# Chapter 8
# Concrete and Cement

**Mariano Velez**

**Abstract** Inorganic concretes are reviewed, emphasizing two major areas: construction concretes and high temperature (refractory) concretes. Although such materials are intended for completely different applications and markets, they have in common that they are made from inorganic ceramic oxides and both materials are used for structural purposes. Current applications and research topics representing new challenges are summarized.

## 1 Introduction

Concrete usually indicates a construction material made from Portland cement, aggregates (for instance, gravel and sand), water, and additives to improve mixing or specific properties of the final material. Refractory concretes (monolithic refractories) refer to high-temperature materials for the manufacture of shaped refractories. Most concrete refractories are based on calcium aluminates, although some applications require the use of other high-temperature ceramic materials, such as magnesium oxide. The distinguishable feature of these concretes is that the method of preparation does not involve forming or firing at the manufacturing plant as in the fabrication of refractory bricks. This compilation includes only concretes for construction and refractory applications.

Cement is a binder that sets and hardens by itself or binds other materials together. The most widely known application of cements is in construction; a second one is the area of "bone cements." Cements used in construction are characterized as hydraulic or nonhydraulic and mostly for the production of mortars and concrete. Hydraulic cements set and harden after combining with water. Most construction cements are hydraulic and based on Portland cement, which consists of calcium silicates (at least 2/3 by weight). Nonhydraulic cements include the use of nonhydraulic materials such as lime and gypsum plasters. Bone cements and bone cement composites refer to compounds that have a polymer matrix with a dispersed phase of particles. For instance, polymethylmethacrylate (PMMA) is reinforced with barium sulphate crystals (for radio-opacity) or with hydroxyapatite

J.F. Shackelford and R.H. Doremus (eds.), *Ceramic and Glass Materials: Structure, Properties and Processing*.

to form a bioactive cement. These composites are currently used in orthopaedics for bone trauma repair.

## 2 Construction Concrete

Natural cementitious materials have existed for very long time; however, synthetic materials were perhaps first used by Egyptians and Chinese thousands of years ago [1, 2], and the Romans used pozzolanic materials (a volcanic rock in powder form and used to make hydraulic cement) to build the Rome Coliseum. It was only until around 1824 when Joseph Aspdin, bricklayer of England, invented Portland cement by burning finely ground chalk with finely divided clay until carbon dioxide was driven off. The sintered product was ground and named as Portland cement after the building stones quarried at Portland, England.

Portland type cements are calcium silicates, which when mixed with water form a paste, producing a hardened mass of valuable engineering properties. The clinker (the fused or partly fused by-product that after grinding becomes cement) chemistry is (by weight) 50–70% 3CS (*alite*, $3CaO{\cdot}SiO_2$), 15–30% 2CS (*belite*, $2CaO{\cdot}SiO_2$), 5–10% 3CA ($3CaO{\cdot}Al_2O_3$), and 5–15% 4CAF (*ferrite*, $4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$). Concrete is a mix of cement paste and aggregates (inert granular materials such as sand, gravel, recycled concrete), which the cement binds together into a rock-like composite. Main applications are for civil infrastructures such as buildings, highways, underground mass transit systems, wastewater treatment facilities, and marine structures. A compilation on materials, properties, working operations, and repair is given by Dobrowolski [3].

Approximately, 1.6 billion tons of Portland cements are produced worldwide annually with an estimated 5% generation of the $CO_2$ emission. Global cement and concrete additives (fiber and chemical additives) demand is forecast to grow 6.3% annually through 2006, driven by construction and by higher standards for concrete that require more additives per ton [4].

The US is the third largest cement producing country in the world (after China and India). The US concrete industry is the largest manufacturing sector in the United States (cement, ready-mixed concrete, concrete pipe, concrete block, precast and prestressed concrete, and related products), with over two million jobs related directly and including materials suppliers, designers, constructors, and repair and maintenance. The value of shipments of cement and concrete production exceeds $42 billion annually. Currently, there are a total of 115 cement manufacturing plants in the US, with about 75% of the total plants owned by only ten large companies: Lafarge North America, Inc., Holcim (US) Inc, CEMEX, SA de CV, Lehigh Cement Co., Ash Grove Cement Co., Essroc Cement Corp., Lone Star Industries Inc., RC Cement Cp., Texas Industries Inc. (TXI), and California Portland Cement Company.

