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Refractory Concrete

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This report was written to fulfill the requirements of Civil Engineering Reports E9201and was done under the guidance of Professor Christian Meyer. The objective was to investigate the fire-resistant properties of concrete and to understand its behavior under extreme temperature conditions. Of particular interest were the properties and behavior of refractory concrete. A summary of the important characteristics of refractory concrete have been compiled to serve as a preliminary guide for additional research and development of new types of fire-resistant concrete. Current fireproofing techniques are also examined to provide a better understanding of refractory concretes' wide-ranging applications and its implications on structural systems.

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Introduction

Concrete has been used in construction for the past 2000 years and is today the most widely used building materials. There are several reasons for the widespread acceptance of concrete, namely its formability, relative low cost, and its resistance to fire. The formability of freshly mixed concrete allows for creative design limited only by the ability to put up the necessary formwork to achieve the desired shape and form. Concrete's main constituent materials are cement, aggregate, and water, all of which are readily available and at a low cost. Finally, concrete's resistance to high temperatures gives it a marked advantage over other building materials such as timber or steel, which behave poorly when exposed to fires.

In light of the tragic events of September 11, 2001 the importance of the behavior of structures exposed to high temperatures has become quite evident. Experts agree that the heat created by the burning jet fuel was a critical factor in the eventual failure of the steel columns in the World Trade Center. While the initial impact did not immediately cause the towers to collapse, the subsequent fire and heat caused the steel columns to weaken significantly and buckle. Although fireproofing was applied to the structural steel members, it proved to be inadequate because the impact of the planes may have knocked off much of the fireproofing or it may have simply peeled off over the years. Though purely speculative, questions have arisen over whether the towers would have survived had they been built of concrete and if indeed the fire was the key element in the failure mechanism of the trade towers.

While the fire resistance of regular structural concrete is adequate for normal fires, there is a type of special concrete designed specifically to resist temperatures as high as 3400°F (1870°C). Refractory concrete and heat resistant concrete have been developed over the last century for applications where significantly high temperatures are attained. Heat resistant concrete has been defined by the American Concrete Institute (ACI) as any concrete which will not disintegrate when exposed to constant or cyclical heating up to any temperature below which a ceramic bond is formed, which is usually around 900-1000°C. Refractory concrete, on the other hand, is concrete that can perform satisfactorily at temperatures above 1000°C and up to 1870°C. Unlike regular structural concrete made of Portland cement, most of these concretes use special types of cement and aggregates in order to achieve their heat resistive properties.

To understand why refractory concrete behaves the way it does, we must first understand the limitations of regular Portland cement based concrete.

Regular Portland Cement Concrete

Portland cement *

Portland cement is made up of essentially four different minerals: tricalcium silicate C_3S, dicalcium silicate C_2S, tricalcium aluminate C_3A, and tetracalcium aluminoferrite, C_4AF. These minerals are found in naturally occurring limestone and clay, which when combined with water forms a slurry. This slurry is then burned in a kiln oven at about 1450°C until a hard stone called clinker is formed. In the chemical composition of clinker, the main constituents generally lie in the following ranges:

* In cement chemistry, the following abbreviations are used: C = CaO (calcium oxide or lime), S = SiO_2 (silicate), A = Al_2O_3 (alumina), F = Fe_2O_3 (ferric oxide), H = H_20 (water), and <u>S</u> = SO_3 (sulfur trioxide)

C = 62-67%, S = 18-25%, A = 4-8%, F = 2-5%, and $\underline{S}$ = 0.5-2%. This clinker is finely ground and blended with a small amount of gypsum to produce the grayish cement powder we see at many construction sites.

The mineral composition of cement takes on an important role in understanding how concrete behaves under high temperatures, especially after they undergo a chemical reaction known as hydration. Hydration is the process resulting from the mixing of water and cement as shown in several simplified steps below:

For the tricalcium silicate,

$$2C_3S + 11H \rightarrow C_3S_2H_8 + 3CH + \text{Heat}$$

(tricalcium silicate + water = C-S-H gel + calcium hydroxide)

For the dicalcium silicate,

$$2C_2S + 4H \rightarrow C_3S_2H_8 + CH + \text{Heat}$$

(dicalcium silicate + water = C-S-H gel + calcium hydroxide)

For tricalcium aluminate,

$$C_3A + 3C\underline{S}H_2 + 26H \rightarrow C_6A\underline{S}_3H_{32}$$

(tricalcium aluminate + gypsum + water = ettringite)

followed by a second reaction (after consumption of the gypsum) given by,

$$2C_3A + C_6AS_3H_{32} + 4H \rightarrow 3C_4A\underline{S}H_{12} \text{ (monosulfoaluminate)}$$

Perhaps the most significant product of this hydration process is the $C_3S_2H_8$, commonly referred to as C-S-H gel or cement gel. It is the manner in which this cement gel is formed that determines the cement paste's ultimate strength and resistance to fire. The ultimate strength of the cement paste depends largely upon its water/cement ratio and the resulting porosity of the paste.

While the overall level of fire resistance in concrete is dependent on the composition of the cement and the type of aggregate used, it is important to understand the interactions between the individual cement components when they are heated. The use of a phase diagram is particularly helpful in showing exactly how these minerals change as the temperature is increased. For instance, by knowing the melting point of these individual or combinations of components, we can roughly estimate the maximum temperatures the concrete can be expected to withstand.

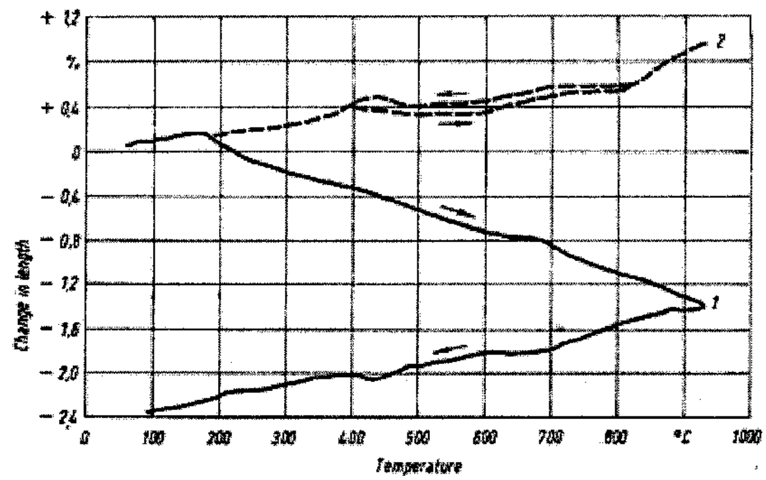
Portland cement's main constituents are CaO, SiO_2, and Al_2O_3, which when combined have a melting point of approximately 1455°C. Because these compounds compose almost 90% of Portland cement, they are a good indication of the cement's melting point. However, the inevitable presence of impurities such as Fe_2O_3, MgO, and SO_3 can significantly lower this temperature. A system consisting of CaO-SiO_2-Al_2O_3-Fe_2O_3-MgO-NaO has been found to begin melting at around 1280°C, a drop of nearly 200°C. Although these temperatures are comparable to temperatures reached in refractory concrete, they are not necessarily the temperatures attained by regular Portland cement concrete, since numerous factors such as the presence of other impurities in the cement, any cement aggregate interactions, and the water/cement ratio must also be considered.

Another important factor to remember is the meaning of the aforementioned temperatures. They are the point at which the cement begins to actually melt, or turn into a liquid phase. Clearly this is unacceptable in actual concrete structures, as this would imply that the concrete no longer can carry any load, including its own weight. A more useful measure of the concrete's maximum service temperature would be that at which failure occurs. Whether this is explosive spalling, complete collapse, or excessive deformations depends on the application. In the case of true fire resistance, this is measured by fire ratings that are determined by the American Society of Testing Methods (ASTM) E119 Standard, which is discussed in a later section.

