

Monolithic Refractories: Manufacture, Properties, and Selection

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Documents

Document Sharing Hub

Introduction

API TR 978 is the first in a series of three API technical reports updating the state-of-the-art use of refractory concrete (castables), plastics, and ramming mixes in applications for the Hydrocarbon Processing Industry (HPI). This technical report is complemented by two additional reports in this series:

- API TR 979, *Applications of Refractory Lining Materials*
- API TR 980, *Monolithic Refractories: Installation and Dryout*

These three API technical reports are based on two original reports written by the American Concrete Institute (ACI) Committee 547 and published by ACI in 1979 and 1989. The original ACI reports are ACI 547.R-79, *State-of-the Art Report: Refractory Concrete* and ACI 547.1R-89, *State-of-the Art Report: Refractory Plastics and Ramming Mixes*. ACI granted API a license to use all material from the two original ACI reports, in need of revision at the time, for the betterment of the oil and gas industry.

ACI Committee 547 was organized in 1969 to provide a reliable and comprehensive source of information on monolithic refractories technology. In subsequent years, ACI support from the refractory technical community waned and shifted in favor API. API has an Individual Certification Program (ICP) for refractory practitioners based on the API Standard 936, *Refractory Installation Quality Control-Inspection and Testing Monolithic Refractory Linings and Materials*. To facilitate development of updated content in API's certification program, ACI has allowed API to use the material from the two ACI reports, mentioned above, as the starting point for three new API technical reports, which add to and revise the content of the two ACI reports.

The American Petroleum Institute formed the Vessel Refractory Task Group in the late 1980s with the objective of providing a standard for inspection and application quality control of monolithic refractories used in refining applications. In response to demands for greater reliability and cycle life objectives, refiners had already developed their own company specifications for refractory installations for the most important applications where unit availability is critical. A cottage industry of supporting quality control experts and inspectors evolved to help owner-operators reduce the gap between ideal and actual cycle life. Prior to the Vessel Refractory Task Group (the predecessor of the SCRM), manufacturers and installers largely had little say in these efforts and uniform industry standards were never developed or adopted.

To address this issue, the Vessel Refractory Task Group allowed for a broad representation of all the stake holders as part of the API's spring and fall Refining Equipment Standards Meetings. Addressing the standards gap and noting the many similarities in owner-operator and OEM developed specifications, the API Task Force undertook the task of identifying useful industry practices and/or negotiating to agreement best fits for standards applications. API's *Refractory Installation Quality Control Guidelines—Inspection and Testing Monolithic Linings and Material* was first issued in 1996 as a recommended practice. After a number of subsequent revisions, it was published as API Standard 936 in 2006, with a certification program beginning in 2004.

In addition to maintaining API Standard 936 and overseeing the certification program, in 2014 the Task Force reorganized under the Committee on Refinery Equipment (CRE) as the Refractory Project Group (RPG). As a project group, work expanded to ceramic fiber and brick quality control standards; unit specific applications, such as SRU and hydrogen furnaces; and technical reports, including this report. In response to this broadening recognition of the need to advance this technology for HPI applications, the CRE reclassified the group as a full subcommittee in 2016 and it now works under the title of the Subcommittee on Refractory Materials.

Monolithic Refractories: Manufacture, Properties, and Selection

1 Scope

This technical report covers the installation and dryout of monolithic refractory lining materials for Hydrocarbon Processing Industry (HPI) applications. It discusses the best practice procedures and techniques used in the installation of refractory concrete, as well as those for air and heat setting plastics and ramming mixes. In addition, it addresses the need for curing and dryout procedures to achieve successful results. This instruction is consistent with API Standard 936, which is the HPI industry standard for the installation quality control of monolithic refractories. API 936 also serves as a body of knowledge document for the API certification program for refractory practitioners.

NOTE API TR 979 and API TR 980 are additional reports listed in Section 2, designed to provide a complete discussion of the monolithic refractory subject.

2 Referenced Documents

API 936, *Refractory Installation Quality Control—Inspection and Testing Monolithic Refractory Linings and Materials*

API TR 977, *ASTM C704 Test Variability Reduced to Allow Further Optimization of Erosion Resistant Refractories for Critical Oil Refining Applications*¹

API TR 979, *Applications of Refractory Lining Materials*¹

ASTM C16, *Standard Test Method for Load Testing Refractory Shapes at High Temperatures*

ASTM C20, *Standard Test Methods for Apparent Porosity, Water Absorption, Apparent Specific Gravity, and Bulk Density of Burned Refractory Brick and Shapes by Boiling Water*

ASTM C24, *Standard Test Method for Pyrometric Cone Equivalent (PCE) of Fireclay and High-Alumina Refractory Materials*

ASTM C92, *Standard Test Methods for Sieve Analysis and Water Content of Refractory Materials*

ASTM C115, *Standard Test Method for Fineness of Portland Cement by the Turbidimeter*

ASTM C129, *Standard Specification for Nonloadbearing Concrete Masonry Units*

ASTM C133, *Standard Test Methods for Cold Crushing Strength and Modulus of Rupture of Refractories*