Two types of manufacturing processes have become prevalent in the cement industry: "wet process" and "dry process." Although these processes are similar in many respects, in the older "wet process," ground raw materials are mixed with water to form a thick liquid slurry, while in the "dry process," crushed limestone is used and raw materials are mixed together, with consequent higher energy efficiency as drying is eliminated. Figure 1 represents schematically the cement manufacturing process and the rotary kiln for clinker production.

## 2.1 Fiber-Reinforced Concrete

Fiber-reinforced concrete (FRC) has a randomly oriented distribution of fine fibers in a concrete mix [5]. Fiber size varies with typical length less than 50 mm and diameter less than 1 mm. Many fibers have been used for concrete reinforcement (Table 1), with additions of 0.1–3% by volume of fibers, which improves the strength of the concrete by up to 25% and increasing the toughness by a factor of 4. This means that FRC is less susceptible to cracking than ordinary concrete showing longer service life.

Structural concrete is reinforced with steel to carry tensile forces that are internally generated when a structure undergoes elastic and inelastic deformations. Steel fiber-reinforced concrete (SFRC) consists of cement containing aggregates and discontinuous steel fibers (low-carbon steels or stainless steel; ASTM A-820 [6] provides a classification for steel fibers). In tension, SFRC fails after the steel fiber breaks or is pulled out of the cement matrix. The strain and force interaction is complex and depends on factors such as chemical and mechanical bond between concrete and reinforcement, time-dependent properties (creep, shrinkage), environmental aspects (freezing, chemicals), geometric configuration, location and distribution, and concrete/reinforcement volume ratio.

The applications of SFRC take advantage of the static and dynamic tensile strength, energy absorbing characteristics, toughness, and fatigue endurance of the composite [7]. Uniform fiber dispersion provides isotropic strength properties. The applications include