The following section will look at the effect of elevated temperatures on the structure, strength, and behavior of Portland cement paste. With Portland cement's intrinsically low melting point, it is already evident that it is unsuitable for use in refractory concrete where temperatures over 1300°C may be reached. ACI Committee 547, has determined that Portland cement can be used in some refractory applications up to an approximate maximum of 1090°C, but only with selected aggregates and mineral additives.

Expansion/Shrinkage at Elevated Temperatures

The heating of hardened Portland cement results in an initial expansion of the cement, just as you would find in other materials such as steel. As the temperature increases to about 150°C, the water in the cement gel (C-S-H) begins to evaporate, resulting in the shrinkage of the cement paste. This contraction caused by the evaporating water counters the initial thermal expansion of the cement until it becomes the more dominant effect. The rate of shrinkage depends on the rate of moisture loss from the concrete and thus depends on such factors as the water/cement ratio, aggregate content, specimen geometry, and drying conditions at the surface. Figure 1 exhibits shrinkage behavior of Portland cement, while Figure 2 demonstrates the effect of temperature on the magnitude and rate of shrinkage.



1: First temperature cycle ; 2: Second temperature cycle

Figure 1. Expansion/Shrinkage behavior of Portland cement (adapted from Petzold p.29)

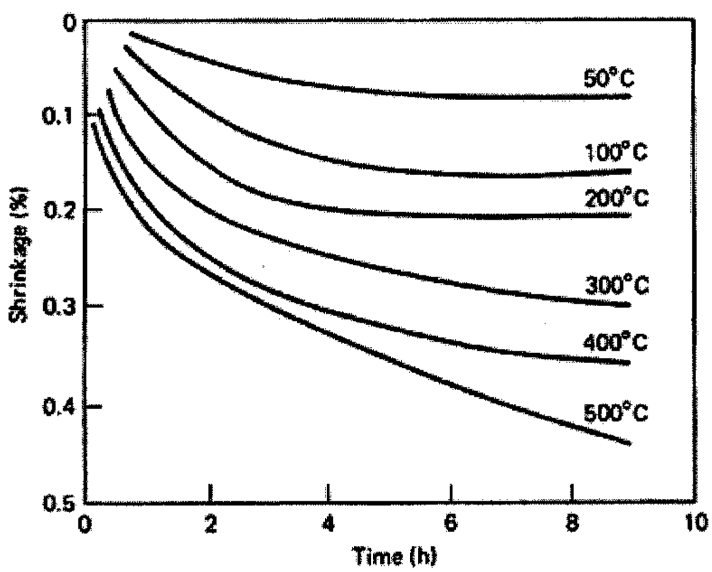


Figure 2. Effect of temperature on magnitude and rate of shrinkage (from N.G. Zoldners, in Temperature and Concrete, SP-25, American Concrete Institute, Detroit, Mich., 1971, pp 1-31.) (reproduced from Mindess p.531)

The beginning of the shrinkage at around 200°C can be attributed to the evaporation of water and the decomposition of the dehydrated cement gel and ettringite

($C_6AS_3H_{32}$) formed during the hydration process. The rate of shrinkage increases at higher temperatures as the structural decomposition of the hydration products continues, much of which is irreversible.

Another important reaction that takes place during this heating is the dehydration of the calcium hydroxide ($Ca(OH)_2$ or CH) which forms as a result of hydration of C_3S and C_2S. At approximately 400°C the calcium hydroxide dissociates to become CaO or lime. This free lime can cause severe cracking in the cement paste if it is allowed to cool and react with the moisture in the air to rehydrate back into $Ca(OH)_2$. The difference in densities of CaO and $Ca(OH)_2$, which are 210 lb/ft^3 and 146 lb/ft^3 respectively, results in cracking due to the almost 44% increase in volume of the free lime. Extensive cracking, while not a catastrophic failure, may be sufficient to preclude Portland cement from use for high temperature applications.

The effect of using different types of aggregate undoubtedly also plays a role in the behavior of concrete, as they too experience expansion/shrinkage effects. When the thermal coefficients of expansion of the aggregate and cement paste differ considerably, the resulting differential thermal movement within the concrete can cause cracking. Most natural aggregates have a coefficient of thermal expansion ranging from 1- $4x10^{-6}$/°C, while that of cement paste is about 5- $6x10^{-6}$/°C. Some aggregates, however, have expansions as low as 0.5-$1x10^{-6}$/°C. While there is evidence that this contributes to concrete's deterioration, it is not the sole significant factor in the failure of Portland cement concrete exposed to high temperatures.

Modulus of Elasticity at Elevated Temperatures

The modulus of elasticity of a material is most closely associated with its stiffness and is defined as the ratio of stress to strain when deformation remains elastic. Thus, a low modulus of elasticity can result in excessive deformations and a "softening" of the structure. A study conducted by Dias et al. showed that the cement paste's modulus of elasticity decreased markedly as the temperature increased, as seen in Figure 3.

The modulus of elasticity has been observed to reach as low as 5% of its original value at temperatures above 800 °C. This general decrease in the modulus of elasticity is found in all concrete, regardless of the aggregate used, as Figure 4 demonstrates.

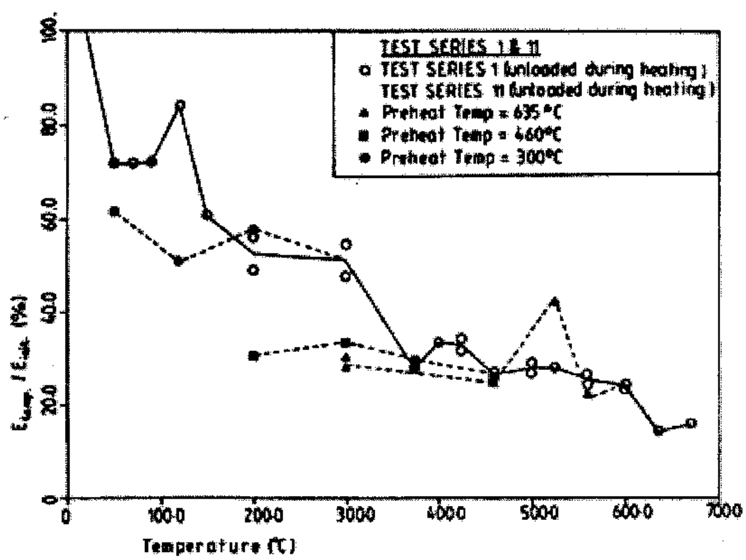


Figure 3. Static modulus of elasticity as a percentage of initial static modulus, for specimens brought to test temperature without load (adapted from ACI Materials Journal March/April 1990, "Mechanical Properties of Hardened Cement Paste Exposed to Temperatures up to 700°C")

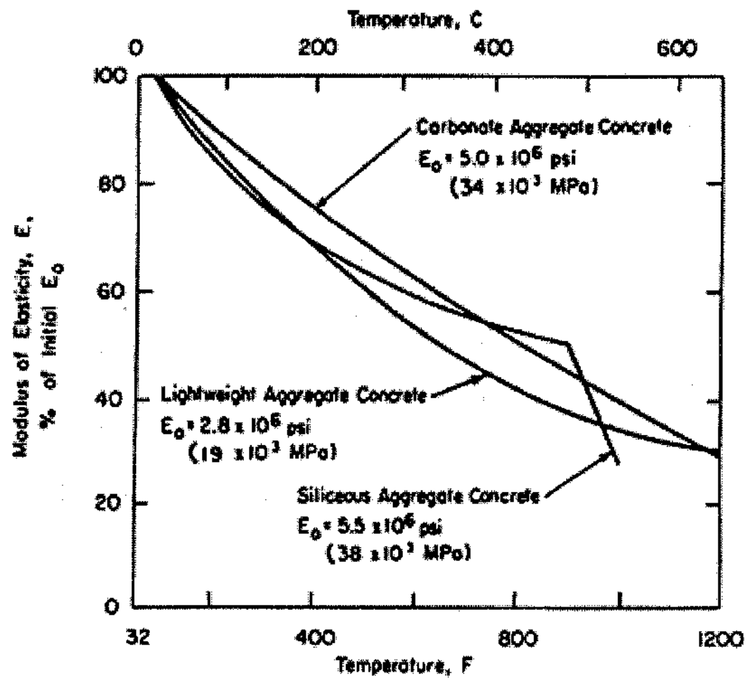


Figure 4. Modulus of elasticity of concrete at high temperatures (adapted from ACI Committee 216, Guide to Determining the Fire Endurance of Concrete Elements, ACI 216R-89)

The decrease in the modulus can be attributed to internal microcracking, increasing porosity in the cement paste, and the change in bonding energies as the water is expelled from the concrete.