ASTM C134, *Standard Test Methods for Size, Dimensional Measurements, and Bulk Density of Refractory Brick and Insulating Firebrick*

ASTM C150, *Standard Specification for Portland Cement*

ASTM C179, *Standard Test Method for Drying and Firing Linear Change of Refractory Plastic and Ramming Mix Specimens*

ASTM C181, *Standard Test Method for Workability Index of Fireclay and High-Alumina Refractory Plastics*

ASTM C191, *Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle*

ASTM C201, *Standard Test Method for Thermal Conductivity of Refractories*

ASTM C204, *Standard Test Methods for Fineness of Hydraulic Cement by Air-Permeability Apparatus*

ASTM C288, *Standard Test Method for Disintegration of Refractories in an Atmosphere of Carbon Monoxide*

ASTM C357, *Standard Test Method for Bulk Density of Granular Refractory Materials*

ASTM C417, *Standard Test Method for Thermal Conductivity of Unfired Monolithic Refractories*

ASTM C577, *Standard Test Method for Permeability of Refractories*

ASTM C583, *Standard Test Method for Modulus of Rupture of Refractory Materials at Elevated Temperatures*

ASTM C673, *Standard Classification of Fireclay and High-Alumina Plastic Refractories and Ramming Mixes*

ASTM C704, *Standard Test Method for Abrasion Resistance of Refractory Materials at Room Temperature*

ASTM C830, *Standard Test Methods for Apparent Porosity, Liquid Absorption, Apparent Specific Gravity, and Bulk Density of Refractory Shapes by Vacuum Pressure*

ASTM C832, *Standard Test Method of Measuring Thermal Expansion and Creep of Refractories Under Load*

ASTM C860, *Standard Test Method for Determining the Consistency of Refractory Castable Using the Ball-in-Hand Test*

ASTM C885, *Standard Test Method for Young's Modulus of Refractory Shapes by Sonic Resonance*

ASTM E11, *Standard Specification for Woven Wire Test Sieve Cloth and Test Sieves*

3 Terms and Definitions

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

NOTE See ASTM C71 and API 936 for additional information on the following definitions.

3.1

abrasion

A wearing away of the surface of a solid by rubbing, scouring, or friction action of other solids.

3.2

abrasion resistance¹

The ability to withstand the effects of eroding particles for an extended period without significant loss of material or other damage.

3.3

acid refractories

Refractories containing a substantial amount of silica that may react chemically with basic fluxes, basic slags, or basic refractories at high temperatures.

NOTE Although technically not correct, alumina is generally considered an acid refractory.

¹ Definition from API Standard 936, Fourth Edition.

3.4**aggregate²**

As applied to refractories, a ground mineral material consisting of particles of various sizes, combined with finer sizes for making formed or monolithic bodies.

3.5**air-setting refractories²**

Compositions of refractory materials that develop a strong bond at ambient temperatures by virtue of chemical reactions within the binder phase that is usually activated by water addition.

NOTE These refractories include cement and phosphate-bonded castables.

3.6**anchor or tieback²**

A metallic or refractory device that retains refractory or insulation materials in place.

3.7**apparent porosity**

The relationship of the volume of the open pores in a refractory specimen to its volume, expressed as a percentage.

3.8**basic refractories³**

Refractories whose major constituent is lime, magnesia, or both, and which may react chemically with acid fluxes, acid slags, or acid refractories at high temperatures.

NOTE Commercial use of this term also includes refractories made of chrome ore or combinations of chrome ore and dead, burned magnesite.

3.9**binder²**

Cementing material.

3.10**bloating²**

A subsurface defect that can occur in plastic refractory lining systems caused by steam pockets entrapped in the pore structure of the refractory during initial heating due either to rapid heat-up or insufficient permeability in the refractory.

3.11**calcium aluminate cement**

The product obtained by pulverizing clinker, which consists of hydraulic calcium aluminates formed by fusing or sintering a suitably proportioned mixture of aluminous and calcareous materials.

3.12**castable refractory**

A packaged dry mixture of binder and specially selected and proportioned refractory aggregates which, when mixed with water or other liquid, will produce refractory concrete.

3.13**casting²**

The application of wet, mixed castable refractory by placing (possibly with the aid of vibration), pouring, or rodding.

² Definition from *Harbison-Walker Handbook of Refractory Practices*, First Edition, 1992.

3.14
ceramic bond ²

The high-strength bond that is developed between materials, such as clay and aggregates, as a result of thermo-chemical reactions that occur when materials are subjected to elevated temperature.

3.15
chemical-setting ²

Refractory developing a strong bond by chemical reaction.

NOTE These refractories include phosphate-bonded plastics and ramming mixes.

3.16
cold face ²

The surface of a refractory section not exposed to the source of heat.

NOTE Commonly the surface furthest from the source of heat.

3.17
cold-setting refractories

A composition which develops a bond at normal ambient temperature prior to drying.

3.18
construction joint

See "joint."