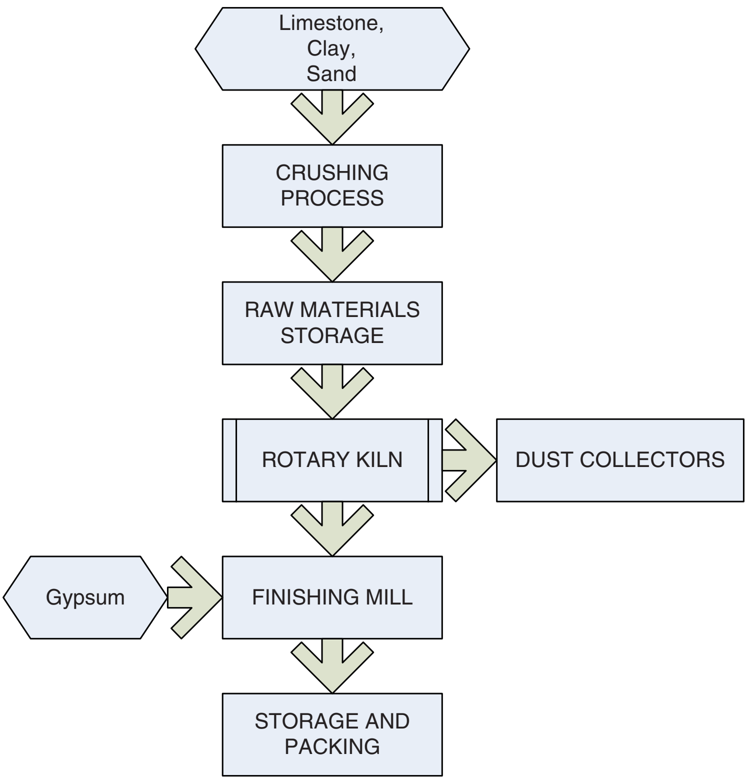


**Fig. 1** Flow diagram of main process

**Table 1** Fibers for concrete reinforcement

| | Advantages | Disadvantages | Comparison of properties of selected materials [8]: Density (g cm$^{-3}$) | Unidirectional tensile strength (GPa) |
|---|---|---|---|---|
| Steel | Provide very good, reasonably priced reinforcement | Corrode over time, after 6–8 years provide little reinforcement | 8.0 | 207 (steel 4130) |
| Stainless Steel | Very good reinforcement | Very expensive | | |
| Glass fiber | Good reinforcement | Alkaline nature of concrete causes the strength of silica-based fibers to degrade with time | 1.99 (E-glass, S-glass) | 52–59 |
| Carbon and Kevlar | Excellent reinforcement, high strength | Very expensive; brittle behavior (Fig. 2) | 1.55–1.63 (Carbon) | 145–207 |
| Plastic fiber | Good reinforcement | Low cost | 1.38 (reinforced epoxy aramid) | 83 |

cast-in-place SFRC (slabs, pavements industrial floors), precast SFRC (vaults and safes for instance with fiber content from 1 to 3 vol%), shotcrete (a sprayed concrete developed for civil construction, for instance in slope stabilization and in repair and reinforcing of structures), and slurry infiltrated fiber concrete (called SIFCON, where a formwork mold is randomly filled with steel fibers and then infiltrated with a cement slurry, containing a much larger fiber fraction between 8–12% by volume). Corrosion of steel reinforcement and the tendency of concrete to lose bond, and reducing structural performance over time, promote the development of economical, thermodynamically stable metallic and nonmetallic, corrosion-resistant reinforcements. Therefore, other reinforcement has been developed such as polypropylene fibers (most common in the market), glass fibers, and carbon fibers.

## 2.2 *Carbon and Organic-Based Fibers*

The evolution of fiber-reinforced plastic (FRP) as reinforcement in concrete began in the 1960s to solve the corrosion problem associated with steel-reinforced concrete in highway bridges and structures [8]. This is a class of materials defined as a polymer matrix, whether thermosetting (e.g., polyester, vinyl ester, epoxy, phenolic) or thermoplastic (e.g., nylon, PET) reinforced by fibers (e.g., aramid, carbon, glass). Each of the fibers considered suitable for use in structural engineering has specific elongation and stress–strain behavior. Composite reinforcing bars have more recently been used for construction of highway bridges and it appears that the largest market will be in the transportation industry. Figure 2 shows an example of repairing a small bridge by preparing a network of FRP beams and then casting a construction concrete. The engineering benefits of these fibers include the inhibition of plastic and shrinkage cracking (by increasing the tensile strain capacity of plastic concrete), reducing permeability, and providing greater impact capacity, and reinforcing shotcrete.

**Fig. 2** Setting a FRP network for casting a construction concrete in the repair of a bridge (Courtesy of D. Gremmel, Hughes Brothers)

Carbon fiber-reinforced plastic (CFRP) in grid form has demonstrated potential as a reinforcing material in lightweight concrete. A high tensile capacity allows the grid to work efficiently with compressive strength in bending. Additionally, carbon fiber may act as thermal insulator. It allows a reinforced mold for production when used in grid form. However, a CFRP grid is an expensive and brittle material, and the grid form can melt under a fire accident.

## *2.3 Glass Fiber-Reinforced Concrete*

Glass fibers have relevance in civil engineering applications because of cost and specific strength properties. The worldwide glass reinforcement market is estimated in 2.5 million tons (2001), with an average growth of 5.4% per year [9]. Original GFRC pastes used conventional borosilicate glass fibers (E-glass) and soda-lime-silica glass fibers (A-glass), which lose strength due to high alkalinity (the pH value for concrete environment is above 12.8 [10]) of the cement-based matrix. Other compositions include S-glass (an Mg–Al–silicate of high strength), S-2 glass (an S-glass composition with surface treatment), and C-glass (a Na-borosilicate) used in corrosive environments [8]. Improved alkali-resistant fibers have compositions containing 16% zirconia. Another potential alternative is the use of novel high-alkaline-resistant Fe-phosphate glasses [11]. Extended exposure of silica-based GFRC to natural weather results in changes in mechanical properties and volumetric dimension changes. Dimensional changes in GFRC can be considerably greater than those of conventional concrete, as a result of the high cement content in the mortar matrix. Over stressing or stress concentrations can cause cracks. This can be critical in components that are overly restrained.

