

5.3.1.3 Density of Mix Water and Liquid Additives

The density or relative density of the mix water and any liquid additives may be determined by the use of a hydrometer as outlined in API 13J [2]. Alternatively, a pycnometer may be used for determining the density of these materials.

NOTE Two types of hydrometers can be used, one type is directly measuring a fluid density (see 3.1.14), and the second one is measuring a relative density (see 3.1.36).

5.3.2 Laboratory Slurry Design Calculations

5.3.2.1 General

For the purpose of laboratory slurry design calculations, 1 cm³ is equivalent to 1 mL. Fresh water density at 23 °C (73 °F) is considered at 0.9976 kg/L (8.325 lbm/gal).

NOTE Fresh water, i.e. tap water, density is higher than distilled water [0.9975 kg/L at 23 °C (8.324 lbm/gal at 73.4 °F)].

Laboratory cement, additives, and mix water requirements (see 5.3.3) may be calculated by use of the formulas based on slurry design recipes per Equation (21) and by Equations (22) to (26) in SI units or by Equations (27) to (31) in USC units. Alternatively, suitable equations may also be used to calculate laboratory requirements.

Slurry composition is based on additive concentrations expressed for solids in kilograms per metric ton of cement (1 metric ton = 1000 kg) or in percent by weight of cement (BWOC) and for liquids in liters per metric ton of cement (gallons per sack of cement) or liters per cubic meter (gallons per barrel) of mix water.

In SI units, based on a slurry design that includes solid additives or liquid additives or both, calculations are provided in 5.3.2.2 [Equations (1) to (8)]; mix water requirement, if not given, is calculated by Equation (9) or (10). The slurry yield (V_s) is calculated based on Equation (3).

In USC units, based on a slurry design that includes solid additives or liquid additives or both, calculations are provided in 5.3.2.3 [Equations (11) to (18)]; mix water requirement, if not given, is calculated by Equation (19) or (20). The slurry yield (V_s) is calculated based on Equation (13).

NOTE Design slurry calculations and equations based on design concentrations by weight by metric ton of cement or in percent BWOC and volume by metric ton of cement (sack of cement) are also applicable to slurry design with concentrations expressed by weight or in percent by weight of blend (BWOB) and volume per metric ton of blend (sack of blend, sack weight shall be defined).

5.3.2.2 Sodium Chloride Additive in Cement Slurry

The measurement of sodium chloride (NaCl) as an additive in cement slurry is normally defined in percent by weight of water (BWOW). Other salts (e.g. calcium chloride, potassium chloride) are defined in percent BWOC unless noted otherwise by the practitioner.

For testing purposes, if sodium chloride is included in a slurry formulation, it is recommended to consider mix water as a sodium chloride brine and to calculate mix water mass from brine density and brine volume requirement. An alternate method to calculate the sodium chloride in the slurry is to use a graph or table containing an equivalent relative density [specific gravity (SG)] for the actual sodium chloride when it is in

solution. Using this method, sodium chloride can be treated as any other additive as long as the concentration is BWOW.

5.3.2.3 SI Units Design Calculations

Density of slurry, ρ_s , expressed in kilograms per liter shall be given by Equation (1):

$$\rho_s = \frac{m_s}{V_s} \quad (1)$$

where

m_s is the slurry mass prepared using 1 metric ton (1000 kg) of cement (including mix water and additives), expressed in kilograms per metric ton of cement, as given by Equation (2):

$$m_s = m_c + m_w + \sum m_{ad.liq} + \sum m_{ad.sol} \quad (2)$$

and

V_s is the slurry yield prepared with 1 metric ton (1000 kg) of cement, in liters per metric ton of cement, as given by Equation (3):

$$V_s = V_c + V_w + \sum V_{ad.liq} + \sum V_{ad.sol} \quad (3)$$

where for Equation (2) and Equation (3), respectively:

m_c is the cement mass of 1 metric ton (1000 kg) of cement, expressed in kilograms;

V_c is the cement volume of 1 metric ton of cement, expressed in liters;

m_w is the mix water mass, expressed in kilograms per metric ton of cement;

V_w is the mix water volume, expressed in liters per metric ton of cement;

$\sum m_{ad.liq}$ is the sum of masses for all liquid additives ($V_{ad.liq}$), expressed in kilograms per metric ton of cement;

$\sum V_{ad.liq}$ is the sum of volume concentrations for all liquid additives, expressed in liters per metric ton of cement;

$\sum m_{ad.sol}$ is the sum of mass concentrations for all solid additives, expressed in kilograms per metric ton of cement;

$\sum V_{ad.sol}$ is the sum of volumes for all solid additives ($m_{ad.sol}$), expressed in liters per metric ton of cement.

Masses of solid additives can be defined by solid additive concentrations, $c_{ad.sol}$, expressed in percent BWOC. In that case, each solid additive mass of additive per metric ton of cement ($m_c = 1000$ kg) is given by Equation (4):

$$m_{\text{ad.sol}} = 0.01 \times m_c \times c_{\text{ad.sol}} = 10 \times c_{\text{ad.sol}} \quad (4)$$

Masses are related to volumes, and volumes to masses.

Mass of mix water, m_w , expressed in kilograms per metric ton of cement is given by Equation (5):

$$m_w = V_w \times \rho_w \quad (5)$$

where

ρ_w is the density of mix water, expressed in kilograms per liter.

Volume of 1 metric ton of cement, V_c (mass m_c), is given by Equation (6):

$$V_c = \frac{m_c}{\rho_c} = \frac{1000}{\rho_c} \quad (6)$$

where

ρ_c is the density of cement, expressed in kilograms per liter.

For each additive, liquid or solid:

mass of a liquid additive, $m_{\text{ad.liq}}$, expressed in kilograms per metric ton of cement is given by Equation (7):

$$m_{\text{ad.liq}} = V_{\text{ad.liq}} \times \rho_{\text{ad.liq}} \quad (7)$$

where

$V_{\text{ad.liq}}$ is the liquid additive volume concentration, expressed in liters per metric ton of cement;

$\rho_{\text{ad.liq}}$ is the density of the liquid additive, expressed in kilograms per liter;

and volume of a solid additive, $V_{\text{ad.sol}}$, expressed in liters per metric ton of cement is given by Equation (8):

$$V_{\text{ad.sol}} = \frac{m_{\text{ad.sol}}}{\rho_{\text{ad.sol}}} = \frac{10 \times c_{\text{ad.sol}}}{\rho_{\text{ad.sol}}} \quad (8)$$

where

$m_{\text{ad.sol}}$ is the solid additive mass concentration, expressed in kilograms per metric ton of cement;

$c_{\text{ad.sol}}$ is the solid additive concentration, expressed as a percentage BWOC;

$\rho_{\text{ad.sol}}$ is the density of the solid additive, expressed in kilograms per liter.

When the mix water requirement is not provided, calculate the mix water volume requirement, V_w , expressed in liters per metric ton of cement (mass $m_c = 1000$ kg) by solving Equation (1) using Equations (2) to (8). Mix water requirement shall be given by Equation (9):

$$V_w = \frac{m_c \left(1 - \rho_s / \rho_c\right) - \sum \left[V_{ad.liq} \left(\rho_s - \rho_{ad.liq} \right) \right] + \sum \left[m_{ad.sol} \left(1 - \rho_s / \rho_{ad.sol} \right) \right]}{(\rho_s - \rho_w)} \quad (9)$$

and the use of fresh water at 23 °C (73 °F) (density 0.9976 kg/L) in Equation (9) results in Equation (10):

$$V_w = \frac{1000 \times \left(1 - \rho_s / \rho_c\right) - \sum \left[V_{ad.liq} \left(\rho_s - \rho_{ad.liq} \right) \right] + \sum \left[m_{ad.sol} \left(1 - \rho_s / \rho_{ad.sol} \right) \right]}{(\rho_s - 0.9976)} \quad (10)$$

where

- $V_{ad.liq}$ is the volume concentration of a liquid additive, expressed in liters per metric ton of cement (1000 kg); all liquid additives shall be considered by the calculation;
- $m_{ad.sol}$ is the mass concentration of a solid additive, expressed in kilograms per metric ton of cement (1000 kg) or calculated by Equation (4) and solid additive concentration, $c_{ad.sol}$, expressed in percent; all solid additives shall be considered by the calculation;
- ρ_s is the density of slurry, expressed in kilograms per liter;
- ρ_c is the density of cement, expressed in kilograms per liter;
- ρ_w is the density of mix water, expressed in kilograms per liter;
- $\rho_{ad.liq}$ is the density of the liquid additive, expressed in kilograms per liter;
- $\rho_{ad.sol}$ is the density of the solid additive, expressed in kilograms per liter.