3.19
comminution

Reduction of materials to fine particles.

3.20
compactability ³

The ease with which the volume of a freshly placed plastic refractory or ramming mix is reduced to a practical minimum, usually by ramming.

3.21
conversion (of high-alumina cement)

The transformation of the hexagonal metastable hydrates (CARD or C₂AH₆) to the stable, cubic hydrate (C₃AH₅). The cubic hydrate occupies less volume than the hexagonal hydrates and this results in an increase in matrix porosity and a possible reduction in concrete strength.

NOTE C = CaO, A = Al₂O₃, and H = H₂O

3.22
corrosion ²

Disintegration or deterioration by chemical attack, including electrolysis.

3.23
creep ²

Time-dependent deformation due to sustained load.

³ Definition from ACI CT-13, *ACI Concrete Terminology*.

3.24
curing ²

Process of bond formation in a newly installed monolithic refractory.

NOTE For hydraulic bonded castables, curing occurs at room temperature and is facilitated by an excess of water being present to react with a cement component. For phosphate-bonded plastic refractories, heating to 500 °F to 700 °F (260 °C to 370 °C) is typically required to form the bond.

3.25
drying

Removal of free moisture from a material.

3.26
dryout ²

The initial heating of a newly installed castable lining in which heating rates and hold times are controlled to safely remove free moisture without explosive spalling and to form a well distributed network of shrinkage cracks in the lining.

3.27
erosion

Progressive disintegration of a solid by the abrasion or cavitation action of gases, liquids or solids in motion.

3.28
expansion joint ²

A separation between adjoining parts of a refractory lining to allow small expansive movements such as those caused by thermal changes.

3.29
explosive spalling ²

A sudden fragmentation of a refractory lining which occurs as the result of a buildup of steam pressure due to inappropriately rapid heating, generally on first firing.

3.30
extrude ³

To force a plastic refractory through a die by the application of pressure.

3.31
field mix ³

A mix formulated at or near the job site.

3.32
firing

The process of heating refractories to develop desired properties.

3.33
grog

See aggregate.

3.34
gun-casting

A method of placing castables using a pneumatic gun as a conveyor of the material by reducing the velocity of the castable at the nozzle (see "gunning").

3.35**gunning²**

Act of emplacing refractory material by projecting onto a surface via an air placement gun.

3.36**gunning mix³**

A refractory material which is emplaced by projecting onto a surface via an air placement gun.

3.37**heat resistant concrete**

Any concrete which will not disintegrate when exposed to constant or cyclical heating at any temperature below which a ceramic bond is formed.

3.38**heat-setting refractories²**

Compositions of refractory materials that require relatively high temperatures for the development of an adequate bond, commonly called a “ceramic bond.”

3.39**hot face**

The surface of a refractory section exposed to the source of heat.

3.40**hydraulic cement**

A cement that sets and hardens by chemical interaction with water and that is capable of doing so under water.

3.41**insulating castable²**

A castable with relatively low thermal conductivity, which usually has a low installed density (less than 100 lb/ft³ (1.6 MT/m³)).

NOTE Joint (also construction joint): a separation between adjacent parts of a refractory construction.

3.42**lamination⁴**

A plane of weakness within a monolithic refractory lining that is parallel to the hot face of the lining and permits separation into layers.

3.43**lightweight castable**

See insulating castable.

3.44**matrix²**

The continuous phase in the emplaced refractory.

3.45**monolithic refractory²**

Castable or plastic refractories applied by casting, gunning, or hand/ram packing to form monolithic lining structures of any shape.

⁴ Definition from ASTM C71.

3.46**neutral refractories**

Refractory materials that are resistant to chemical attack by both acidic and basic slags, refractories, and fluxes at high temperatures.

3.47**normal weight refractory concrete ²**

Refractory concrete having a unit weight greater than 100 lb/ft³ (1.6 MT/m³) in place.

3.48**plastic refractories ²**

A moldable refractory material that can be extruded and has a level of workability that permits it to be pounded into place to form a monolithic structure.

3.49**plasticity ²**

A property of a material which allows it to be molded or shaped.

3.50**punkiness**

Friable or spongy appearance.

3.51**ramming mix ⁵**

A refractory material, usually tempered with water that cannot be extruded, but has suitable properties to permit ramming into place to form a monolithic structure.

3.52**rapid fire technology**

A refractory material designed to allow the installed lining to be fired safely (i.e. without explosive spalling) when the lining is exposed to faster firing rates.

NOTE Rapid fire technology allows the installed lining to pass through the phase where the chemically combined water is released from the cement matrix.

3.53**rebound ²**

Aggregate or cement, or both, which bounces away from a surface against which refractory is being projected by gunning.

3.54**reducing atmosphere**

An atmosphere which, at high temperatures, lowers the state of oxidation of exposed materials.

3.55**refractory**

Resistant to high temperatures.

3.56**refractory aggregate**

Materials having refractory properties which form a refractory body when bound into a conglomerate mass by a matrix.

3.57**refractory concrete (castable)**

Concrete which is suitable for use at high temperatures and contains hydraulic cement as the binding agent.