Creep at Elevated Temperatures

Creep is a phenomenon of a structural element experiencing time-dependent long-term deformation under sustained loads. This effect is found in all building materials, but is more profound in concrete structures, regardless of the type of cement used. Increased temperature has been found to increase the amount of creep in a structure, and it is thought that the amount of creep depends on the extent of moisture loss from the concrete. Figure 5 shows the effect of temperature on the rate of creep.

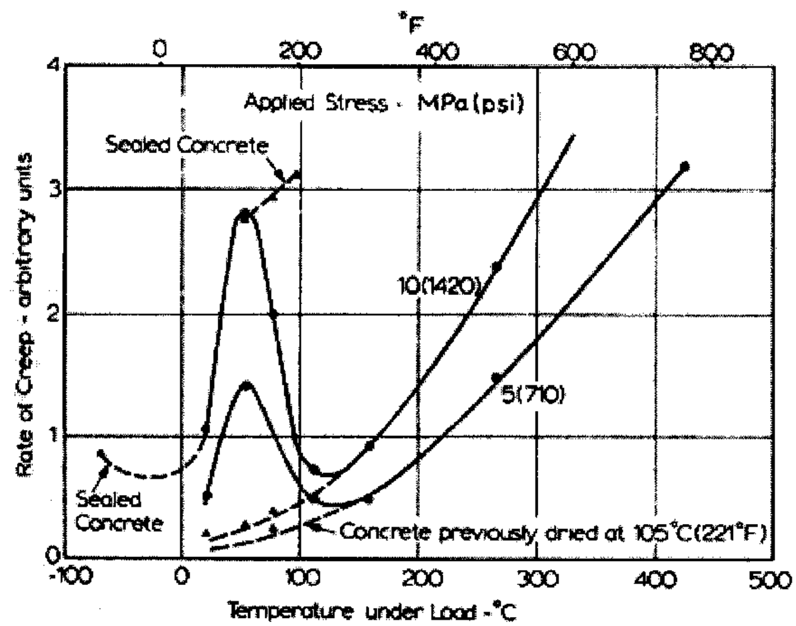


Figure 5. Influence of temperature on rate of creep (from Neville p.411)

Some factors that influence creep are the aggregate's modulus of elasticity and porosity. A high modulus of elasticity provides greater restraint to the potential creep of the cement paste; conversely, a highly porous aggregate provides less resistance due to its lower modulus of elasticity.

Additional information on creep can also be found in the section on refractory concretes.

Compressive Strength at Elevated Temperatures

Concrete structural elements are frequently used to take advantage of concrete's high compressive strength, therefore it is important to know how this strength is affected by heat. The compressive strength of concrete is dependent upon the water/cement ratio, cement/aggregate ratio, type of aggregate, and numerous other factors such as the curing method, age, and the presence of admixtures. At elevated temperatures however, the type of aggregate used and the internal structure play increasing roles in the behavior of the concrete. Naturally the type of cement used will also affect the performance of the concrete, but this will be discussed later under refractory concretes, which indeed does use cement other than Portland cement.

Research conducted by Dias et al. focused specifically on the compressive strength of Portland cement paste in order to understand the effects of high temperatures just on the binding agent of concrete. This approach highlights the limitation of Portland cement use in refractory concrete. Figure 6 shows the variation of strength with temperature.

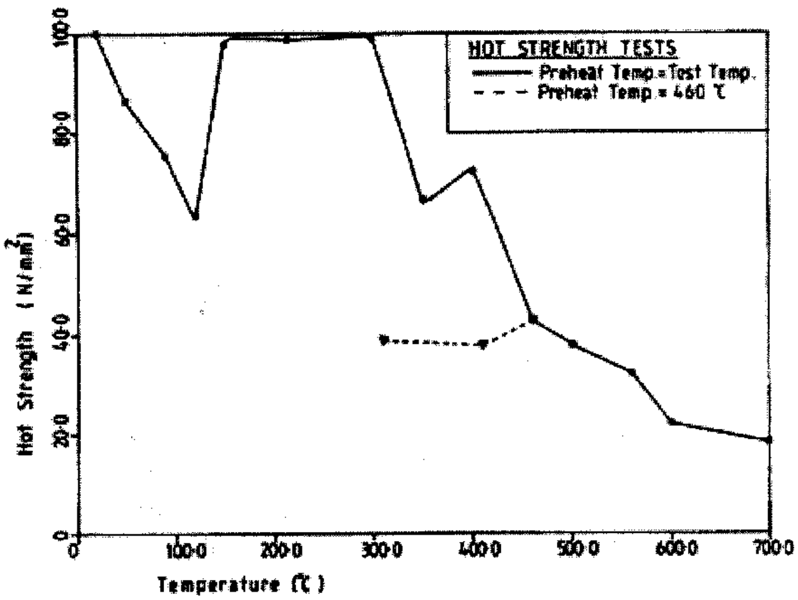


Figure 6. Strength of unsealed hardened cement paste at various temperatures for specimens brought to test temperature without load (adapted from ACI Materials Journal March/April 1990, "Mechanical Properties of Hardened Cement Paste Exposed to Temperatures up to 700°C")

The significant drop in strength as the specimen is heated is attributed to the thermally energized swelling of the physically bound water layers, which causes disjoining pressures and weakening of the bonds. After reaching a minimum strength at around 120°C, there is a regaining of strength due to the relief of these pressures as the cement dries. This gives rise to greater Van der Waal's forces as a result of the cement gel layers moving closer to each other. Once the initial strength has been regained, the specimen maintains its strength as the temperature increases to about 300°C, beyond which a steep drop in strength is observed.

Beyond 300°C, microcracking around the $Ca(OH)_2$ crystals and grains of unhydrated cement results in a strength decrease. The rapid decrease in strength is most likely due to the increasing porosity and microcracking within the cement paste. Although mentioned earlier, it is important to note that at 400°C, there is extensive cracking, if the cement specimen is cooled again, due to the dehydration and rehydration of the $Ca(OH)_2$. Hence for Portland cement concrete, it can be concluded that temperatures above 400°C cannot be sustained without its disintegration on subsequent postcooled exposure to atmospheric moisture. Additional experimentation found that replacement of some (10%) of the Portland cement with fly ash was sufficient to eliminate this effect of $Ca(OH)_2$. The effectiveness of the fly ash replacement suggests that if the constituents of Portland cement are modified in the appropriate quantities, a more suitable cement for refractory concrete could be developed.