Then mix water mass expressed in kilograms per metric ton of cement is calculated by Equation (5).

Slurry yield, V_s , expressed in liters per metric ton of cement shall be given by Equation (3).

5.3.2.4 USC Units Design Calculations

USC equations are based on 1 sack (1 ft³ ≡ 3.59 gal) of cement normally considered to be 94 lbm (see 3.1.37). For a cement blend, the equivalent sack weight shall be defined by the user and Equation (13) modified accordingly. Density of slurry, ρ_s , expressed in pounds-mass per gallon shall be given by Equation (11):

$$\rho_s = 0.1337 \times \frac{m_s}{V_s} \quad (11)$$

where

- m_s is the slurry mass prepared with 1 sack of cement (including mix water and additives), as given by Equation (12):

$$m_s = m_c + m_w + \sum m_{ad.liq} + \sum m_{ad.sol} \quad (12)$$

and

V_s is the slurry yield prepared with 1 sack of cement (94 lbm), in cubic feet per sack of cement, as given by Equation (13):

$$V_s = 0.1337 \times (V_c + V_w + \sum V_{ad.liq} + \sum V_{ad.sol}) \quad (13)$$

where for Equation (12) and Equation (13), respectively:

m_c is the cement mass of 1 sack of cement, taken to be 94 lbm;

V_c is the cement volume of 1 sack of cement, expressed in gallons per sack;

m_w is the mix water mass, expressed in pounds-mass per sack of cement;

V_w is the mix water volume, expressed in gallons per sack of cement;

$V_{ad.liq}$ is a liquid additive volume concentration, expressed in gallons per sack of cement; all liquid additives shall be considered by the calculation;

$m_{ad.sol}$ is the mass of a solid additive for 1 sack of cement based on its concentration, $c_{ad.sol}$, expressed in percent BWOC as given by Equation (14); all solid additives shall be considered by the calculation;

$$m_{ad.sol} = 0.01 \times m_c \times c_{ad.sol} = 0.94 \times c_{ad.sol} \quad (14)$$

where

$m_{ad.liq}$ is the mass of the liquid additive, expressed in pounds-mass per sack of cement; all liquid additives shall be considered by the calculation;

$V_{ad.sol}$ is the volume of the solid additive, expressed in gallons per sack of cement; all solid additives shall be considered by the calculation.

NOTE Slurry yield, V_s , can be expressed in gallons per sack of cement; in that case, the coefficient 0.1337 is not required in Equation (13) to calculate its value. To calculate cement slurry density expressed in pounds-mass per gallon using Equation (11), the coefficient 0.1337 is omitted.

Volumes are related to masses, and masses to volumes.

Volume of 1 sack of cement, V_c (mass m_c normally taken to 94 lbm), expressed in gallons per sack of cement is given by Equation (15):

$$V_c = m_c \times v_{c.abs} = 94 \times v_{c.abs} \quad (15)$$

where

$v_{c.abs}$ is the absolute volume of cement, expressed in gallons per pound-mass.

Volume of mix water, V_w , expressed in gallons per sack of cement is given by Equation (16):

$$m_w = V_w \times \rho_w \quad (16)$$

where

ρ_w is the density of mix water, expressed in pounds-mass per gallon;

Mass of a liquid additive, $m_{ad.liq}$, expressed in gallons per sack of cement is given by Equation (17):

$$m_{ad.liq} = V_{ad.liq} \times \rho_{ad.liq} \quad (17)$$

where

$V_{ad.liq}$ is the liquid additive volume concentration, expressed in gallons per sack of cement; all liquid additives shall be considered by the calculation;

$\rho_{ad.liq}$ is the density of the liquid additive, expressed in pounds-mass per gallon.

The volume of a solid additive, $V_{ad.sol}$, expressed in gallons per sack of cement (mass m_c normally taken to 94 lbm) is given by Equation (18):

$$V_{ad.sol} = 0.01 \times m_c \times c_{ad.sol} \times n_{ad.sol} = 0.94 \times c_{ad.sol} \times n_{ad.sol} \quad (18)$$

where

$c_{ad.sol}$ is the solid additive concentration expressed in percent BWOC;

$V_{ad.abs}$ is the absolute volume of the solid additive, expressed in gallons per pound-mass;

When the mix water requirement is not provided, calculate the mix water volume requirement, V_w , expressed in gallons per sack of cement (m_c normally taken to 94 lbm) by solving Equation (11) using Equations (12) to (18). Mix water requirement shall be given by Equation (19):

$$V_w = \frac{m_c \times [1 - (\rho_s \times V_{c.abs})] - \sum [V_{ad.liq} (\rho_s - \rho_{ad.liq})] + (0.01 \times m_c) \times \sum [c_{ad.sol} (1 - (\rho_s \times V_{ad.abs}))]}{(\rho_s - \rho_w)} \quad (19)$$

and the use of fresh water at 23 °C (73 °F) (density 8.325 lbm/gal) in Equation (19) results in Equation (20):

$$V_w = \frac{94 \times [1 - (\rho_s \times V_{c.abs})] - \sum [V_{ad.liq} (\rho_s - \rho_{ad.liq})] + 0.94 \times \sum [c_{ad.sol} (1 - (\rho_s \times V_{ad.abs}))]}{(\rho_s - 8.325)} \quad (20)$$

where

ρ_s is the density of slurry, expressed in pounds-mass per gallon;

$V_{c.abs}$ is the absolute volume of cement, expressed in gallons per pound-mass;

$V_{ad.liq}$	is a liquid additive volume concentration, expressed in gallons per sack of cement; all liquid additives shall be considered by the calculation;
$\rho_{ad.liq}$	is the density of the liquid additive, expressed in pounds-mass per gallon;
$c_{ad.sol}$	is the concentration of a solid additive, expressed in percent BWOC; all solid additives shall be considered by the calculation;
$V_{ad.abs}$	is the absolute volume of the solid additive, expressed in gallons per pounds-mass;
ρ_w	is the density of mix water, expressed in pounds-mass per gallon.

Mix water mass expressed pounds-mass per sack of cement is then calculated using Equation (16).

Slurry yield, V_s , expressed in cubic feet per sack of cement is given by Equation (13).

5.3.3 Laboratory Slurry Design—Mass Calculations

5.3.3.1 General

A slurry volume of 600 mL shall be mixed based on mix water, cement, and additives mass requirements expressed in grams.

NOTE A slurry volume of approximately 600 mL can be sufficient to perform most laboratory test procedures while not overfilling the mixing container.

Mass requirements for 600 mL shall be calculated as given by Equation (21), based on Equations (1) and (2) expressed in SI units or based on Equations (11) and (12) expressed in USC units.

$$m_{s,600} = m_{c,600} + m_{w,600} + \sum m_{ad.liq,600} + \sum m_{ad.sol,600} \quad (21)$$

where

$m_{s,600}$	is the mass of 600 mL of slurry to be mixed, expressed in grams;
$m_{c,600}$	is the cement mass to be mixed for 600 mL of slurry, expressed in grams;
$m_{w,600}$	is the mix water mass to be mixed for 600 mL of slurry, expressed in grams;
$\sum m_{ad.liq,600}$	is the sum of masses for all liquid additives to be mixed for 600 mL of slurry, expressed in grams;
$\sum m_{ad.sol,600}$	is the sum of masses for all solid additives masses to be mixed for 600 mL of slurry, expressed in grams.

5.3.3.2 SI Units Mass Calculations

As per slurry composition and yield calculation, to mix a 600 mL sample, the mass requirements—expressed in grams—shall be calculated using Equations (22) to (26).