3.58**setting ²**

The hardening that occurs with time or temperature, or both.

3.59**sheeting ²**

Spalling of layers from the hot face of the refractory.

3.60**shelf life ²**

Maximum interval during which a material may be stored and remain in a usable condition.

3.61**shotcrete**

Mortar or concrete premixed with liquid and projected at high velocity onto a surface; also known as "air blown mortar," "pneumatically applied mortar or concrete," "blastcrete," "sprayed mortar," and "gunned mortar."

3.62**softening temperature**

The temperature at which a refractory material begins to undergo permanent deformation under specified conditions.

NOTE This term is more appropriately applied to glasses than refractory concretes.

3.63**spall**

A surface fragment, usually in the shape of a flake, detached from a larger mass by impact, the action of weather, pressure, or expansion within the larger mass.

3.64**steam spalling**

See "explosive spalling."

3.65**thermal shock ²**

The exposure of a material to one or more rapid changes in temperature which may have a deleterious effect on the integrity of the refractory.

3.66**thermal spalling ²**

Spalling that occurs as the result of stresses caused by non-uniform heating or cooling, or both.

3.67**thixotropic ²**

A mixture that flows when vibrated, but is stiff and unmoving otherwise.

NOTE Vibration cast refractories are an example.

3.68**vent hole**

An opening into the hot face of the monolithic refractory to permit escape of gas or steam during drying and firing.

3.69**wall seat**

A support for a vertical element of refractory.

3.70**weep hole**

An opening at the cold face of a refractory lining to permit the escape of moisture.

4 Background

4.1 Early Beginnings

Ancient humans contained and controlled fire with a hearth consisting of stones, rocks, soil, and clay. Mankind soon discovered that clay, when properly baked, produced a useful and effective refractory. By 3000 B.C. humans created kilns or furnaces of burned clay brick. This led to the development of techniques for manufacturing copper, iron, and glass.

Except for the Roman period, there was limited use of brick until the 13th and 14th centuries, and it was not until the 1800s that clays having special refractory properties were discovered. This discovery resulted in the creation high-grade firebrick possessing good resistance to elevated temperatures. Together with the further needs created by the Industrial Revolution for more advanced refractories, this resulted in the many varieties of firebrick available today.

Although refractory technology had become fairly sophisticated by the first half of 1900s, literature of the period constantly called for improvement in the design, installation, and maintenance of refractory linings. Thermal conductivity, spalling, and erosion needed to be reduced, while volume stability, abrasion, and slag resistance needed improvement. In 1905, the first mention was made of a new combination of materials, a proprietary “plastic firebrick” consisting of a clay grog and a high-quality fireclay. It was used sparingly until the early 1920s, when a similar combination of crushed firebrick and high-temperature cement (non-hydraulic), blended with a minimum quantity of water or water glass, or both, found wide acceptance.

The terms “plastic firebrick,” “plastic refractories,” “refractory mortar,” and “refractory concrete” were used interchangeably during this period to describe this new material. Today, “plastic firebrick” or “plastic refractory” is the common term in use. After mixing, the product was built-up in small increments by ramming into wooden forms which were sometimes left in place to be burned out on firing. This novel procedure led to the concept of monolithic construction. In this type of construction, modular unit size does not dictate design, and the construction of complex configurations was radically simplified.

During the 1920s, the cement gun (introduced in 1910) was used to pneumatically apply a refractory mixture of crushed firebrick, fireclay, sodium silicate, and water. Following initial success, a number of devices were introduced for the spray application of a similar combination of refractory materials. These innovations, while important, accentuated the need for a truly refractory concrete that could be placed quickly in monolithic form under ambient conditions and would retain its structural and thermal properties without excessive maintenance when fired to high temperatures.

4.2 Formulation Differences

Monolithic refractories consist of a graded refractory aggregate and a bonding medium. For refractory concrete, the binding agent is typically calcium aluminate cement, which is activated by the addition of water during installation, forming a lining structure suitable for use at temperatures of up to about 3400 °F (1870 °C). Plastics and ramming mixes usually consist of a clay and either alumina, aluminosilicate, magnesite, chrome ore, silicon carbide, or graphite as an aggregate base. They are blended with specific binders, such as clay or phosphoric acid for heat-setting and clay or sodium silicate for air-setting. Special properties, such as resistance to acid or slag attack, freezing and low-temperature hardening, may be achieved by including appropriate additives. Plastics can be designed for use to

maximum service temperatures of 3400 °F (1870 °C) and some of the commercial ramming mixes have a 4000 °F (2200 °C) service temperature limit.

Plastics (sometimes referred to as “moldables”) and ramming mixes are manufactured from similar ingredients. They differ primarily in moisture content and particle size gradation, the plastic refractories being easier to form because of higher moisture content. In many respects, plastics and ramming mixes are very similar. Accordingly, the term “plastics” will be used throughout this technical report to represent both plastic refractories and ramming mixes. When differences occur, they will be noted in the text.