Similar tests conducted on concretes using various types of aggregate produce results mostly consistent with those found in Portland cement pastes. There is an initial reduction in strength followed by a regaining of strength, or in some cases an increase in strength. The general loss in strength at around 300°C is similar to that found in the cement paste alone, which is indicative of the predominance of the effects from structural changes in the cement matrix. Figures 7 and 8 illustrate this reduction in strength found in concretes with various types of aggregate.

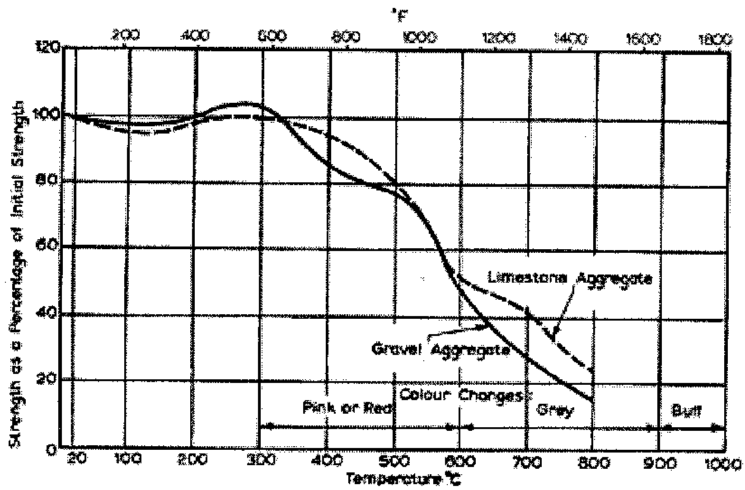


Figure 7. Compressive strength of concrete after heating to high temperatures (adapted from Neville p.502)

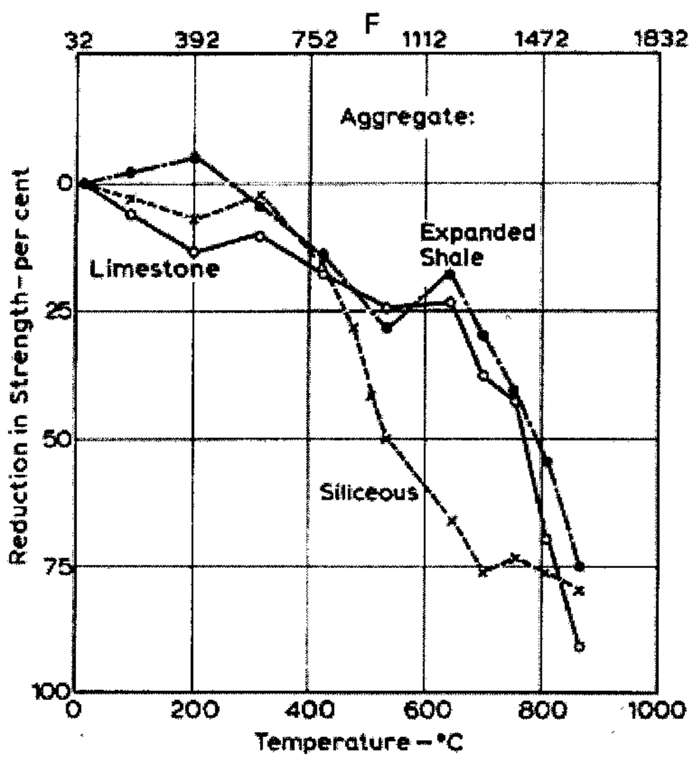


Figure 8. Reduction in compressive strength of concrete heated without application of load and then tested hot; average initial strength of 28 MPa (4000 psi) (adapted from Neville p.504)

Tensile Strength at Elevated Temperatures

The tensile strength of concrete is found to decrease as the temperature is increased, with values of strength at 800°C being only about 20% of that found at 20°C. This remarkable loss of strength can be attributed to the internal pressures caused by the thermal expansion/shrinkage of the aggregate and cement paste, which leads to cracking in the concrete. These cracks appear because of the relatively low tensile strength of the cement paste itself. As cracks appear and propagate, the concrete rapidly loses its ability to resist any additional tensile forces.

Because concrete is weak in tension, steel bars (rebars) are used to resist the tension in reinforced concrete. Fibers made of steel are also used to give concrete, or specifically the cement paste, additional tensile strength to resist the internal pressures created at the aggregate and cement paste interfaces. The use of steel rebars or fibers in concrete poses a problem when they are heated. When steel is not adequately insulated by concrete and reaches temperatures near 593°C (1100°F), it loses much of its strength and the steel concrete interaction from differential expansion can result in spalling and cracking of the concrete. To prevent such occurrences, rebars must have a minimum cover of concrete several inches thick, depending on the member type and the conditions of fire exposure. Like concrete, steel exhibits a decrease in strength and modulus of elasticity as it is heated, which ultimately weakens the reinforced concrete.

While regular Portland cement concrete sufficiently protects steel rebars from regular fires (intensity and duration), exposure to temperatures around 1000°C can lead to severe damage and failure of the reinforced concrete. ASTM Standard E119 specifies the way to determine the fire endurance of concrete elements. In applications where high service temperatures are needed, reinforced concrete may need to be replaced with heat resistant or refractory concrete.

Effect of Aggregate on Fire Resistance

Until now, the effect of high temperatures on Portland cement has been looked at without much consideration for the other main constituent of concrete – aggregate. Most aggregates used in Portland cement concrete are common rocks and sand that has quartz as its principal mineral constituent. Sand, most gravels, acid igneous rocks, and sandstone all contain significant amounts of quartz. Quartz expands steadily as it is heated up to 573°C, but undergoes a sudden expansion of 0.85% at this temperature when the 'low' α-quartz transforms into 'high' β-quartz. This expansion can cause significant cracking in concrete as the expanding aggregate opposes the shrinking of the cement paste.

The best fire resistant aggregates among the igneous rocks are the very finely crystalline or non-crystalline basic rocks such as dolerites and basalts. Limestone is suitable for temperatures up to about 900°C, after which it will begin to decompose and contract. Blast furnace slag is also considered to be a good fire-resistant aggregate. Lightweight aggregate such as pumice, vermiculite, perlite, foamed slag, and expanded clay products have inherently high resistance to fire and are ideal for producing insulating concretes with low heat conductivity. However, one of the main drawbacks of using such aggregates is their extremely poor compressive strength and durability.

Primary factors for the selection of aggregate for concrete exposed to high temperatures are, porosity, volume stability, and a low coefficient of thermal expansion. Minimal thermal expansion of the aggregate can reduce internal cracking and could decrease the rate at which strength drops as the concrete is heated. The porosity is important for the thermal conductivity of lightweight aggregates, while volume stability is necessary to prevent excessive deformations in the aggregates (like in the quartz-based sands and rocks). Thermal conductivity is the ability of the concrete to conduct heat and is of particular interest in the protection of steel rebars from fire and other applications requiring insulation.

Table 1. Aggregates for High Temperature Exposures* (from *Concrete Construction Handbook* 34.21)

Material	Max temp. °C	Strength	Conductivity	Abrasion resistance	Insulating value	Volume stability
Siliceous sand	260	High	High	Good	Poor	Poor
Calcined clay or shale	1093	High	Medium to low	Good	Good	Fair to good
Vermiculite and perlite	1093	Low	Low	Poor	Excellent	Good
Traprock igneous	982	High	High	Good	Poor	Fair
Crushed firebrick	1371	Medium	Medium	Fair	Fair	Good
Granulated blast furnace slag	538	Low	Low	Low	Good	Fair

* Ratings are comparative only and may vary widely for different materials.

The selection of aggregate for concrete must be carefully weighed with its effects on overall strength, durability, and desired service temperature of the concrete. Table 1 summarizes some of these properties for various types of commonly used aggregate. For Portland cement based concrete, the selection of a highly fire-resistant aggregate may not be beneficial because the cement paste may deteriorate before the aggregate melts or undergoes excessive deformations. In refractory concrete however, the choice of aggregate becomes crucial in attaining maximum service temperatures.