Mass of cement ($m_{c,600}$) to be mixed is given by Equation (22):

$$m_{c,600} = \frac{600}{V_s} \times 1000 \quad (22)$$

into the mass of mix water ($m_{w,600}$) as given by Equation (23):

$$m_{w,600} = \frac{600}{V_s} \times V_w \times \rho_w \quad (23)$$

Equation (23) is reduced when mixed with fresh water at 23 °C (density 0.9976 kg/L) to Equation (24):

$$m_{w,600} = \frac{598.56}{V_s} \times V_w \quad (24)$$

The masses of each liquid additives ($m_{ad.liq,600}$) and each solids additives ($m_{ad.sol,600}$) to be mixed are given respectively by Equation (25) and Equation (26):

$$m_{ad.liq,600} = \frac{600}{V_s} \times V_{ad.liq} \times \rho_{ad.liq} \quad (25)$$

$$m_{ad.sol,600} = \frac{600}{V_s} \times m_{ad.sol} \times \rho_{ad.sol} \quad (26)$$

where

V_s	is the slurry yield prepared with 1 metric ton of cement (1000 kg), expressed in liters per metric ton of cement;
V_w	is the mix water volume per 1 metric ton of cement (1000 kg), expressed in liters per metric ton of cement;
ρ_w	is the density of mix water, expressed in kilograms per liter;
$V_{ad.liq}$	is a liquid additive volume concentration per 1 metric ton of cement (1000 kg), expressed in liters per metric ton of cement;
$\rho_{ad.liq}$	is the density of a liquid additive, expressed in kilograms per liter;
$m_{ad.sol}$	is a solid additive mass concentration per 1 metric ton of cement (1000 kg), expressed in kilograms per metric ton of cement, or as given by Equation (4) when solid additive is based on its concentration, $c_{ad.sol}$, in percent BWOC.

5.3.3.3 USC Units Mass Calculations

As per slurry composition and yield calculation, to mix a 600 mL sample the mass requirements expressed in grams shall be calculated using Equations (27) to (31) [based on a 94 lbm sack (3.59 gal) of cement].

Mass of cement ($m_{c,600}$) to be mixed as given by Equation (27):

$$m_{c,600} = \frac{9.611}{V_s} \times 94 = \frac{903.4}{V_s} \quad (27)$$

into the mass of mix water ($m_{w,600}$) as given by Equation (28):

$$m_{w,600} = \frac{9.611}{V_s} \times V_w \times \rho_w \quad (28)$$

Equation (27) is reduced when mixed with fresh water at 73 °F (density 8.325 lbm/gal) to Equation (29):

$$m_{w,600} = \frac{80.01}{V_s} \times V_w \quad (29)$$

The masses for each liquid additives ($m_{ad.liq,600}$) and each solids additives ($m_{ad.sol,600}$) to be mixed are given respectively by Equation (30) and Equation (31):

$$m_{ad.liq,600} = \frac{9.611}{V_s} \times V_{ad.liq} \times \rho_{ad.liq} \quad (30)$$

$$m_{ad.sol,600} = \frac{0.09611}{V_s} \times 94 \times c_{ad.sol} = \frac{9.034}{V_s} \times c_{ad.sol} \quad (31)$$

where

V_s is the slurry yield prepared with 1 sack of cement (normally, 94 lbm), expressed in cubic feet per sack of cement;

V_w is the mix water volume, expressed in gallons per sack of cement;

ρ_w is the density of mix water, expressed in pounds-mass per gallon;

$V_{ad.liq}$ is a liquid additive volume concentration per 1 sack of cement, expressed in gallons per sack of cement;

$\rho_{ad.liq}$ is the density of the liquid additive, expressed in pounds-mass per gallon;

$c_{ad.sol}$ is the concentration of a solid additive, expressed in percent BWOC;

9.611 is a unit conversion of SI to USC.

5.3.4 Temperature of Water and Cement

The temperature of the mix water, and dry cement or cement blend, should be a representation of field mixing conditions. If field conditions are unknown, the temperature of the mix water (including any premixed additives) and dry cement should be 23 °C ±1 °C (73 °F ±2 °F) immediately prior to mixing. In all cases, the temperatures of the mix water and dry cement shall be measured and documented.

NOTE Temperature of mixing and blending devices should also be a representation of field mixing conditions.

5.3.5 Mix Water and Mix Fluid

Water composition can affect slurry performance. Water from the field source should be used. If field mix water is unavailable, water of similar composition should be used. If field mix water composition is unknown, distilled or tap water may be used. Deionized water should be avoided due to known contributions to inconsistent slurry behavior and additive behavior, especially when pre-hydrating.

The type of mix water shall be documented in the lab report. The mix water shall be weighed into a clean, dry blender container. If used, additives may be weighed into the water in the blender container or may be weighed separately and added to the water while agitating at low speed. A vortex should be observed in the container without air entrainment. No extra water shall be added to compensate for evaporation or wetting.

5.3.6 Mixing of Cement and Water

A slurry volume of approximately 600 mL should be sufficient to perform most laboratory test procedures while not overfilling the blender container. The following procedure and instructions should be applied.

- a) Weigh dry materials and then blend uniformly prior to adding them to the mix fluid.
- b) Place the blender container with the mix water and liquid additives (if previously added) on the blender base after weighing the required quantities of each.
- c) Turn on the motor and maintain at 4000 r/min $\pm$ 250 r/min. If additives are present in the mix water, stir at the above rotational speed to thoroughly disperse them prior to the addition of cement.

In some cases, additives (dry or liquid) may be added to the mix water in the field. In such cases, add the additives to the mix water while mixing at low speed at which a slight vortex is observed.

In certain cases, the order of addition of the additives to the mix water can be critical, in which case add and mix the additives in the same order to take place during field mixing. Document any special mixing procedure mixing time or hydration time for pre-hydrated additive.

- d) While mixing at 4000 r/min $\pm$ 250 r/min, add the cement or cement/dry additive blend at a uniform rate to completely wet the solids in not more than 15 s, if possible; document the actual time.

Some slurry designs may take longer to completely wet the cement blend; however, the time used to add the blend shall be kept to a minimum. If more than 15 s were required to add the cement blend to the water, document that time.

- e) Place the cover on the mixing container and continue mixing at 12,000 r/min $\pm$ 500 r/min for 35 s $\pm$ 1 s. Measure and document the rotational speed under load.

5.4 Test Fluid Conditioning

5.4.1 General

Conditioning simulates the anticipated conditions the test fluid will encounter during placement into the wellbore. Conditioning shall use a representative test schedule, which includes the anticipated temperatures and pressures in the well, that reflects expected conditions under which the test fluid will be exposed during placement. Conditioning should include anticipated surface atmospheric pressure retention conditions (time and temperature) if batch mixing is to be used. Alternatively, the conditioning can be done at atmospheric pressure.

5.4.2 Procedure: Pressurized Conditioning

The following procedure shall be applied using a pressurized consistometer (see 5.2.4).

- a) After mixing the slurry according to 5.3.6, pour the test fluid into the slurry container of a pressurized consistometer. Start the test by applying the initial pressure and starting the temperature ramp. No more than 5 min shall have elapsed after mixing the slurry and the beginning of the test. If surface batch mixing time is to be included in the schedule, this can be done at the minimum initial pressure for consistometer operation [e.g. 0.35 MPa (50 lbf/in.²)] and appropriate surface mixing temperature.
- b) Heat to T_{PBHC} in accordance with the pressure/temperature schedule designed to simulate conditions in the well (see 9.4). During the pressure and temperature ramp, the temperature and pressure shall be maintained within ± 3 °C (± 5 °F) and ± 2 MPa (± 300 lbf/in.²) of the appropriate temperature and pressure target vs elapsed time. Within 10 min after the end of the ramp, temperature and pressure shall be within ± 1 °C (± 2 °F) and ± 0.7 MPa (± 100 lbf/in.²) of the specified values.
- c) Hold test temperature and pressure for 30 min ± 30 s to allow the test fluid temperature to reach equilibrium. This hold time may be modified to simulate cementing operations. A proper note shall be made of this in the test report.
- d) If the test temperature is greater than 88 °C (190 °F), cool the test fluid as quickly as possible to 88 °C (190 °F). If the boiling point of water at the testing facility is less than 100 °C (212 °F), adjust temperatures accordingly. A common practice for some labs is to cool to 82 °C (180 °F) before proceeding. Maintain test pressure while decreasing the temperature. When 88 °C (190 °F) is reached, release the pressure slowly [about 1400 kPa/s (200 lbf/in.²·s)].
- e) Remove the slurry container from the consistometer. Keep the container upright to prevent oil from mixing with the test fluid. Do not cool the slurry container further after removal from the pressurized consistometer.
- f) Remove the flange ring and the backup plate and syringe or blot oil from the top of the diaphragm.
- g) Remove the diaphragm and the support ring. Syringe or blot the top of the test fluid with an absorbent cloth or paper towel to remove any visible oil. If the contamination is severe, discard the test fluid and condition a fresh test fluid.
- h) Remove the paddle and stir the test fluid briskly with a spatula to ensure it is uniform.
- i) Continue with the desired test.