Packaged plastics are available in either a moist “ready to use” form or dry. Water is usually added to the dry form at the job site. Formulations that become hard and rigid after forming are classified as “castables,” which by definition are air-setting. Heat-setting material may stiffen due to the dehydration of forming water but they require heating in order to form bonding and rigid durable structures. Whether plastic, ramming mix, or castable, however, they are all classified as “monolithic refractories” because of their ability to be installed in a continuous lining that can be smoothly applied to the contour of the equipment they are intended to insulate or protect, or both.

Monolithic refractories are installed by gunning, casting, ramming, and hand packing. This technical report covers the following topics pertaining to refractories technology: constituent ingredients, manufacturing processes, material characteristics, selection criteria, and testing. Installation techniques, construction details, methods of curing, and firing and repair procedures are covered in API TR 979. Applications of refractories in HPI and related industries are addressed in API TR 980.

4.3 Cement Bonded Refractories

The development of Portland cement concrete and refractory concrete occurred in two basic advancements. The first was the evolution from brick and stone-size building units to larger monolithic construction utilizing readily accessible local materials. The second development was the discovery of an effective high-strength binder or cement to form concrete when used with the proper aggregate. This latter change occurred in conventional concrete technology with Joseph Aspdin and the formulation of Portland cement in 1824⁵. The corresponding development of refractory concrete technology was the use, by H. Sainte-Claire Deville in 1856^[1], of a calcium aluminate bond when making laboratory crucibles.

The development of a refractory concrete using calcium aluminate cement as a binder is usually ascribed to P. J. Kestner^[1, 2], who received patents in France (in 1924), England (in 1925), and the United States (in 1926) for a mixture of calcium aluminate cement, refractory grog, and calcined bauxite. Almost simultaneously in the United States, a new type of concrete, incorporating a calcium aluminate cement binder, found limited use as a patch material for furnace linings and ash pits^[3]. In 1926, a few special precast refractory shapes were reportedly made of similar ingredients. Thereafter, many field-mix refractory concretes consisting of calcium aluminate cement and local refractory aggregates were tested. An early mention of using a cement gun for placing or gunning refractory mortars was in April 1929^[4].

Prior to this time, the commercial production of bagged mixes of refractory aggregate and calcium aluminate cement for monolithic refractory concrete construction was started. These factory proportioned mixes, known as “castable refractories,” were packaged and sold on a limited basis by various refractory specialty companies as early as 1928, and were favorably received by many users. By 1934, there were 25 trademarked castable refractory mixtures being marketed. The 1930s found many plants adopting the field-mix and factory-packaged castables for new construction, as well as repair and maintenance. Also during this period, insulating (lightweight) and heavier castables were introduced.

The war years of the 1940s saw increased use of castables because of the minimal labor required for installation and the quick-setting properties, which sped construction and usually eliminated the need for complete rebuilds. The post-war years and 1950s produced a steady increase in the uses and applications of refractory castables, both cast and

⁵ References from this point forward are endnotes and indicate the source appearing in the bibliography section of TR 978.

gunned. Temperature service limits of castables climbed, their abrasion and erosion resistance increased, and their overall quality and uniformity improved, resulting in enhanced performance and durability.

Over the years, gunning or high-velocity, dry-mix shotcrete has evolved into a major alternate method for the efficient installation of refractory materials under either cold or hot conditions. The development of maneuverable, low-velocity concrete placers and pumps (discussed in API TR 980) has resulted in their use for pumping refractory concrete. Both gunning and pumping, after a transitional period of many years, have provided an economical and versatile alternative to traditional methods for placing refractory castables. In addition to these new placing procedures, the improved castables, a continued scarcity of firebrick masons, and positive economic factors have resulted in the dramatic increase in the use of castable refractories from the 1960s through the early 2000s.

4.3.1 Plastic Refractories

By the late 1930s, experience gained from the increased use of plastic refractories resulted in a better understanding of its capabilities. This, in turn, led to improved installation techniques and the development of additional products for a wider range of applications.

Plastics began to be considered as a viable alternative to the use of firebrick. Plastic refractories simplified construction of complex configurations which had previously required many special pre-fired shapes or intricate cutting of firebrick. The demand for refractories during World War II accelerated the use of plastics and this led to a dramatic rise in their production.

Compared to brick, plastics have the following advantages for refractory construction:

- ease of manufacture,
- lower energy requirements for manufacture,
- short installation time,
- minimum use of skilled labor,
- excellent patching characteristics for repairs,
- can withstand bulging and expansion better than brick construction with proper anchoring,
- elimination of joints minimizes leakage, and
- lower thermal conductivity.

Forecasters predict that the use of monoliths, and particularly plastics, will continue to expand. New developments in refractory technology are resulting in more sophisticated plastics with enhanced physical and chemical properties. These new products will provide engineers with improved materials for solving the complex refractory problems of the future.