Refractory Concrete

This section covers the properties and characteristics of refractory concrete and the reasons behind its exceptional resistance to high temperatures. By having a fundamental understanding of how refractory concretes work, improvements can be made to make future concrete structures more fire resistant without sacrificing critical elements such as structural strength, durability, and cost. The next section will address these issues along with some current applications of refractory concrete, namely fireproofing.

There are basically two types of refractory concrete: lightweight and normal. ACI Committee 547 defines refractory concrete as "concrete which is suitable for use at high temperatures and contains hydraulic cement as the binding agent." This binding agent is usually high alumina or calcium aluminate cement, which is substantially different from Portland cement in its mineral constituents. Both categories of refractory concrete use this type of cement in conjunction with refractory or heat resistant aggregates.

Calcium Aluminate (High alumina) Cement

Calcium aluminate cement comprises of mostly CA along with small amounts of C_2S, C_2AS, and impurities such as C_6A_4FeOS and C_6A_4MgOS. The raw materials for the manufacture of calcium aluminate cement are limestone and bauxite, which are first fired at temperatures exceeding 1450°C and then allowed to cool. Once cooled the cement clinker is crushed and ground like Portland cement. Unlike during Portland cement manufacture, no gypsum is added during this process. A major problem in the manufacture of calcium aluminate cement is the high power consumption needed to grind the clinker, which is much harder than Portland cement clinker, and the removal of any impurities.

Depending on the desired service temperature, a wide variety of calcium aluminate cements with alumina (A) contents ranging from 40% to over 80% are produced. To achieve very high temperatures, impurities such as iron are removed to produce highly pure cement that contains only calcium aluminates such as CA, C_3A_5, and $C_{12}A_7$. For temperatures above 1320°C, the purity of the calcium aluminate becomes especially important since refractoriness increases in proportion to the alumina/lime ratio. Table 2 shows the chemical composition of different types of calcium aluminate cements.

Table 2. Composition ranges for calcium aluminate cements (reproduced from Hewlett p.717)

Grade	Color	Al_2O_3	CaO	SiO_2	Fe_2O_3+FeO	TiO_2	MgO	Na_2O	K_2O
Standard low alumina	Grey black	36-42	36-42	3-8	12-20	< 2	~ 1	~ 0.1	~ 0.15
Low alumina low iron	Grey white	48-60	36-42	3-8	1-3	< 2	~ 0.1	~ 0.1	~ 0.05
Medium alumina	White	65-75	25-35	< 0.5	< 0.5	< 0.005	~ 0.1	< 0.3	~ 0.05
High alumina	White	> 80	< 20	< 0.2	< 0.2	< 0.005	< 0.1	< 0.2	~ 0.05

Since calcium aluminate cement consists of mostly alumina (Al_2O_3) and lime (CaO), it is possible to approximate the melting point of the cement by using a CaO – Al_2O_3 phase diagram. For instance, a calcium aluminate cement containing about 65% alumina ($C_{12}A_7$-CA in Figure 9) would have a eutectic, or softening temperature of nearly 1400°C. It is evident from the phase diagram that as the alumina content increases the eutectic temperature also increases, since the eutectic is the boundary at which the CaO-Al_2O_3 system begins to turn into a liquid. Aluminate rich cement systems such as CA + CA_2 and CA_2 + CA_6 have eutectic temperatures of 1590°C and 1700°C respectively. Compared to Portland cement, calcium aluminate cement can withstand substantially higher temperatures, thus making it an ideal binding agent in refractory concrete.

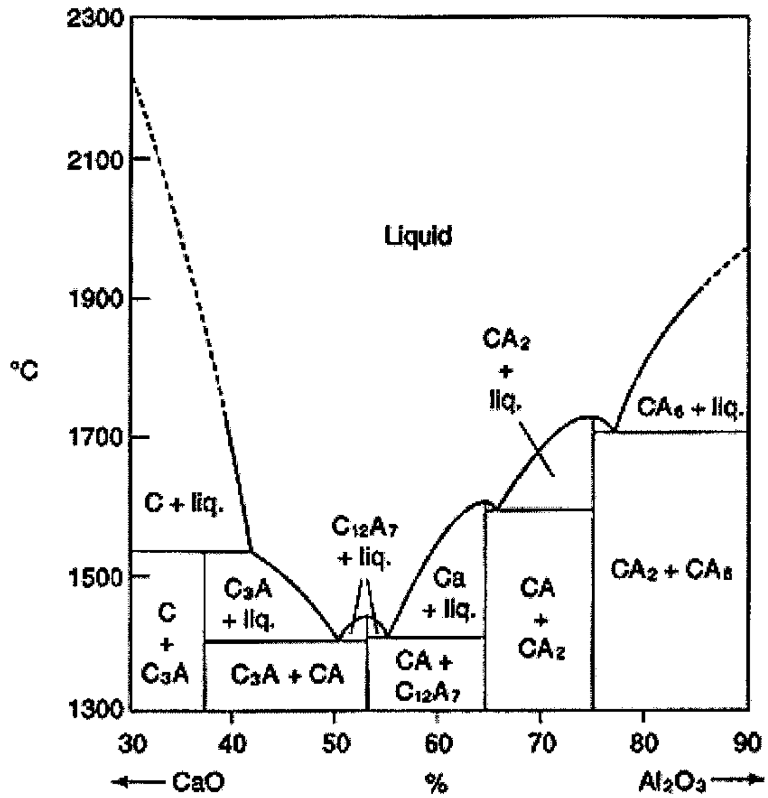


Figure 9. CaO – Al_2O_3 phase diagram (from Hewlett p.718)

The hydration process of calcium aluminate cement is strongly dependent on temperature and is considerable different from that of Portland cement. The possible reactions are given as:

At temperatures below 10°C

$$CA + 10H \rightarrow CAH_{10}$$

$$2CAH_{10} \rightarrow C_2AH_8 + AH_3 + 9H$$

At temperatures between 10 and 27°C both C_2AH_8 and CAH_{10} are formed

$$2CA + 11H \rightarrow C_2AH_8 + AH_3$$

$$3C_2AH_8 \rightarrow 2C_3AH_6 + AH_3 + 9H$$

At higher temperatures CAH_{10} no longer forms

$$3CA + 12H \rightarrow C_3AH_6 + 2AH_3$$

Long-term strength of the hardened cement comes from the formation of the stable hydrates, C_3AH_6 and gibbsite (AH_3). These compounds are relatively stable and do not cause cracking when heated like the hydrated lime (C) in Portland cement does.

Another difference is the heat of hydration, or the heat produced during the hydration process. While the total heat evolved during hydration (~500 KJ/kg) is comparable to that of Portland cement, calcium aluminate cement hydrates more rapidly over a shorter period of time, which requires careful mixing and curing procedures. This is one of the problems faced when using alumina-rich cement in refractory concrete.

The aluminate content of the cement is directly related to the refractoriness of the concrete, and this is clearly illustrated in Table 3, which compares the maximum service temperatures of different types of concrete with varying amounts of alumina content.