5.4.3 Procedure: Atmospheric Pressure Conditioning

Atmospheric consistometer or a pressurized consistometer (see 5.2.4) run at atmospheric pressure may be used. This procedure should be limited to a maximum temperature of 88 °C (190 °F). It is preferred that at temperatures above 60 °C (140 °F), pressurized conditioning be used. If the boiling point of water at the testing facility altitude is less than 100 °C (212 °F), adjust conditioning temperatures accordingly. A common practice for some labs is to limit all atmospheric pressure procedures to 82 °C (180 °F).

NOTE Cement slurry conditioned in an atmospheric consistometer may perform differently than slurry conditioned in a pressurized consistometer regardless of the temperature below the limits of the atmospheric consistometer.

The procedure shall be as per the following.

- a) Within 1 min after mixing according to 5.3.6 using test fluid, fill the slurry container of the atmospheric pressure consistometer to the fill line.

- b) Heat the test fluid from ambient temperature or a temperature that simulates field surface mixing temperature to T_{PBHC} in accordance with the thickening-time schedule that most closely simulates actual field conditions. If the atmospheric consistometer is not capable of heating on a controlled temperature ramp, heat as rapidly as the instrument is capable and record the time to T_{PBHC} . If the atmospheric pressure consistometer is not equipped to measure test fluid temperature, the bath shall be heated in accordance with the appropriate schedule.
- c) With test fluids containing additives that are not affected by sudden temperature increases, the slurry container may be placed in the heating bath preheated to the test temperature [$\pm 3^\circ\text{C}$ ($\pm 5^\circ\text{F}$)] or another temperature that is appropriate. Care shall be taken to prevent unusual behavior such as gelation, increase in free fluid, sedimentation, or poor response to additives such as retarders and fluid-loss control agents when conditioning the fluid.
- d) After the slurry reaches test temperature (the temperature must be verified by measurement), hold the test temperature for 30 min ± 30 s to allow the test fluid temperature to reach equilibrium. This hold time may be modified to simulate cementing operations. However, a proper note shall be made of this in the test report.
- e) Remove the paddle and stir the test fluid briskly with a spatula to ensure it is uniform.
- f) Continue with the desired test.

6 Determination of Slurry Density

6.1 Apparatus

The preferred apparatus for measuring the density of a cement slurry shall be the pressurized fluid density balance (see Figure 4). By pressurizing the sample cup, any entrained air is decreased to a negligible volume, thus providing a slurry density measurement more representative of the true slurry density. The apparatus shall be calibrated according to the requirements found in Annex B.

6.2 Procedure

The following procedure shall be used to determine a slurry density using a pressurized fluid density balance (Figure 4). The fluid density balance shall be clean and dry.

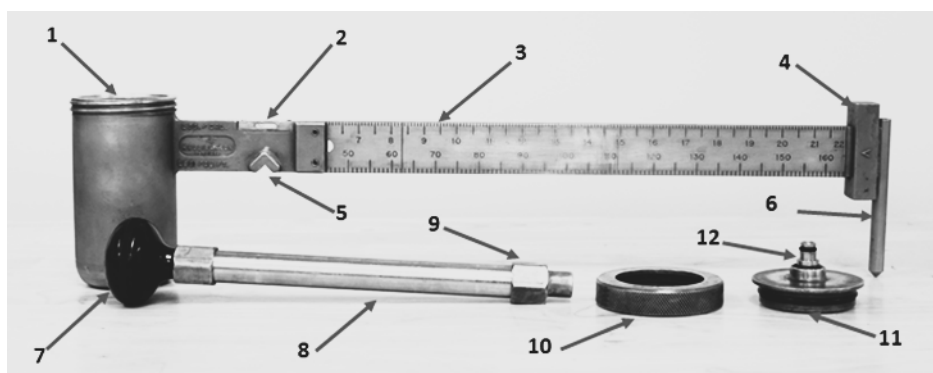
- a) The sample cup shall be filled to a level slightly below the upper edge of the cup.
- b) Place the lid on the cup with the check valve in the down (open) position. Push the lid downward into the mouth of the cup until surface contact is made between the outer skirt of the lid and the upper edge of the cup. Expel excess slurry through the check valve. If slurry does not expel from the check valve, remove lid and add additional slurry. Replace the lid and repeat Step b).

Caution—Slurry can be expelled forcibly; use appropriate personal protective equipment (PPE).

- c) After the lid has been placed on the cup, pull the check valve up into the closed position, rinse off the cup and threads with water, and screw the threaded ring on the cup.
- d) The pressurizing pump is similar in operation to a syringe. Fill the pump by submerging the nose of the pump assembly in the slurry with the piston rod in the completely downward position. Then draw the piston rod upward, thereby filling the pump cylinder with slurry. Return the piston to the downward position to expel air from the piston and then draw the rod upward to refill the pump cylinder with slurry.
- e) Push the nose of the pump onto the mating O-ring surface of the check valve. Pressurize the sample cup by applying a downward force on the pump cylinder housing in order to hold the check valve down (open)

and at the same time push the piston rod downward, forcing the slurry into the cup. Maintain approximately 230 N (50 lbf) force or greater on the piston rod.

- f) The check valve in the lid is pressure actuated, which means the pressure in the cup closes the valve and keeps it closed. Close the valve by gradually lifting the cylinder housing of the pressurizing pump while maintaining pressure on the piston rod. When the check valve closes, release pressure on the piston rod before disconnecting the pump. Check to ensure the valve has closed. Fluid leaking out of the check valve indicates it is not fully closed or the interior O-ring is defective. Correct the problem and restart the test.
- g) Rinse off the exterior of the cup and wipe dry. Then place the V-shape pivot (Figure 4, Key 5) of the instrument on its knife edge. Move the sliding weight right or left until the beam is balanced. The beam is balanced when the bubble is centered in the sight glass. Obtain the density by reading directly one of the four calibrated scales on the arrow side of the sliding weight; density can be read in units of grams per milliliter using the relative density (specific gravity) scale, pounds per gallon, pounds per cubic foot, or as a fluid gradient in pounds-force per square inch and per 1000 ft of vertical depth.
- h) After the measurement, reconnect the pump assembly and push downward on the pump cylinder housing to release the pressure. Empty the cup and pump assembly and thoroughly clean all components. Do not clean the cup and balance using abrasive methods or acids as this may eventually affect the calibration.



Key

1 sample cup	7 plunger
2 bubble level	8 pump's cylinder housing
3 scaled balance beam	9 pump nose
4 sliding weight	10 lid locking ring
5 V-shape pivot to balance on knife edge	11 lid
6 tare adjustment stop	12 check valve

Figure 4—Typical Pressurized Fluid Density Balance

7 Well-simulation Compressive-strength Tests

7.1 General

This section presents procedures for well-simulation compressive-strength testing.

7.2 Sampling

Obtain samples of the cement, additives, and mix water in accordance with Section 4.

7.3 Apparatus

7.3.1 General

Unless otherwise noted, all apparatuses shall be calibrated as per the requirements given in Annex B.

Molds and testing machines for compressive strength tests shall conform to the requirements in ASTM C109/C109M, with the exception described in 7.3.2 and 7.3.3.

7.3.2 Cube Molds

Cement specimens shall be prepared using 50-mm cube or 2-in. cube molds. Exceptions to ASTM C109/C109M shall be as per the following.

- a) Molds may be separable into more than two parts.
- b) Dimensions for 50-mm cube and 2-in. cube molds shall be manufactured in accordance with ASTM C109/C109M. Verification of molds in use shall conform to Annex B.

The molds shall be made of hard corrosion-resistant materials.

Cube-mold baseplate and cover plate shall be of corrosion-resistant materials (brass, stainless steel). They shall have a minimum thickness of 5 mm (0.2 in.). Grooves may be incorporated into the surface of the cover plate contacting the surface of the cement.