**Table 2** Applications of GFRC [7]

| General Area | Examples |
|---|---|
| Agriculture | Irrigation channels, reservoir linings |
| Architectural | Interior panels, exterior panels, door frames, windows |
| Asbestos replacement | Sheet cladding, plain roof tiles, fire-resistant pads, molded shapes and forms, pipes |
| Ducts and shafts | Track-side ducting for cables, internal service ducts |
| Fire protection | Fire doors, internal fire walls, partitions, calcium silicate insulation sheets |
| Buildings | Roofing systems, lintels, cellar grills, floor gratings, hollow nonstructural columns, impact-resistant industrial floors, brick façade siding panels |
| Housing | Single and double skin cladding, prefabricated floor and roof units |
| Marine | Hollow buoys, floating pontoons, marina walkways, workboats |
| Metal placement | Sheet piling for canal, lake or ocean revetments, covers, hoods, stair treads |
| Pavements | Overlays |
| Permanent and temporary | Bridge decking formwork, parapets, abutments, waffle forms, columns and beams |
| Site-applied surface bonding | Bonding of dry-blocks walls, single skin surface bonding to metal lath substrates, ultra-low-cost shelters |
| Small buildings | Sheds, garages, acoustic enclosures, kiosks, telephone booths |
| Small containers | Telecommunication boxes, storage tanks, meter encasements, utility boxes |
| Street furniture | Seats and benches, planters, litter bins, signs, noise barriers, bus shelters |
| Water applications | Low-pressure pipes, sewer linings, field drainage components, tanks |

Fiber is used in larger dosages, i.e., ~2 kg $m^{-3}$ of concrete in commercial applications. The single largest application of GFRC has been the manufacture of exterior building facade panels [12], with at least 80% of all GFRC architectural and structural components manufactured in the US Other application areas are listed in Table 2.

## *2.4 Testing and Evaluation*

There are several techniques for evaluating civil structures [i.e., 13] with pulse echo techniques including radar (reflection and scattering of electromagnetic pulses) [14–16], impact echo (propagation, reflection, and scattering of elastic waves after mechanical impact) [17, 18] and ultrasonic pulse echo (propagation and dispersion of sound waves produced with ultrasonic transducers) [19]. The more widely known techniques are perhaps impulse response (IR) and impact-echo testing. The IR method uses a low-strain impact to send stress waves through a specimen via a sledgehammer with a built-in load cell. The maximum compressive stress at the impact point is related to the elastic properties of the hammer tip. Response to the input stress is measured with a velocity transducer [20]. The IR method is suggested for evaluation of reinforced concrete structures such as floor slabs, pavements, bridge decks and piers, fluid retaining structures, chimneystacks, and silos.

More recently, the impact-echo technique is used to determine the position of intermediate and large defects in concrete structures. It is used to assess the bonding condition between facing stones, mortar, and inner rubble core in stone masonry [21] and the structural integrity of high-performance/high-strength concrete of existing buildings using SAWS (spectral analysis of surface waves) [22]. A mechanical impact on the surface of the structure is used to generate an elastic stress wave that travels through the structure, reflects off external boundaries and internal flaws, and returns to the surface. A receiver located near the point of impact is used to measure the normal surface displacements. Fast Fourier transform (FFT) is used to determine the corresponding frequency spectrum and analyze the location of flaws or (internal or external) surfaces by using [23].

$$d = \frac{C_p}{2f}, \tag{1}$$

where $C_p$ is the P-wave (primary/pressure wave) speed within the material (~2,000–4,000 m $s^{-1}$ for concrete depending on age and other characteristics [24, 25]) and $f$ is the characteristic frequency. Limitations and associated problems of the method include spectral effects of the impactor, the receiving device, and the interpretation of other reflected waves [26]. Improvements are reported using noncontacting devices for both impact generation (shock waves) and response monitoring (laser vibrometer to measure surface velocity) [27].