Table 3. Heat resistant and refractory concretes (from Hewlett p.773)

Cement type	Al_2O_3 (%)	Aggregate type	Approximate temperature limit (°C)
Heat-resistant concretes			
Grey CAC	40	Granite/whinstone/basalt	700–800
Grey CAC	40	Emery	1000
Grey CAC	40	Alag™	1100
Brown CAC	50	Olivine	1200
Dense refractory concretes			
Grey CAC	40	Chamotte (42–44% Al_2O_3), molochite	1300
Brown CAC	50–55		1400
White CAC	70		1450
Grey CAC	40	Sillimanite, gibbsite	1350
Brown CAC	50–55		1450
White CAC	70		1550
Grey CAC	40	Brown fused alumina	1400
Brown CAC	50–55		1550
White CAC	70		1650
White CAC	80		1750
White CAC	70	White fused alumina	1800
White CAC	80		1850
White CAC	70	Tabular alumina	1800
White CAC	80		1900
Thermally insulating concretes			
Grey CAC	40	Pumice, diatomite	900
Grey CAC	40	Vermiculite, perlite	1000
Grey CAC	40	Lytag™, Leca™	1100
Brown CAC	50	Expanded chamotte	1300
White CAC	70	Bubble alumina	1700
White CAC	80		1800

Effect of Aggregate on Fire Resistance

The ultimate service temperature of refractory concrete is quite dependent on the purity of the calcium aluminate cement, but is also greatly influenced by the type of aggregate. It has been found that service temperatures may be increased by 100-200°C beyond the fusion point of the pure cement by formation of higher melting point eutectics with the aggregate.

One of the functions of the aggregate is to form ceramic bonds. These bonds are usually created by solid reactions between the cement paste and the fine aggregate at temperatures above 1000°C, strengthening as the temperature increases and the reactions progress.

Important factors in the selection of aggregate for refractory concrete include aggregate size/grading, specific heat, low coefficient of expansion, temperature stability, and density/porosity.

Aggregate size and grading are important because a high aggregate content will increase the insulating or refractory properties of the concrete. Having a good proportion of fine aggregate will ensure the proper development of the ceramic binding process as higher temperatures are reached. Table 4, which was reproduced from ACI Committee 547, provides suggested guidelines for nominal maximum size and grading for refractory aggregates.

Table 4. Aggregate grading

Maximum size aggregate (except for gun placement)	1.5 in. (3.81 cm.)
Maximum size aggregate for normal gun placement	0.25 in. (0.64 cm.)
Maximum size insulating crushed firebrick	1 in. (2.54 cm.)
Maximum size expanded shales and clays	0.5 in. (1.27 cm.)
Maximum size, with the above exceptions, should not be greater than 20-25 percent of the concrete minimum dimension	
Aggregate of 0.5 in. (1.27 cm) or larger size: Retained on No. 8 Sieve = 50% Passing No. 100 Sieve = 10-15%	
Aggregate less than 0.5 in. (1.27 cm.) maximum size: Retained on No. 50 Sieve = 75% Passing No. 100 Sieve = 10-15%	

The specific heat of the aggregate is basically its thermal capacity, and is directly related to the specific heat of the concrete. Thermal properties (coefficient of thermal expansion, etc.) of the aggregate can affect the maximum service temperatures by reacting unfavorably with the cement paste matrix through expansion, shrinkage, or decomposition.

Density/porosity of the aggregate is more related to the type of aggregate required – lightweight or heavyweight. Lightweight aggregate with its high internal porosity results in low strength, but low thermal conductivity, making it ideal for fireproofing and insulation purposes. Therefore the selection of heavy or lightweight aggregate depends largely upon the concrete's intended application. The use of lightweight aggregate must be carefully weighed with the resulting concrete's relatively low strength and resistance to weathering and chemical attacks.

The maximum service temperatures of selected aggregates mixed with appropriate calcium aluminate cements are listed in Table 5.

Table 5. Maximum service temperatures of selected aggregates mixed with calcium aluminate cements under optimum conditions. (from ACI Committee 547)

Aggregate	Remarks	Maximum temperature Deg C	Maximum temperature Deg F
Alumina, tabular	Refractory, abrasion resistant	1870	3400
Dolomitic limestone (gravel)	Abrasion and corrosion resistant	500	930
Fireclay, expanded	Insulating, abrasion and corrosion resistant	1640	2980
Fireclay brick, crushed	Abrasion and corrosion resistant	1600	2910
Flint fireclay, calcined		1650	3000
Kaolin, calcined	Abrasion and corrosion resistant	1650	3000
Mullite		1650	3000
Perlite	Insulating	1340	2450
Sand	(Silica content less than 90 percent not recommended) Abrasion and corrosion resistant	300	570
Slag, blast furnace (air cooled)	Abrasion resistant	540	1000
Slag, blast furnace (granulated)	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

Properties of Normal and Lightweight Refractory Concretes

Ordinary refractory concretes can sustain service temperatures of about 1350°C and up to 1870°C (3400°F) for super-duty refractory concretes. Tables 11 and 12 at the end of this section (pages 46 and 47) provide a summary of all the important characteristics of various types of normal and lightweight refractory concretes.

Fire Resistance

Fire resistance of an element is determined primarily by 3 factors: First, the capacity of the concrete itself to withstand heat and the subsequent action of water without losing strength unduly and without cracking or spalling; secondly, the thermal conductivity of the concrete; and lastly, the heat capacity of the concrete. ASTM E119 and ACI Committee 216 provide guides for determining the fire endurance of concrete elements.

Fire resistance ratings are usually determined through the use of these guides, and are based upon the fire endurance of the element. These ratings are given in half-hour increments, and are essentially a measure of the elapsed time during which the element continues to exhibit fire resistance under the specified conditions of test and performance as defined by ASTM E119. Figure 10 shows the time-temperature curve for a standard fire test.

Fire resistance ratings and endurance are important for refractory concrete, but these tests are especially significant for structures built using regular structural concrete, where a combination of heavy loads and fire is not uncommon. Many refractory concrete applications require little load-bearing capacity and only a resistance to high service temperatures for insulation or fireproofing purposes.

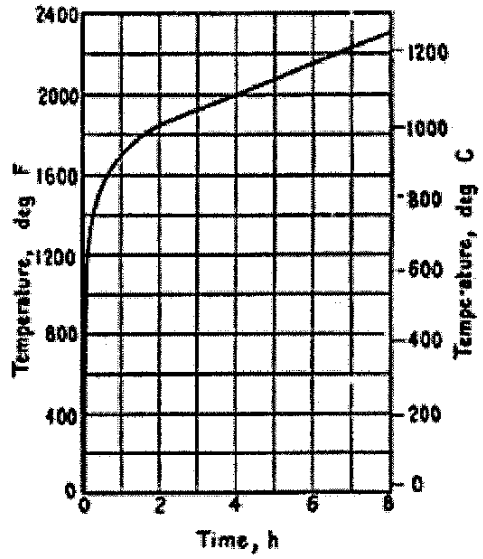
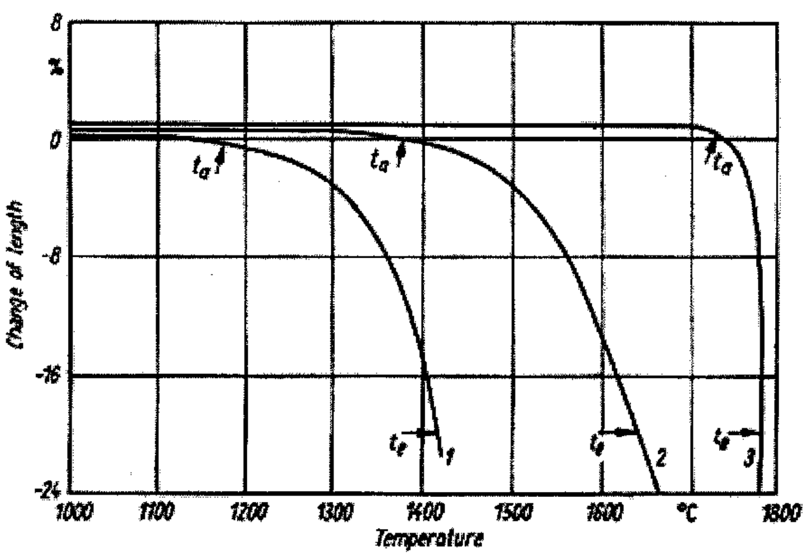


Figure 10. Standard time-temperature curve for ASTM E119 fire tests

Service Temperatures

Maximum service temperature is difficult to accurately measure and can easily be inflated by manufacturers who may use different test methods to determine their product's performance. ACI Committee 547 defines the maximum service temperature to be the point above which excessive shrinkage occurs, which is usually at about 150-200°F below the actual softening point of the concrete. The onset of this softening or melting is often accompanied by significant shrinkage, therefore service temperatures can be judged by the refractoriness under load tests. In this approach, the degree of deformation of a test piece under standard load is measured after being exposed to a given temperature. The limit of 'excessive' deformation, however, is rather subjective and is more dependent upon the limitations set by specific applications than a universally accepted value. It has also been found that the tendency for softening under pressure is often reduced after firing the refractory concrete.