7.3.3 Compressive-strength-testing Machine (Load Frame)

Exceptions to ASTM C109/C109M are as follows.

- a) The two surfaces of the bearing blocks shall have a diameter or diagonal of no less than 70.7 mm (2.83 in.).
- b) The specification of the bearing blocks shall be with a Rockwell hardness of no less than 30 HRc.

The testing load frame bearing block above or beneath the tested specimen shall be free to tilt in any direction. The center of the bearing block shall align with the center of the surface of the specimen to assure even loading across the sample surfaces. A hardened metal bearing block shall be used beneath or above the specimen, depending on how the swivel bearing is tilting to minimize wear on the platens. The lower platen shall be inscribed to assist in the placement of the specimen in the center of the platen surface.

7.3.4 Water Curing Bath or Tank

7.3.4.1 General

Use a water bath or a tank having dimensions permitting the complete immersion of molds for compressive-strength test samples in water and capable of maintaining the specified test temperatures within ± 2 °C (± 3 °F). Two types of water curing baths are used for compressive strength testing: atmospheric unpressurized baths and pressurized baths for high-temperature curing under pressure.

7.3.4.2 Atmospheric Pressure Curing Bath

An atmospheric pressure curing bath is a partially enclosed instrument that is not capable of applying pressure. It may have an agitator or circulating system to ensure uniform temperature. Atmospheric pressure curing baths at or below 88 °C (190 °F) may be used for curing samples for compressive-strength testing when higher pressure is not required.

7.3.4.3 Pressurized Curing Chamber

A chamber suitable for curing samples at the appropriate final test temperature and a pressure of at least 21 MPa (3000 lbf/in.²) shall be used. There are models capable of operating at up to 137 MPa (20,000 lbf/in.²). The vessel shall be capable of being heated at the desired rate.

7.3.5 Cooling Bath

An atmospheric pressure water bath designed to cool cement specimens from the curing temperature by submerging samples in water or other chilling fluid maintained at $27\text{ }^{\circ}\text{C} \pm 3\text{ }^{\circ}\text{C}$ ($80\text{ }^{\circ}\text{F} \pm 5\text{ }^{\circ}\text{F}$) or lower shall be used. Samples must be isolated from cooling fluids other than water.

7.3.6 Temperature-measuring System

7.3.6.1 General

The temperature-measuring system shall meet requirements given Annex B. This includes thermometers, thermocouples, temperature controllers on curing baths, curing chambers and cooling baths, and those that are used separate from or are not an integral part of the instrument.

7.3.6.2 Temperature-measuring Device

A thermometer or a thermocouple with a minimum range from $-20\text{ }^{\circ}\text{C}$ up to at least $105\text{ }^{\circ}\text{C}$, or from $-4\text{ }^{\circ}\text{F}$ up to at least $220\text{ }^{\circ}\text{F}$, or above limitation of the equipment, with minimum scale divisions not exceeding $1\text{ }^{\circ}\text{C}$ ($2\text{ }^{\circ}\text{F}$) shall be used.

A thermocouple with a minimum range of $-20\text{ }^{\circ}\text{C}$ to at least $120\text{ }^{\circ}\text{C}$, or from $-4\text{ }^{\circ}\text{F}$ to at least $250\text{ }^{\circ}\text{F}$, may be used in a non-pressurized atmospheric bath.

A thermocouple of range $-20\text{ }^{\circ}\text{C}$ to at least $205\text{ }^{\circ}\text{C}$, or from $-4\text{ }^{\circ}\text{F}$ to at least $400\text{ }^{\circ}\text{F}$, shall be used in a pressurized curing chamber.

7.3.7 Puddling Rod

A corrosion-resistant rod made of a material not reactive with cement slurry, typically with a diameter of 6 mm ± 2 mm ($1/4$ in. ± 0.08 in.) shall be used.

7.3.8 Mold-sealing Grease

Mold-sealing grease should possess the following properties when subjected to anticipated test temperatures and pressures suitable to seal the exterior contact points of the sample molds:

- a) a consistency to permit ease of application,
- b) sealing properties to prevent leakage,
- c) water resistance,
- d) inert to the cement, and
- e) noncorrosive in the temperature range of the test.

7.3.9 Mold-release Agent (Optional)

A thin layer of mold-release agent may be applied to the interior surfaces of the mold to prevent the sample from being damaged when removed from the mold. The mold-release agent shall comply with 7.3.6.

7.3.10 Timer

A stopwatch or electric timer with time indicated in hours, minutes, and seconds shall be used.

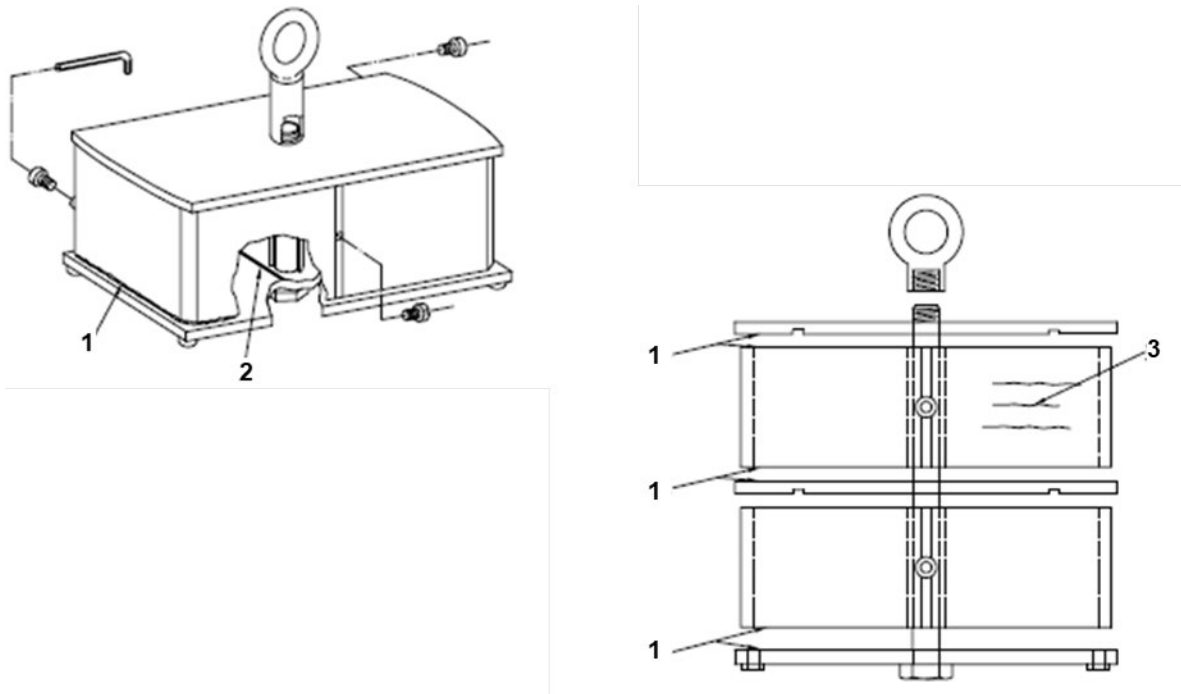
7.3.11 Caliper

A caliper accurate to no less than 0.1 mm (0.004 in.) shall be used to measure dimensions of cement cube specimens.

7.4 Procedure

7.4.1 Preparation of Molds

The base of assembled molds shall be watertight. The interior faces of the molds and the contact surfaces of the plates shall be clean and dry and may be lightly coated with mold-release agent. Avoid beads of sealant on the interior of the mold. See Figure 5.



Key

- 1 grease lightly here
- 2 remove extruded grease
- 3 apply mold-release agent inside sample cavity

Figure 5—Diagram of Mold Preparation

7.4.2 Preparation of Slurry and Filling of Molds

7.4.2.1 Preparation

Cement slurry shall be prepared in accordance with Section 5. If preconditioning is required, then either procedure in 5.4 or 7.5 shall be followed. The procedure in 7.5 is particularly useful to determine the compressive strength at the top of long cement columns.

7.4.2.2 Mold Filling

To prepare samples, the following procedure shall be followed.