Flexural strength is determined according to ASTM C 947 [28] and density is determined according to ASTM C 948 [29]. GFRC made of cement, AR-glass fibers, sand, and water is a noncombustible material and should meet the criteria of ASTM E 136 [30]. Single skin GFRC panels can be designed to provide resistance to the passage of flame, but fire endurances of greater than 15 min, as defined in ASTM E 119 [31], are primarily dependent upon the insulation and fire endurance characteristics of the drywall or back-up core.

## 2.5 Current Research Topics

A substantial amount of research is being carried at the NSF Center for Science and Technology of Advanced Cement-Based Materials at Northwestern University [32]. A survey of the literature is kept by The American Ceramic Society [33, 34]. Four general critical areas, necessary to maintain technological leadership, have been identified by the US industry [35]: (1) *design and structural systems*, (2) *constituent materials*, (3) *concrete production, delivery, and placement*, and (4) *repair and rehabilitation* (Table 3). Topics of current scientific research include characterization of microstructural features (e.g., C–S–H gel, pore shape, heterogeneity), mechanical properties (model prediction, measurement, performance improvement), chemical behavior (e.g., in corrosive environments, hydration process, $CaCO_3$ efflorescence), characteristics of concrete at elevated temperatures. Other specific areas include test methods to determine properties (i.e., fatigue, creep, and chemical properties) of FRP, which are reproducible and reliable. Repair of structures is a relevant area that has several worldwide organizations involved. In addition to the American Concrete Institute (ACI), groups providing information include the International Concrete Repair Institute, Concrete Repair Association (U.K.), Building Research Establishment (U.K.), American Concrete Pavement Association, American Association of State Highway Transportation Officials, The Concrete Society (U.K.), The Cathodic Protection Association (U.K.), and US Army Corps of Engineers.

Table 4 summarizes recent developments regarding cement and concrete materials. Improved materials and advanced sensors are needed for very demanding applications

**Table 3** Main research needs in the concrete industry [adapted from 35]

| Design and Structural Systems | |
|---|---|
| Structural concrete | System survivability |
| Reinforced concrete | Design methodologies for reinforcement and fibrous concrete |
| Modeling and measurement | Interaction prediction, monitoring |
| High-performance concrete | Improved technologies and advanced testing methods |
| Technology Transfer | Accelerating technology transfer from 15 to 12 years |
| | Appraisal services by standard and code bodies |
| Fire-, blast-, and earthquake-resistant materials and systems | Smart systems for design of fire-, blast-, and heat-resistant alternative reinforced structures |
| | Survivability reserach |
| Crosscutting innovations | Concrete as part of multimaterials systems |
| Constituent materials | |
| New materials | Noncorroding steel reinforcement |
| | Concrete with predictable performance |
| | Materials with reduced shrinkage and cracking |
| | Reduction of alkali-silica reactions in concrete |
| Measurement and prediction | Prediction methods and models for permeability, cracking, durability, and performance |
| | Quantifying benefits of using alternative materials |
| Recycling | Reuse of high-alkali wastewater |
| | Aggregate recycling |
| | Reuse of cementitious materials |
| Concrete production, delivery, and placement | |
| Information and control | Intelligent, integrated knowledge systems |
| | Improved control over nonspecified concrete |
| | On-line batching control |
| Production | Increased applications for robotics and automation |
| Test methods and sensors | Improved sensing technologies and portability |
| | Technologies to insure performance requirements |
| | Nondestructive test methods |
| Energy and environment | Reuse and recycling issues |
| | Reduction of transportation energy use |
| | Increased use of waste from crosscutting technologies |
| | Life-cycle model for $CO_2$ impact |
| Repair and rehabilitation | |
| New repair methods | New repair materials and applications technologies |
| | Self-repairing concrete |
| Assessment tools and modeling | Nondestructive testing for stress |
| | Long-term monitoring of structures |
| Repair field | Mitigation of alkali-silica reactivity |
| | Corrosion-canceling technologies |
| | Low-maintenance, long-life repair of concrete for corrosion protection of embedded steel |