The entire firing process involves the incremental heating of the refractory concrete to ensure that there is proper development of its refractory properties. Initially there should be a firing at 220°F (105°C) for at least 6 hours. This is to ensure that all the free water evaporates. The temperature is then raised at a rate of 50-100°F per hour up to 1000°F (540°C) where it is held for another 6 hours. The second hold is done to eliminate the combined water without danger of spalling. Beyond 1000°F the temperature can be raised more rapidly, and should be held whenever there is steam observed during the heat-up. Once the steam has dissipated the temperature can be further increased. The concrete begins to form ceramic bonds and takes on its refractory properties between 1600°F (820°C) and 2500°F (1370°C).



1 Chamotte concrete ; 2 Silicon carbide concrete ; 3 Corundum concrete

t_e = temperature at which there is a 20% change in length
t_a = temperature at which there is a 0.6% change in length

Figure 11. Temperatures of softening under pressure for refractory concretes made with SECAR high aluminous cement (from Petzold p.145)

Figure 11 shows 3 different types of calcium aluminate cement concretes with their respective softening temperatures when under 28 psi pressure. The aggregates used in these concretes have the following maximum service temperatures: chamotte = 1960°C, silicon carbide = 2200°C, and corundum =1630-1770°C.

The definition of excessive deformations is somewhat relative, although it is evident from Table 6 that refractory concretes using Portland cement exhibit lower temperatures at which 4% or 10% deformations occur compared to aluminous cement. However, it is also interesting to note that depending on its exact constituents, even concretes using Portland cement can attain temperatures comparable to those using low purity calcium aluminate cement.

Table 6. Temperatures of softening under pressure for cement-bound high-temperature concretes (partially reproduced from Petzold p.141)

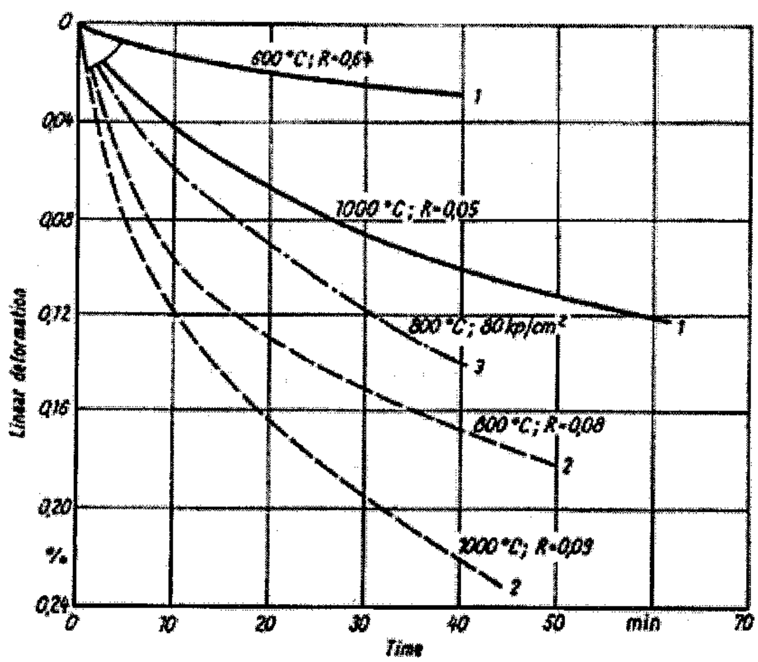
Cement	Very fine aggregate	Aggregate	Mix proportions	4% deformation temperature	10% deformation temperature
Portland	Clay	Chamotte	20:7:73	1200	1240
Portland	Magnesia	Chrome ore + quartz	1:2:0.3:0.2	1400	1510
Aluminous	-	Chamotte	15:85	1330	1450
Aluminous	-	Chrome ore	30:70	1330	1500
High alumina	-	Chrome ore	20:80	> 1480	
High alumina	-	Corundum	20:80	> 1550	

See Table 9 on page 40 for relationships between concrete softening temperatures, water/cement ratio, calcium aluminate cement purity, and strengths.

Resistance to Creep

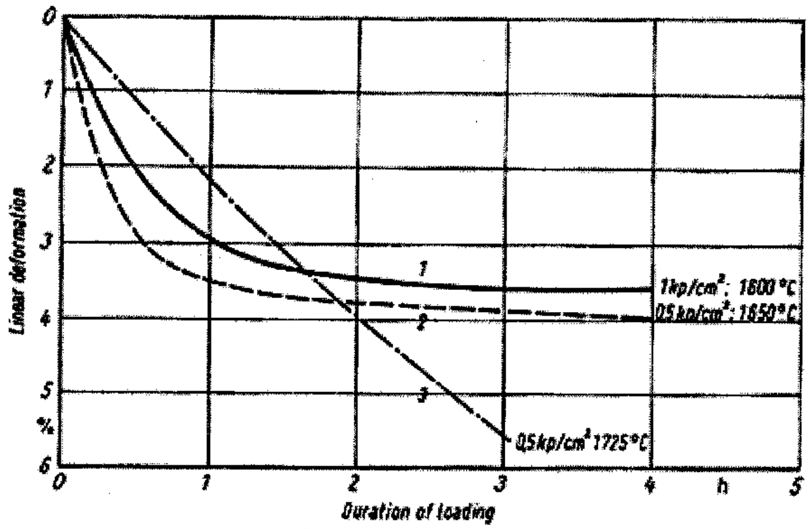
Refractory concrete's resistance to creep deformation is extremely important because it is usually subjected to a constant compression at an operating temperature for a long period of time. In certain applications, the refractory concrete's resistance to creep may be more desirable than resistance to extremely high temperatures.

Figure 12 demonstrates creep deformation of Portland cement and aluminous cement based concretes when exposed to temperatures up to 1000°C. Although these results are by no means long term, they do show that as the temperature increases, the amount of deformation begins to level off, which suggests that perhaps the creep resistance of the concrete increases as it is continually heated. This would be similar in effect to refractory concrete's increased resistance to softening after being fired. Figure 13 shows the creep resistance of concrete composed of high-alumina cement and different types of corundum aggregate.