4.4 Comparison with Other Refractories

The design of a refractory installation is a complex procedure, difficult and uncertain at times. Knowledge of the entire spectrum of refractories is usually required because one type of product rarely satisfies all conditions that can exist within a process vessel. Other types of refractory are discussed in this report, including refractory brick, concrete, mortars and coating, and special gunning mixes. Ceramic fibers and block-type insulation are also used as refractories.

For new construction, the choice between plastics and other types of refractories usually depends on economics and the design requirements. For repair work, however, other considerations, such as minimizing downtime, are important in the choice of material (see API TR 980). Each material has distinct qualities and advantages that influence selection for a specific application.

4.4.1 Plastics versus Castables

The service capabilities of plastics and castables differ because of their physical and chemical makeup. Each can be used for a specific purpose, either side by side or in separate locations of a heat-containment vessel. In many applications, both are replacing firebrick. This trend is expected to continue with further improvements in aggregate and binder technology.

Plastics are formulated to be used in the same temperature regimes as castables. Except for the phosphate-bonded plastics cured above 600 °F (315 °C), the hot and cold strengths of plastics are generally lower than those of refractory concretes. The strength variation through the cross-section of the lining (lower on the cold face) is greater with plastics. The strength reduction of refractory concretes in the intermediate temperature range is not observed in plastics. Most plastics are more resistant to spalling and to chemical and slag attack than are concretes.

Plastics can generally be placed without the use of forms. In contrast, refractory concretes require forms except when applied by gun or trowel. Placement of refractory concrete can normally be accomplished faster than for plastics. However, the mixing, forming, curing, drying, and firing schedules are usually more complex than with plastics.

The final selection of either a plastic or castable will be determined by its ability to meet the design criteria. It is recommended that a refractories manufacturer be consulted prior to specification and use of a particular material.

4.5 Other Types of Refractories

The information in Sections 4.5.1 through 4.5.3 is not pertinent to the main theme of this technical report; however, it will be of some interest and use to the reader.

4.5.1 Refractory Brick

For centuries, ordinary burned clay building brick was the only brick available for refractory use. This type of brick was satisfactory for normal use, but the upper temperature limit was too low for many refractory applications. During the industrial revolution, the discovery of special refractory clays introduced a new era in refractory brick technology. High-quality brick, known as “firebrick,” with unique chemical and physical properties, was developed by blending different types of clay and other ingredients and by varying both the method of processing and the burning temperatures. In addition to the many varieties of fireclay brick, high alumina, insulating, silica, fused aggregate, and basic firebrick were developed over the following years. All are manufactured using strict quality control, so as to meet the exacting standards and needs of the refractory user.

Despite competition from castables and plastics, refractory brick remains a major construction material for applications in which heat containment and control is necessary. In many instances, refractory brick is the only satisfactory solution to a specific problem. Refractory bricks come in various standard sizes, shapes, and special configurations, and have properties suitable for almost all high-temperature and corrosive applications.

Brick has a number of disadvantages, as compared to monolithic refractories. These disadvantages include multiple joints, complicated anchoring, more difficult repair procedures, the need to maintain inventories of special or scarce items, inflexibility in structural design, and higher fuel requirements during manufacture.

4.5.2 Mortars and Coatings

Refractory mortars use raw materials similar to plastics, except that all solid materials are ground much finer before mixing with the binder. These mortars are used for laying refractory brick and are available in air-setting and heat-

setting form. When thinned with water, they can be used as a joint crack sealer or as a wash or coating to protect against aggressive attack and to reduce the irregularity of brick walls.

Refractory coatings are similar to mortars, but are designed specifically to resist slag penetration, adhesion, and attack, and to close pore structure and to densify the refractory surface. This helps to minimize abrasion and resists molten metal or slag attack. Some heavier thickness coatings are used to patch spalled areas, thereby increasing the service life of the lining. It is essential that these coatings exhibit low shrinkage qualities, be compatible with the refractory being repaired, and have excellent bonding qualities. Most coatings can be applied to brick surfaces, but some are designed for use with plastics and refractory concretes.

4.5.3 Gunning Mixes Other than Refractory Concretes [5, 6]

As used in this section, the term “gunning mixes” does not refer to refractory concrete, and should not be confused with gunned refractory materials, which produce refractory concrete. Gunning mixes in this section are classified in the *Bureau of Census Report on Refractories* under product codes different from hydraulic setting castables.

Gunning mixes are mixtures of non-hydraulic setting ingredients, which are installed hot or cold, usually by the shotcrete method. Under certain circumstances they can be placed by other means, depending on material and application. Gunning mixes are available in clay or non-clay varieties, air- or heat-setting; and consist of graded aggregates, plasticizers, non-hydraulic or chemical binders, and at times, a small quantity of calcium aluminate cement for cold strength. The clay gunning mixes are available in fireclay, high-alumina, and insulating varieties; while the non-clay mixes are classified as “basic” (chrome, chrome-magnesite, magnesite-chrome, magnesite, and dolomite) or “other” (extra-high alumina, mullite, zircon, etc.).