such as concrete in offshore oil platforms [36] and in the nuclear industry where concrete structures have performed well [37]. However, as these structures age, degradation due to environmental effects threaten their durability. Items of note are corrosion of steel reinforcement following carbonation of the concrete or ingress of chloride ions, excessive loss of posttensioning force, leaching of concrete, and leakage of posttensioning system corrosion inhibitor through cracks in the concrete.

**Table 4** Recent US patents on cement-related materials development

| Assignee | Number | Short title |
|---|---|---|
| MBT Schweiz | 6,489,032 | Cement structure containing a waterproofing layer |
| Aso Cement | 6,464,776 | Dusting-inhibited cement with improved strength |
| Sumitomo Osaka | 6,419,741 | Cement clinker and cement containing the same |
| Sika AG | 6,387,176 | Polymers for high-flow and high-strength concrete |
| Daicel-Huels | 6,376,580 | Cement retarder and cement retardative sheet |
| Taiheiyo Cement | 6,358,311 | Additives for cement materials and cement materials |
| RoadTechs Europe | 6,315,492 | Road repair material comprising cement and resin |
| Polymer Group | 6,258,159 | Synthetic polymer fibers into cement mixtures |
| Takemoto Yushi | 6,176,921 | Cement dispersants |
| Daicel-Huels | 6,114,033 | Cement retarder and cement retardative sheet |
| U. of Michigan | 6,060,163 | Fiber reinforcement of cement composites |
| Arco Chemical | 6,034,208 | Copolymers as cement additives |
| FMC Corporation | 6,022,408 | Compositions for controlling alkali-silica reaction |
| Toho Corporation | 5,997,631 | Hardener for waste-containing cement articles |
| W. R. Grace & Co | 5,938,835 | Cement composition inhibit drying shrinkage |
| DPD, Inc. | 5,935,317 | Accelerated curing of cement-based materials |
| Lafarge Canada | 5,928,420 | Alkali-reactive aggregate and sulphate resistance |
| W. R. Grace & Co | 5,840,114 | Early-strength-enhancing admixture for precast cement |
| College of Judea | 5,772,751 | Light-weight insulating concrete |
| Elkem ASA | 5,769,939 | Cement-based injection grout |
| MBT Holding | 5,728,209 | Unitized cement admixture |
| Dipsol Chemicals | 5,653,796 | (Phosphorous acid) Admixture for cement |
| Union Oil of California | 5,599,857 | (Waterless) Polymer concrete composition |
| Dow Chemical | 5,576,378 | High Tg polymer for portland cement mortar |
| C F P I | 5,567,236 | Improved rheology of cement-products |
| Louisiana State US | 5,565,028 | Alkali-activated class C fly ash cement |
| ENCI Nederland | 5,482,549 | Cement and products using such cement |
| Takenaka Corporation | 5,466,289 | Ultra high-strength hydraulic cement compositions |

## 3 Refractory Concretes (Monolithic Refractories)

Monolithic refractories, or unshaped refractories, are made from almost same raw materials as firebricks. The distinguishable feature is that the method of preparation does not involve forming or firing at the manufacturing plant. A general definition includes batches or mixtures consisting of additives and binders, prepared for direct use either in state of delivery or after adding suited liquids. The final mix may contain metallic, organic, or ceramic fibers [38, 39].