- a) Immediately after mixing or conditioning as appropriate, pour the cement slurry into each compartment of the prepared molds in a layer approximately one-half of the mold depth.
- b) Place the slurry in all the specimen compartments before commencing the puddling operation.
- c) Use the puddling rod to puddle efficiently the slurry in an evenly distributed pattern (minimum 30 times per specimen) to remove air bubbles.
- d) After puddling the layer, stir the remaining slurry by hand using a puddling rod or spatula to minimize segregation.

If it is determined that a slurry has severe air entrainment, either via atmospheric vs pressurized density measurement or visual observation, discard slurry and start over after taking steps to remove air entrainment. See G.3.

- e) Fill each mold compartment with cement slurry to overflow and puddle the same as for the first layer.
- f) After puddling, use a straight edge to strike off the excess slurry level with the top of the mold.
- g) Discard specimens in molds that leak.
- h) Place a clean, dry cover plate on top of the mold.

NOTE No less than three cube samples shall be used for each test determination.

7.4.3 Curing

7.4.3.1 Curing Periods

Curing periods are defined according testing conditions and the temperature of the curing vessel.

For curing temperature at or below 88 °C (190 °F), the curing period is the time elapsed from subjecting the specimens to the specified temperature in the curing vessel (or initiating the temperature/pressure schedule for testing above atmospheric pressure) to testing the cured sample for strength. The strength of the cured samples shall be tested within 45 min at the appropriate time, as specified in Table 2 or Table 3, or at a specific designed schedule.

For curing temperature above 88 °C (190 °F), the curing period is the time elapsed from subjecting the specimens to the specified temperature in the curing vessel (or initiating the temperature/pressure schedule for testing above atmospheric pressure) to the point the heating is discontinued and cured samples are allowed to cool.

For specimens cured at atmospheric pressure, the curing period starts when specimens are initially placed in the curing bath preheated to the test temperature.

For specimens cured at above atmospheric pressures, the curing period starts with the initial application of pressure and temperature.

7.4.3.2 Curing at Atmospheric Pressure

To cure samples at atmospheric pressure, the following procedure shall be applied.

- a) After the molds have been filled and covered with the cover plate and within 5 min after mixing of the slurry or slurry conditioning (removal of conditioned slurry from the slurry cup), place them in a curing vessel maintained at the desired curing temperature.

When placed in an atmospheric pressure water bath, raise the molds off the bottom of the bath using a perforated baffle plate, wire rack, or suitable spacers to allow water to completely circulate around the samples during the curing period.

- b) At 45 min $\pm$ 5 min prior to the age at which the samples are to be tested, remove the molds from the curing vessel.
- c) Immediately remove the samples from their molds and cool them by immersing in a water-cooling bath maintained at 27 °C $\pm$ 3 °C (80 °F $\pm$ 5 °F) for 40 min $\pm$ 5 min, until the samples are ready for testing.

Do not leave the cured samples out of water for more than 5 min to avoid dehydration.

7.4.3.3 Curing Above Atmospheric Pressure

To cure samples above atmospheric pressure, the following procedure shall be applied.

- a) After the molds have been filled and covered with the cover plate and within 5 min after mixing the slurry or after slurry conditioning (removal of conditioned slurry from the slurry cup), place them in a curing vessel at the desired test initiation temperature [normally 27 °C $\pm$ 3 °C (80 °F $\pm$ 5 °F) or at the desired preheated curing vessel temperature].
- b) Apply heat and pressure in accordance with the test schedule. Cement samples may be cured in accordance with pressure/temperature standard schedules provided either in Table 2 or Table 3, or by a schedule designed to simulate conditions in a specific well. For depths greater than 6,600 m or 22,000 ft, user-defined schedules shall be used.

NOTE Standard API compressive strength schedules are designated by an "Sg number." Do not misinterpret this appellation as a relative density "SG."

- c) For samples cured at or below 88 °C (190 °F), maintain test temperature and pressure until 45 min $\pm$ 5 min prior to testing.
- d) For test temperatures above 88 °C (190 °F), maintain the maximum scheduled temperature and pressure until the desired curing time.
- e) Discontinue heating and allow samples to cool at such a rate that the sample temperature is below 88 °C (190 °F) or less without a reduction in the pressure other than caused by the reduction in temperature.
- f) At 45 min $\pm$ 5 min prior the time at which the cured samples will be tested, release the remaining pressure gradually and remove the cured samples from the curing vessel.
- g) Immediately remove the samples from their molds and cool them by immersing in a water-cooling bath maintained at 27 °C $\pm$ 3 °C (80 °F $\pm$ 5 °F) for 40 min $\pm$ 5 min, until the samples are ready for testing.

Do not leave the cured samples out of water for more than 5 min to avoid dehydration.

- h) Record the total elapsed time between when the samples are cooled down to the time the cube samples are tested [see Step e) and Step f)].

7.4.3.4 Specimen Acceptance

Cube test samples that are damaged shall be discarded prior to testing. If fewer than two test samples are left for determining the compressive strength at any given conditions, new samples shall be prepared and a retest performed.

7.4.4 Strength Testing Procedure

To conduct the compressive strength test, the following procedure shall be followed.

- a) Remove cured sample from the water-cooling bath that has been maintained at $27^{\circ}\text{C} \pm 3^{\circ}\text{C}$ ($80^{\circ}\text{F} \pm 5^{\circ}\text{F}$); wipe each sample to remove any loose material from the faces that will be in contact with the bearing blocks of the testing machine.
- b) Cube height dimensions shall be measured to $\pm 1.6\text{ mm}$ (50-mm molds) or to $\pm 1/16\text{ in.}$ (2-in. molds) for calculation of the cross-sectional area.

If the cube height is less than 47.5 mm (cube prepared using a 50-mm mold) or less than 1.9 in. (cube prepared using a 2-in. mold), the cube shall be discarded.

- c) Place the cube sample in the load frame centered below the upper bearing block (i.e. the top surface during curing shall not be in contact with the platen).
 - 1) The load will be applied to the sample faces that were in contact with the plane (vertical) surfaces of the mold (not in contact with the base or the cover plates).
 - 2) Prior to the testing of each cube, confirm that the spherically seated block is free to tilt.
 - 3) Use no cushioning or bedding materials between the plates and the cube sample.
- d) Apply the load to the cube sample.

Caution—Use appropriate safety and handling procedures for testing the specimens.

- 1) The rate of loading for samples with expected strength greater than 3.5 MPa (500 lbf/in.²) should be 72 kN/min ± 7 kN/min (16,000 lbf/min ± 1600 lbf/min). For a nominal 25.8-cm² (4-in.²) sample surface, adjust the load rate to obtain a gauge indicator change of 18 kN (4000 lbf) in gauge reading in 15 s.
- 2) The rate of loading for samples with expected strength lower or equal than 3.5 MPa (500 lbf/in.²) should be 18 kN/min ± 2 kN/min (4000 lbf/min ± 400 lbf/min). For a nominal 25.8-cm² (4-in.²) sample surface, adjust the load rate to obtain a change of 18 kN (4000 lbf) in gauge reading in 1 min.

NOTE Depending on the type of compressive strength test machine used, it can require some time for the load frame to build up the required load rate after initial contact with the cement sample.

Report the rate of loading applied to determine compressive strength on cement cube.

- e) Calculate the compressive strength expressed in megapascals (pounds-force per square inch) as the force required to break the sample divided by the smallest calculated cross-sectional area in contact with the load-bearing plates of the load frame.
- f) Record compressive strengths, averaged to the nearest 0.1 MPa (10 lbf/in.²), of each acceptable test specimen made from the same sample and tested at the same period.

NOTE In case of a reduced number of cube samples to be crushed, if the calculated compressive strength of any sample appears as an outlier, do not delete it without reasonable cause (e.g. identifiable cause such as suspected

faulty cube based on pretest physical examination, unusual failure behavior, clearly unreasonable result), as the outlier may be a result of the other sample data clumping, thus removing the suspected outlier without cause may introduce bias.

- g) Average the compressive strength of all acceptable test samples (made from the same slurry and tested at the same time) and report, including the test conditions used, the compressive strength of the tested cement sample averaged to the nearest 0.1 MPa (10 lbf/in.²).

7.5 Determination of Cement Strength at the Top of a Long Cement Column

7.5.1 Guidelines for Use

This procedure should be used if the predicted bottomhole circulating temperature (T_{PBHC}) is higher than the top-of-cement (TOC) static temperature (T_{TOCS}) (at the TOC column).