These mixes are usually applied with various types of wet or dry shotcrete equipment, depending on the manufacturer's recommendations. Hot gunning requires specially designed nozzle-lances (see API TR 979) which may incorporate cooling devices to aid installation. Certain gunning mixes are designed to combine the dry ingredients with a liquid binder rather than water, and therefore require special attention during installation. Some manufacturer's data sheets recommend a maximum surface temperature during application and occasionally may specify a minimum temperature.

Gunning mixes generally have low rebound loss, are predominately used for patching or resurfacing brick or other refractories, have a strong internal bond, and exhibit excellent adhesion or bonding to the existing refractory lining. They find extensive use in erosion-resistant fluid solids applications, basic oxygen, electric arc, and open hearth furnaces, among other applications.

4.6 Non-refractory Applications of Calcium Aluminate Cement [1, 7, 8, 9, 10]

Calcium aluminate cement was originally developed to provide a hydraulic cement which would be an alternative to Portland cement and which would have improved durability in sea water. Subsequently, it was found that they achieved strengths in 24 hours, comparable to the 28-day strengths of Portland cement, and had refractory properties and resistance to certain acids.

The high, early strength properties led to the use of calcium aluminate cement in rapid hardening concrete to speed construction and form removal. The high heat generated during hydration allows calcium aluminate concretes to be placed at low temperatures, minimizing the cold weather protection required. Calcium aluminates have good resistance to the attack of most sulfates and will resist many acids and organic materials, provided the pH of the environment is not less than 4.0. The corrosion-resisting qualities of calcium aluminate cement concrete makes it useful in some structural applications. The reader should be cautioned, however, about the use of calcium aluminate cements for structural and load-bearing purposes. A complex chemical phenomenon known as “conversion” or “alkali hydrolysis,” which depends on time, temperature, and the presence of water, can cause a significant decrease in strength and an increase in permeability [1, 7, 8, 10, 11]. The effects of conversion can be controlled in non-refractory applications by employing mix designs and installation practices which enable sufficiently low water/cement ratios.

However, for structural applications it is recommended that the manufacturer be consulted prior to its specification and use.

5 Constituent Ingredients of Refractory Concretes

5.1 Introduction

A variety of hydraulic and non-hydraulic materials can be used either individually or in combination for different refractory applications. Both the binders and aggregates can be obtained separately by the consumer and combined prior to making concrete. Packaged materials containing appropriately proportioned binders and graded aggregates are called “castables.” They are commercially available and only require a liquid addition, typically water, for placement.

5.2 Binders

The binders principally used in refractory concretes are calcium aluminate cements. However, ASTM-type Portland cements can be used in some refractory applications up to an approximate maximum of 1000 °F (540 °C) with selected aggregates, if special precautions are taken to ensure a sound refractory concrete. Cyclic heating and cooling tends to disrupt Portland cement concretes. Adding a fine siliceous material to react with the calcium hydroxide, formed during hydration, is helpful in alleviating this problem.

The specific gravity generally ranges from 2.95 gm/cm³ to 3.25 gm/cm³, with higher values for the low and intermediate purity cements, which reflects larger amounts of Fe₂O₃ in the composition.

Cement colors range from black to white depending on the amount and state of iron oxidation. Low purity grades can be black to dark gray if reduced iron oxide is present, or light brown if oxidized. Intermediate purity grades can be light gray if reduced iron oxide is present or tan if oxidized, and high-purity grades are typically white.

After establishing a suitable product, the producer must ensure that the material quality is maintained throughout the processing of subsequent lots and that quality does not change as production continues.

Calcium aluminate (high-alumina) cements are commercially available hydraulic binders. They are specifically designed for use in monolithic refractory concrete construction. These binders are proportioned with selected refractory aggregates in various combinations to obtain specific high-temperature properties.

Calcium aluminate cements are generally classified under three basic categories:

- Low Purity,
- Intermediate Purity,
- High Purity.

Some chemical oxide and physical property ranges of commercial cements are shown in Table 1.

Binder selection is primarily based on the service temperature desired for the refractory concrete. Maximum service temperatures are increased with increasing Al₂O₃ and decreasing iron contents. Lower iron content binders are also beneficial in reducing carbon monoxide (CO) disintegration of concrete (see 11.16).

Table 1—Characteristics of Calcium Aluminate Cement Binders

Characteristic	Low Purity	Intermediate Purity	High Purity
Al ₂ O ₃ (ASTM C114), %	36–47	48–62	70–80
SiO ₂ , %	7–16	1–3	0.1–0.2
Fe ₂ O ₃ (total iron), %	35–42	26–39	18–26
CaO, %	3.5–9.0	3.5–9.0	0–0.5
Wagner Surface Area (ASTM C115), gm/cm ³	1500–1700	1600–2000	> 2500
Blaine Surface Area (ASTM C204), gm/cm ³	2600–4400	3200–6200	3600–10300
Initial Set Time, Vicar (ASTM C191), hr-min	4:00–7:00	1:30–8:00	0:30–4:00

5.3 Aggregates

Refractory aggregates are granular materials which are mixed with calcium aluminate cements and water to form a suitable concrete mass. Selection of the proper type and gradation is essential for obtaining desired refractory properties in a specific installation.