### *3.1 Compositions and Applications*

Several ways of classifying these refractories have been listed according to physical and chemical properties or applications [40, 41]:

- Method of installation: pouring/casting, trowelling, gunning (shotcreting), vibrating, ramming, and injecting
- Use or application: materials for monolithic constructions, materials for repairs, materials for laying and forming joints (mortars)
- Type of bond: hydraulic bond with hardening and hydraulic setting at room temperature, ceramic bond with setting by sintering during firing, chemical bond (inorganic or

organic–inorganic) with setting by chemical but not hydraulic reaction at room temperature or at temperature below the ceramic bond, and organic bond by setting or hardening at room temperature or at higher temperatures
- Chemical composition: silica-based and silica-alumina-based materials, chrome, magnesia, chrome-magnesia, spinel, SiC, materials containing carbon (more than 1% carbon or graphite), and special materials (containing other oxides or materials such as zircon, zirconia, $Si_3N_4$, etc.)
- Bulk density: lightweight (bulk density below 1.7 g cm$^{-3}$) and dense castables
- Norms and Standards: for instance ISO (International Organization for Standardization), and ASTM (American Society for Testing and Materials)

Calcium aluminate cements are examples of conventional refractory castables. Development of low, ultralow cement, no-cement pumpables, and self-flow castables has increased the applications of monolithics [42]. Steel-reinforced refractories (SFRR) are used in applications that include ferrous and nonferrous metal production and processing, petroleum refining, cement rotary kilns, boilers, and incinerators. Steel fibers are added to refractory concretes to improve resistance to cracking and spalling in applications of heavy thermal cycling and thermal shock loads.

Phosphate-bonded monolithic refractories are available both as phosphate-bonded plastic refractories and phosphate-bonded castables. Phosphate-bonded plastic refractories contain phosphoric acid or an Al-phosphate solution. They are generally heat setting refractories, developing high cold strength after setting, and are highly resistant to abrasion. Phosphate-bonded castables contain no cement, and magnesia may be added as setting agent [40].

## 3.2 Drying and Firing of Refractory Castables

Refractory monolithic linings are dried on site by one-side heating. During drying, rapid heating rates might lead to degradation of mechanical properties, and in extreme cases, to excessive buildup of pore pressure and even explosive spalling. A slow heating rate, on the other hand, is more energy and time consuming. Drying involves coupled heat and mass transfer in a porous solid undergoing microstructural changes (i.e., pore size and shape) and chemical changes (i.e., dehydration). Steam pore pressure is the main driving force for moisture transfer, as well as the force that could cause failure of the refractory concrete when it builds above its mechanical strength. Several material properties (such as permeability, thermal conductivity, and mechanical strength) are strongly affected by temperature and moisture content during the drying process. Dewatering is affected by the coupled and interactive influences of a number of variables, which include texture, mix constitution, permeability, strength, thermal conductivity, moisture content, casting and curing practice, binder level and type, dry-out schedule, and installation geometry. A common method for improving the spalling resistance of refractory concretes has been to add organic fibers to the mixes to increase permeability.

Permeability is the material property that most influences the drying process of refractory castables [43–45]. The permeability of compressible fluids flowing through rigid and homogeneous porous media is described by the Forchheimer equation, which includes a quadratic term for the flow rate $q$. For small changes in pressure, the Forchheimer's equation leads to Darcy's law:

$$q = k\frac{\Delta p}{L}, \tag{2}$$

where the pressure drop $\Delta P$ is the difference between the absolute fluid pressure at the entrance and at the exit of the sample, $L$ is the sample thickness, and $K$ is the coefficient of permeability, used in computer simulations [i.e., 46]. Very low permeabilities of refractory castables are measured using a vacuum decay approach [47, 48]. A vacuum decay curve is generated by monitoring the pressure change across a specimen-slab in a vacuum chamber, as a function of time.

## *3.3 Evaluation Techniques*

### 3.3.1 Wall Thickness

Several methods have been proposed to nonintrusively measure the thicknesses of walls, corrosion profiles, and macrodefects [i.e., 49]. Two methods at room temperature that require point contact with the cold face of the furnace are known. The first is impact-echo method, used in construction concretes and pavements (Sect. 1.4). The second method is the frequency-modulated continuous-wave (FM-CW) radar technique [50], which can produce wall thickness data in real time.