7.5.2 Procedure

To prepare a cement sample at top of a long cement column, the following procedure shall be applied.

- a) Prepare cement slurry in accordance with Section 5. Pour the slurry into the slurry container of a pressurized consistometer, and start to apply pressure in accordance with 5.4.2 a) and heat to T_{PBHC} in accordance with the pressure/temperature schedule designed to simulate conditions in the well. Continue testing in accordance with 5.4.2 b).
- b) Upon completion of the appropriate test schedule, initiate a cooldown schedule predicted by placement thermal modeling at a depth of investigation in the annulus. In lieu of an available cooldown schedule, lower the temperature at a rate of 1.0 °C/min (1.8 °F/min) to the top-of-cement circulating temperature (T_{TOCC}). Use one of the following equations to determine the cooldown time (t_{cd}), expressed in minutes:

— Equation (32) when temperatures are expressed in degrees Celsius:

$$t_{cd} = T_{PBHC} - T_{TOCC} \quad (32)$$

— Equation (33) when temperatures are expressed in degrees Fahrenheit:

$$t_{cd} = \frac{T_{PBHC} - T_{TOCC}}{1.8} \quad (33)$$

where

T_{PBHC} is the predicted bottomhole circulating temperature, expressed in degrees Celsius (degrees Fahrenheit);

T_{TOCC} is the top-of-cement circulating temperature or 88 °C (190 °F), whichever is lower, expressed in degrees Celsius or degrees Fahrenheit.

As the temperature cools, allow the test pressure to decrease in accordance with the corresponding decrease in hydrostatic pressure as a function of decreasing vertical depth.

NOTE Alternatively, the temperature and/or pressure reduction schedule may be determined by placement thermal modelling simulator.

- c) When the temperature reaches T_{TOCC} or 88 °C (190 °F), whichever is lower, release the pressure slowly and remove the slurry container. Minimize oil contamination of the slurry by maintaining the slurry container upright (with the paddle shaft up). Syringe or blot oil from the top of the slurry container.

NOTE Do not cool the slurry container further after removal from the pressurized consistometer.

- d) Open the slurry container from the top (paddle shaft end), leaving the paddle in place. This eliminates the need for inverting the slurry container and reduces contamination that could be caused by oil migrating through the slurry. Syringe and blot the oil from the top of the slurry with an absorbent cloth or paper towel.
- e) Remove the paddle and stir the slurry briskly with a spatula to ensure it is uniform and to resuspend any solids that may have settled.
- f) Pour the slurry into prepared molds as specified in 7.4.2.2 and place the molds in a preheated curing vessel [preheated to T_{TOCC} or 88 °C (190 °F), whichever is lower]. Alternatively, a preheated nondestructive sonic test device as described in Section 8 may be used.
- g) Within 15 min after removing the slurry from the pressurized consistometer, apply pressure simulating well pressure at top of the cement, within the limitations of the apparatus being used.
- h) Adjust temperature of the sample to the final curing temperature (T_{TOCS}) over a time period appropriate to well conditions, while maintaining curing pressure. This may require cooling the slurry to T_{TOCS} . If the time to reach final conditions is not known or specified, use 6 hr.
- i) Remove samples as specified in 7.4.3.3.
- j) Test the samples for strength in accordance with procedures in 7.4.4 (compressive strength) or Section 8 (sonic strength).

Table 2—Well-simulation API Test Schedules for Curing Strength Specimens (SI Units)

Temperature Gradient ^d (°C/100 m)	Schedule ^a (SI)	1 Sg	2 Sg	3 Sg	4 Sg	5 Sg	6 Sg	7 Sg	8 Sg	9 Sg	10 Sg	11 Sg	12 Sg
	Depth (m)	300	600	1200	1800	2400	3000	3600	4200	4800	5400	6000	6600
	Pressure ^c (MPa)	5.5	11.0	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7
	Time to T_{BHC}^b (min)	13	17	25	32	40	49	57	65	73	81	89	96
	Total Time to T_{BHS}^b (min)	240	240	240	240	240	240	240	240	240	240	240	240
1.6	T_{BHC}^f (°C)	27	32	37	44	52	60	62	71	80	90	101	113
	Temp. ramp to T_{BHC} (°C/min)		0.30	0.41	0.52	0.62	0.67	0.61	0.68	0.73	0.78	0.84	0.89
	T_{BHS}^e (°C)	32	37	46	56	65	75	85	94	104	113	123	133
	Temp. ramp to T_{BHS} (°C/min)	0.02	0.02	0.04	0.06	0.07	0.08	0.12	0.13	0.14	0.15	0.15	0.14
2.0	T_{BHC} (°C)	27	32	38	45	53	63	73	84	96	108	122	137
	Temp. ramp to T_{BHC} (°C/min)		0.30	0.45	0.55	0.64	0.73	0.81	0.88	0.95	1.00	1.07	1.14
	T_{BHS} (°C)	33	39	51	63	75	87	99	111	123	135	147	159
	Temp. ramp to T_{BHS} (°C/min)	0.03	0.03	0.06	0.09	0.11	0.13	0.14	0.15	0.16	0.17	0.17	0.15
2.4	T_{BHC} (°C)	27	32	38	46	57	69	84	97	111	126	143	161
	Temp. ramp to T_{BHC} (°C/min)		0.30	0.45	0.58	0.74	0.85	1.00	1.08	1.15	1.23	1.31	1.39
	T_{BHS} (°C)	34	41	56	70	85	99	113	128	142	157	171	185
	Temp. ramp to T_{BHS} (°C/min)	0.03	0.04	0.08	0.12	0.14	0.16	0.16	0.18	0.19	0.19	0.18	0.17
2.8	T_{BHC} (°C)	27	32	39	48	60	75	94	110	126	144	163	185
	Temp. ramp to T_{BHC} (°C/min)		0.30	0.49	0.65	0.82	0.98	1.17	1.28	1.36	1.45	1.54	1.64
	T_{BHS} (°C)	35	44	61	77	94	111	128	145	161	178	195	212

Temperature Gradient ^d (°C/100 m)	Schedule ^a (SI)	1 Sg	2 Sg	3 Sg	4 Sg	5 Sg	6 Sg	7 Sg	8 Sg	9 Sg	10 Sg	11 Sg	12 Sg
	Depth (m)	300	600	1200	1800	2400	3000	3600	4200	4800	5400	6000	6600
	Pressure ^c (MPa)	5.5	11.0	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7	20.7
	Time to T_{BHC}^b (min)	13	17	25	32	40	49	57	65	73	81	89	96
	Total Time to T_{BHS}^b (min)	240	240	240	240	240	240	240	240	240	240	240	240
	Temp. ramp to T_{BHS} (°C/min)	0.04	0.05	0.10	0.14	0.17	0.19	0.18	0.20	0.21	0.21	0.21	0.19
3.2	T_{BHC} (°C)	27	33	39	49	65	84	105	122	141	162	184	208
	Temp. ramp to T_{BHC} (°C/min)		0.36	0.49	0.68	0.94	1.16	1.37	1.46	1.57	1.67	1.77	1.88
	T_{BHS} (°C)	37	46	65	85	104	123	142	161	181	200	219	238
	Temp. ramp to T_{BHS} (°C/min)	0.04	0.06	0.12	0.17	0.19	0.20	0.20	0.23	0.24	0.24	0.23	0.21
3.6	T_{BHC} (°C)	27	33	40	53	74	96	115	135	157	180	205	232
	Temp. ramp to T_{BHC} (°C/min)		0.36	0.53	0.80	1.16	1.40	1.54	1.66	1.78	1.90	2.01	2.13
	T_{BHS} (°C)	38	49	70	92	113	135	157	178	200	221	243	265
	Temp. ramp to T_{BHS} (°C/min)	0.05	0.07	0.14	0.19	0.20	0.20	0.23	0.25	0.26	0.26	0.25	0.23

^a Sg is API schedule number designation.

^b Temperature shall be increased on a double temperature ramp to meet the targets designated by the schedule until the 240-min temperature (T_{BHS}) is reached. First ramp to T_{BHC} , duration time to T_{BHC} ; second ramp from T_{BHC} to T_{BHS} , duration 240 min minus time to T_{BHC} .