The maximum service temperatures of selected aggregates mixed with appropriate calcium aluminate cements under optimum conditions are listed in Table 2. Because this table is for optimum conditions, some of the values may be higher than those given in Table 9 and Table 10 for refractory concretes in normal service where the conditions may be less than optimal.

Table 2—Maximum Service Temperatures of Selected Aggregates Mixed With Calcium Aluminate Cements under Optimum Conditions

Aggregate	Remarks	Maximum Temperature	
		°C	°F
Alumina, Bubble	Refractory, insulating	1820	3300
Alumina, Fused	Refractory, abrasion resistant	1870	3400
Alumina, Tabular	Refractory, abrasion resistant	1870	3400
Bauxite, Calcined	N/A	1650	3000
Chrome-magnesite	N/A	1650	3000
Chromite	Slag resistant, high thermal conductivity, and heavy	1650	3000
Corundum	N/A	1800	3270
Diatomaceous Earth, Calcined	Insulating	1000	1830
Dolomitic Limestone (Gravel)	Abrasion and corrosion resistant	500	930
Emery	N/A	1100	2010
Fireclay, Expanded	Insulating, abrasion, and corrosion resistant	1640	2980
Fireclay Brick, Crushed	Abrasion and corrosion resistant	1600	2910
Fireclay Brick	(Maximum temperature depends on Al ₂ O ₃ content)	1500	2730
Crushed Insulating Flint Fireclay, Calcined	Insulating	1650	3000
Fly Ash, Expanded	Insulating, depends on composition	1200	2190

Table 2—Maximum Service Temperatures of Selected Aggregates Mixed With Calcium Aluminate Cements under Optimum Conditions (Continued)

Aggregate	Remarks	Maximum Temperature	
		°C	°F
Kaolin, Calcined	Abrasion and corrosion resistant	1650	3000
Kyanite, Calcined	N/A	1650	3000
Limestone (Gravel)	Abrasion and corrosion resistant	700	1290
Mullite	N/A	1650	3000
Olivine	N/A	1370	2500
Perlite	Insulating	1340	2450
Pumice, Expanded	Insulating	1090	2000
Pyrophyllite ^a	N/A	1300	2370
Sand	Abrasion and corrosion resistant (silica content less than 90 % not recommended)	300	570
Shale, Expanded	Insulating, abrasion, and corrosion resistant	1200	2190
Silicon Carbide	High thermal conductivity	1700	3090
Sillimanite	N/A	1600	2910
Slag, Blast Furnace (Air Cooled)	Abrasion resistant	540	1000
Slag, Blast Furnace (Granulated)	Insulating, abrasion, and corrosion resistant	1200	2190
Slate, Expanded	Insulating, abrasion, and corrosion resistant	1200	2190
Trap Rock, Diabase	(Basic igneous rock-minimal quartz) abrasion and corrosion resistant	1000	1830
Vermiculite	Insulating	1100	2010
^a The properties of pyrophyllite vary considerable depending on the source and type. It should be noted that both calcined and uncalcined pyrophyllite can be used, however, uncalcined pyrophyllite may undergo significant volume change on heating.			

These maximum temperatures are based on optimum conditions of binder and aggregate. Thermal properties of aggregates, such as volume change (expansion, shrinkage or crystalline inversion) and decomposition, can affect these maximum temperatures, along with the chemical composition of both aggregate and binder and the reactivity between these mix constituents. The above properties are discussed further in API TR 979.

Temperature stability of the aggregate determines the maximum service conditions below approximately 2400 °F (1320 °C). Therefore, any type of calcium aluminate cement listed in aggregates up to 2700 °F (1480 °C), intermediate purity to 3000 °F (1650 °C) and high purity to 3400 °F (1870 °C).

Aggregate gradation is an important consideration in designing refractory concrete. Differences in the grain sizes of a specific type of aggregate can produce variations in cement/aggregate volume, water requirements and workability or plasticity characteristics. These variations will subsequently affect the porosity, strength, unit weight and linear change of the concrete. Table 3 provides suggested guidelines for nominal maximum size and grading of refractory aggregates.

Table 3—Aggregate Grading

Maximum size aggregate (except for gun placement)	1 1/2 in. (3.81 cm)
Maximum size aggregate for normal gun placement	1/4 in. ^a (0.64 cm)
Maximum size insulating crushed firebrick	1 in. (2.54 cm)
Maximum size expanded shales and clays	1/2 in. (1.27 cm)
Maximum size, with the above exceptions, should not be greater than 20 %–25 % of the concrete minimum dimension.	
Aggregate of 1/2 in. (1.27 cm) or larger size:	
Retained on No. 8 Sieve = 50 %	
Passing No. 100 Sieve 10 %–15 %	
Aggregate of less than 1/2 in. (1.27 cm) maximum size:	
Retained on No. 50 Sieve = 75 %	
Passing No. 100 Sieve 10 %–15 %	
^a In special cases larger sizes have been used successfully.	