Use of ultrasonic testing techniques has been attempted in harsh environments including high temperatures and radiation [i.e., 51]. Testing is complicated because wave-guides with special high temperature couplants and cooling systems are necessary to protect ultrasonic transducers from reaching their Curie point. Newer transducers, based on AlN films, capable of emitting and receiving ultrasonic energy at temperatures exceeding 900°C and pressures above 150 MPa have also been reported [52].

### 3.3.2 Moisture Profile

The measurement of moisture profiles while drying construction concretes has been reported using strain gauges on laminated specimens [53] and by using magnetic resonance imaging (MRI) [54]. This last procedure has been shown to determine moisture profiles nondestructively and with very high resolution, on the order of millimeter or less. Size of specimens is limited to small cylinders (~ 2.5 cm diameter) and in situ heating of specimens limits the technique to research applications. Electromagnetic modeling of the interaction of microwave signals with moist cement-based materials [55, 56] provides the necessary insight to evaluate water content distribution and movement in refractory castables in a nonintrusive manner and with potential high resolution (1 mm).

### 3.3.3 Castable Rheology

Refractory castable mixing is influenced by particle-size distribution (PSD) and the water addition method used. Castables require a minimum of mixing energy to reach maximum flow values, which is supplied by a two-step water-addition and can be designed with PSDs that result in high mixing efficiency combining low torque values, short mixing times, and controlled heating [57]. Rheological evaluation is accomplished with a novel rheometer used also for development of improved mixes [58]. Besides flowability, set time, and strength-gain measurements, exothermic profile measurements have also been used to assess rheology [59]. An exothermic profile on a neat cement paste (a mixture of water and hydraulic cement) gives information about the composition and reactivity, and it is suggested for use in quality control applications. Such applications include verifying setting time, troubleshooting problem castables, and screening reactive materials.

## 3.4 Current Research Topics

Refractory concretes are used today in a wide variety of industrial applications where pyro-processing or thermal containment is required [60]. Calcium aluminate cement (CAC)-based monolithics represent the most important chemical category, and the fundamental properties and behavior have been recently summarized (production, uses, CAC clinker, mineralogy, microstructure and hydration, and environmental issues) [61]. The general current working topics are depending on economic trends of the industry. The demand for refractories in the US is projected to increase 2.2% per year to $2.4 billion in 2007 [62]. The demand is expected to improve the steel market since steel manufacturing consumes about 60% of total refractories. Preformed shapes (shapes manufactured with refractory castables) and castables (for in situ monolithic manufacturing) are expected to be the fastest growth segment. Table 5 summarizes the expected refractory demand in the US.

A common trend seen today in this industry is plant integration through the merger and alliance of refractories companies. In general, the global refractory production has increased, due in part to process optimization (better usage of refractories) or to improved refractory materials with better performance. Monolithic refractories consumption, however, has markedly increased and represents today a large portion of the total. For instance, it is about 60% of the total production in Japan [63].

Current issues on refractory monolithics include no-cement castables, self-flow and free-flow mixes [64], and special compositions such as spinel-based [65], placement techniques [66], new applications (i.e., crown superstructures for glass melters [67]), characterization [68, 69], and basic castables [70, 71]. Specialized publications have compiled and reproduced most of the most important topics [i.e, 72–74], which include the following:

- Development of high performance castables (i.e., high-strength under corrosion conditions at high temperatures)
- Application, installation issues; drying and firing equipment; development of very large shapes

**Table 5** Refractory product demand in the US (US$ million [62])

| | 1997 | 2002 | 2007 |
|---|---|---|---|
| Total demand | 2,518 | 2,180 | 2,430 |
| Bricks and shapes | 1,480 | 1,210 | 1,345 |
| Monolithics | 652 | 575 | 635 |
| Other | 386 | 395 | 450 |

- New binders for castables without affecting refractory properties; new dispersants and rheology studies
- Study of thermo-mechanical properties, chemical behavior, theoretical predictions, and computer simulation
- Development of basic castables: for instance, use of MgO, CaO, and dolomite for making high-temperature basic castables; coating of aggregates (i.e., silanes) for preserving clinkers
- Study and optimization of drying and firing: experimental and theoretical simulation of drying and its effects on mechanical strength and refractoriness.

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