The curing temperature (temperature at 240 min) shall be maintained within ± 2 °C throughout the remainder of the curing period until cooling, if necessary, is required (see 7.4.3).

^c Test temperature shall be applied as soon as specimens are placed in the pressure vessel and the pressure seal is complete and maintained at the given pressure within the following limits for the duration of the curing period:

Schedule 1 Sg 5.5 MPa $\pm$ 0.7 MPa;

Schedule 2 Sg 11.0 MPa $\pm$ 1.400 MPa;

Schedule 3 Sg to 12 Sg 20.7 MPa $\pm$ 3.4 MPa.

^d Temperature gradient = $(T_{BHS} - 27 \text{ °C})/100 \text{ m depth}$.

^e T_{BHS} = bottomhole static temperature, temperature at 240 min.

^f T_{BHC} = bottomhole circulating temperature.

Table 3—Well-simulation API Test Schedules for Curing Strength Specimens (USC Units)

Temperature Gradient ^d (°F/100 ft)	Schedule ^a (USC)	1 Sg	2 Sg	3 Sg	4 Sg	5 Sg	6 Sg	7 Sg	8 Sg	9 Sg	10 Sg	11 Sg	12 Sg
	Depth (ft)	1000	2000	4000	6000	8000	10,000	12,000	14,000	16,000	18,000	20,000	22,000
	Pressure ^c (lbf/in. ²)	800	1600	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
	Time to T_{BHC} ^b (min)	13	17	25	33	41	50	58	66	74	82	90	98
	Total Time to T_{BHS} ^b (min)	240	240	240	240	240	240	240	240	240	240	240	240
0.9	T_{BHC} ^f (°F)	80	89	99	112	126	141	148	164	182	201	222	244
	Temp. ramp to T_{BHC} (°F/min)		0.53	0.76	0.97	1.12	1.22	1.17	1.27	1.38	1.48	1.58	1.67
	T_{BHS} ^e (°F)	89	98	116	134	152	170	188	206	224	242	260	278
	Temp. ramp to T_{BHS} (°F/min)	0.04	0.04	0.08	0.11	0.13	0.15	0.22	0.24	0.25	0.26	0.25	0.24
1.1	T_{BHC} (°F)	80	89	100	114	129	146	165	185	207	231	256	284
	Temp. ramp to T_{BHC} (°F/min)		0.53	0.80	1.03	1.20	1.32	1.47	1.59	1.72	1.84	1.96	2.08
	T_{BHS} (°F)	91	102	124	146	168	190	212	234	256	278	300	322
	Temp. ramp to T_{BHS} (°F/min)	0.05	0.06	0.11	0.15	0.20	0.23	0.26	0.28	0.30	0.30	0.29	0.27
1.3	T_{BHC} (°F)	80	90	101	116	135	158	183	207	233	261	291	324
	Temp. ramp to T_{BHC} (°F/min)		0.59	0.84	1.09	1.34	1.56	1.78	1.92	2.07	2.21	2.34	2.49
	T_{BHS} (°F)	93	106	132	158	184	210	236	262	288	314	340	366
	Temp. ramp to T_{BHS} (°F/min)	0.06	0.07	0.14	0.20	0.25	0.27	0.29	0.32	0.33	0.34	0.33	0.30
1.5	T_{BHC} (°F)	80	90	102	118	140	167	201	228	258	291	326	364
	Temp. ramp to T_{BHC} (°F/min)		0.59	0.88	1.15	1.46	1.74	2.09	2.24	2.41	2.57	2.73	2.90
	T_{BHS} (°F)	95	110	140	170	200	230	260	290	320	350	380	410

Temperature Gradient ^d (°F/100 ft)	Schedule ^a (USC)	1 Sg	2 Sg	3 Sg	4 Sg	5 Sg	6 Sg	7 Sg	8 Sg	9 Sg	10 Sg	11 Sg	12 Sg
	Depth (ft)	1000	2000	4000	6000	8000	10,000	12,000	14,000	16,000	18,000	20,000	22,000
	Pressure ^c (lbf/in. ²)	800	1600	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
	Time to T_{BHC} ^b (min)	13	17	25	33	41	50	58	66	74	82	90	98
	Total Time to T_{BHS} ^b (min)	240	240	240	240	240	240	240	240	240	240	240	240
	Temp. ramp to T_{BHS} (°F/min)	0.07	0.09	0.18	0.25	0.30	0.33	0.32	0.36	0.37	0.37	0.36	0.32
1.7	T_{BHC} (°F)	80	91	103	120	146	180	219	250	284	321	360	404
	Temp. ramp to T_{BHC} (°F/min)		0.65	0.92	1.21	1.61	2.00	2.40	2.58	2.76	2.94	3.11	3.31
	T_{BHS} (°F)	97	114	148	182	216	250	284	318	352	386	420	454
	Temp. ramp to T_{BHS} (°F/min)	0.07	0.10	0.21	0.30	0.35	0.37	0.36	0.39	0.41	0.41	0.40	0.35
1.9	T_{BHC} (°F)	80	91	104	126	160	200	236	271	309	350	395	444
	Temp. ramp to T_{BHC} (°F/min)		0.65	0.96	1.39	1.95	2.40	2.69	2.89	3.09	3.29	3.50	3.71
	T_{BHS} (°F)	99	118	156	194	232	270	308	346	384	422	460	498
	Temp. ramp to T_{BHS} (°F/min)	0.08	0.12	0.24	0.33	0.36	0.37	0.40	0.43	0.45	0.46	0.43	0.38

^a Sg is API schedule number designation.

^b Temperature shall be increased on a double temperature ramp to meet the targets designated by the schedule until the 240-min temperature (T_{BHS}) is reached. First ramp to T_{BHC} , duration time to T_{BHC} ; second ramp from T_{BHC} to T_{BHS} , duration 240 min minus time to T_{BHC} .

The curing temperature (temperature at 240 min) shall be maintained within ± 3 °F throughout the remainder of the curing period until cooling, if necessary, is required (see 7.4.3).

^c Test temperature shall be applied as soon as specimens are placed in the pressure vessel and the pressure seal is complete and maintained at the given pressure within the following limits for the duration of the curing period:

Schedule 1 Sg 800 lbf/in.² $\pm$ 100 lbf/in.²;

Schedule 2 Sg 1600 lbf/in.² $\pm$ 200 lbf/in.²;

Schedule 3 Sg to 12 Sg 3000 lbf/in.² $\pm$ 500 lbf/in.².

^d Temperature gradient = (T_{BHS} – 80 °F)/100 ft depth.

^e T_{BHS} = bottomhole static temperature, temperature at 240 min.

^f T_{BHC} = bottomhole circulating temperature.

8 Nondestructive Sonic Correlation of Compressive Strength of Cement

8.1 General

This section presents a sonic nondestructive testing procedure to correlate compressive strength to sonic compressional transit time (compressional sonic slowness). Acoustic impedance of the cement may also be calculated. Strength correlations are specific to certain cement compositions. Cement compositions with sonic properties vastly different than the correlations used by the device may require development of custom correlations or testing using destructive methods.

8.2 Apparatus

The apparatus shall include the following systems.

- Temperature-measuring system, meeting requirements in Annex B.
- Sonic signal measuring system.
- A pressure cell, which can be subjected to controlled temperature and pressure for curing the cement slurry.
- A control unit to regulate pressure and temperature according to a simulated well schedule.

The apparatus shall be calibrated according to Annex B.

8.3 Sampling

Samples of the cement, additives, and mix water shall be obtained in accordance with Section 4.

8.4 Preparation of Slurry

The slurry shall be prepared in accordance with the requirements given in 5.3. If preconditioning is appropriate, follow 5.4 or 7.5.2 for top of the cement column.

8.5 Procedure

Follow the detailed operating instructions and safety precautions furnished by the manufacturer. The presence of free fluid may change the transit time measurements.

8.6 Curing Time

Curing period begins when transit time is recorded along with pressure and temperature and continues until the test is terminated.

Start the test within 15 min after mixing of the slurry or slurry conditioning (removal of conditioned slurry from the slurry cup) with the application of pressure and initiation of the temperature schedule.

8.7 Curing Schedules

Cement samples may be cured in accordance with pressure/temperature schedules provided in Section 7 or using a schedule designed to simulate specific well conditions.

NOTE Planned or unplanned changes in temperature or pressure alter the transit time and consequently the strength result.