The magnitude of loading R is the ratio of the pressure exerted to the maximum compressive stress at temperature T. 1=aluminous cement + chrome ore ; 2=Portland cement + chrome ore ; 3=Portland cement + chamotte

Figure 12. Relationship between the deformation of Portland cement and aluminous cement concretes and the temperature, loading, and time. (Al'tsuler, Salmanov, and Tarasova) (from Petzold p.147)

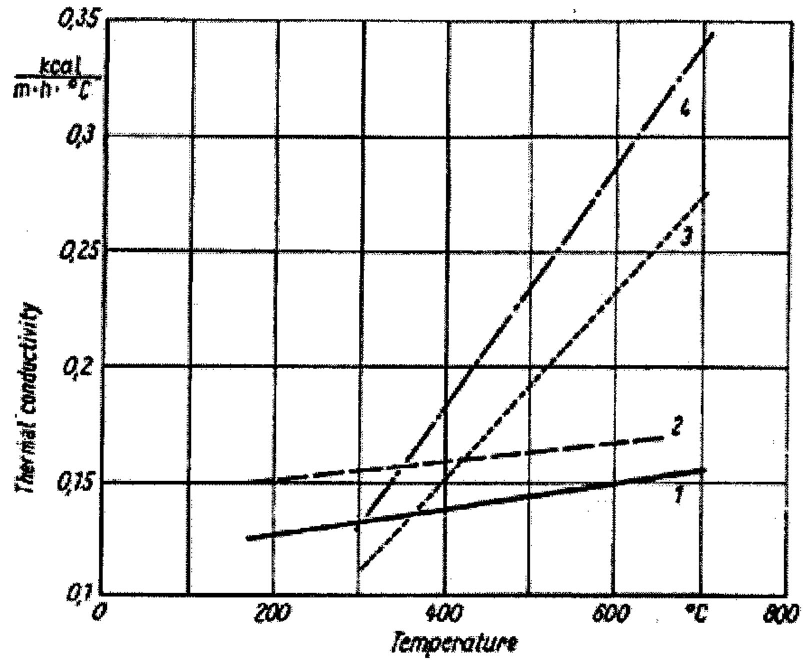


1: Normal corundum ; 2: Normal corundum ; 3: Special fused alumina

Figure 13. Creep resistance of concrete made with high alumina cement and corundum (Arnould) (from Petzold p.148)

Thermal Conductivity

Thermal conductivity is a measure of the amount of heat flow through a unit area for a unit temperature gradient, or basically the ability to conduct heat. It is indicative of the amount of stresses that can develop in response to thermal loads. Conductivity is dependent upon the individual thermal conductivities of the concrete's constituents, the grading of the aggregate, the volume of the pores in the concrete (density), and the service temperature. In many cases however, the thermal conductivity of the concrete lies below that of its pure aggregates. Concrete generally has a low thermal conductivity due to its water content and the fact that water has a high specific heat. Figure 14 and Table 7 report thermal conductivities of various types of concrete, as well as the generally found trend of increasing thermal conductivity at increasing temperatures.



1: Aluminous cement + vermiculite (1:6) ; 2: Aluminous cement + vermiculite (1:4) ;
3: Portland cement foamed concrete (41 pcf) ; 4: Porland cement foamed concrete (50 pcf)

Figure 14. Variation with temperature of thermal conductivity with temperature for various lightweight refractory concretes (Hansen and Livovich, Krivickij) (from Petzold p.170)

Table 7. Thermal conductivities of various high-temperature concretes (Hammond). Ratio of aluminous cement:aggregate ≈ 1:3 to 1:4 (reproduced from Petzold p.159)

Aggregate	Coefficient of thermal conductivity (kcal/m·h·°C)
Chamotte	0.7
Chrome ore magnesia	1.0
Sillimanite	1.25
Calcined bauxite	1.5
Sintered magnesia	1.5
Fused corundum	2.0
Fused magnesia	3.0
Silicon carbide	≈ 6.0

ACI Committee 547 provides the following values for most refractory concretes: 0.62 kcal/m·h·°C (.72 W/m-°C or 5 Btu-in./ft^2-hr-°F) to 1.24 kcal/m·h·°C (1.44 W/m-°C or 10 Btu-in./ft^2-hr-°F) for concrete densities of 1920 kg/m^3 (120 pcf) to 2560 kg/m^3 (160 pcf) respectively. Lightweight refractory concrete have k-values ranging from 0.086 to 0.516 kcal/m·h·°C.

Low thermal conductivities are desirable in most applications because this means that the heat can be contained in a general area and not spread rapidly. In fireproofing, the low thermal conductivity is crucial in protecting the structural steel from reaching excessively high temperatures. Lightweight refractory concrete, or less dense concrete tends to have a low conductivity due to the presence of pores inside the concrete. These pores contain air, which has a very low thermal conductivity (.02 W/m-°C or .02 kcal/m·h·°C), enabling it to significantly slow the transfer of heat through the concrete.

Porosity

Porosity greatly affects the thermal conductivity and strength of concrete. The pores are usually caused by air bubbles in the cement paste matrix during the mixing process and remain when the cement hardens. These pockets of air can greatly reduce the thermal conductivity of the concrete, but these same pores can also decrease its strength.

An important function of these pores is to allow for the release of the steam pressure build up from the heated water in the concrete. Without this release in pressure, there is the danger of explosive spalling in the concrete, a problem encountered in high-performance concretes, which are extremely dense and are of low porosity.

Refractory concrete normally has a porosity in the range of 20-30%. The porosity of concrete largely depends upon the water content and the presence of special air-entraining admixtures. It has been found that the porosity in an aluminous cement concrete fired at 950°C increased from 27 to 31% as the water content was increased from 7 to 16%.

During heating, this increase in porosity is immediately followed by a decrease due to the closing of the pores caused by smelted material in the concrete as shown in Figure 15. Most operating temperatures are limited to the point at which this decrease in porosity commences, because chemical action in the smelted material may be detrimental to the concrete.

Lightweight concretes possess high porosity, which explain their low densities. For this reason, lightweight refractory concrete is almost exclusively used for fireproofing applications.

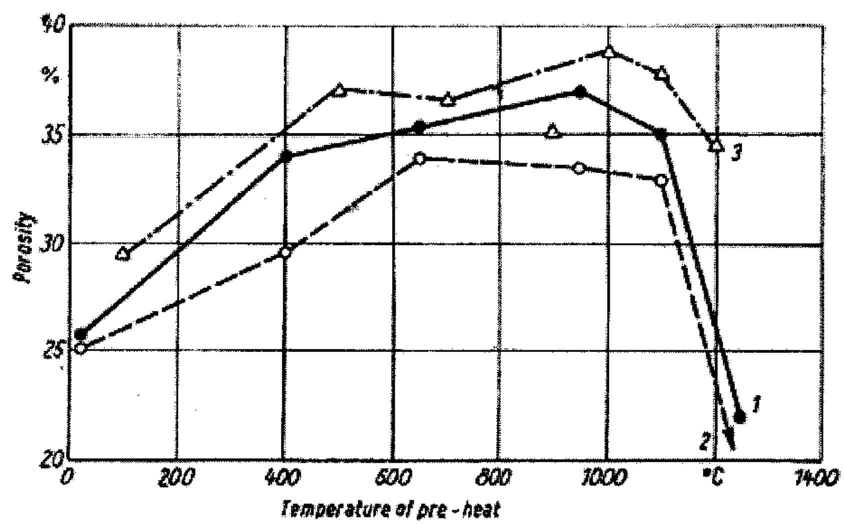


Figure 15. Variation of porosity in refractory concretes with temperature of pre-heat (Gibbels, Schmid) (from Petzold p.135)

Density

The density of concrete is closely related to its porosity, specific gravity, and individual densities of the constituent materials. Since both high and low densities can be desirable in certain applications, there is no set value for an 'ideal' density for refractory concrete. For cases in which resistance to weathering and chemical attack are necessary, a denser concrete is more beneficial since this will protect the concrete better, but for insulation and fireproofing, a low density concrete is more efficient. Most refractory concretes tend to have a density of less than 130 pcf, compared to densities ranging from 140-160 pcf for normal-weight structural concrete. Lightweight refractory concretes have densities between 20 pcf (320 kg/m^3) and 100 pcf (1600 kg/m^3).

Figure 16 shows the general effect of having lower densities in lightweight concrete on its thermal conductivity.

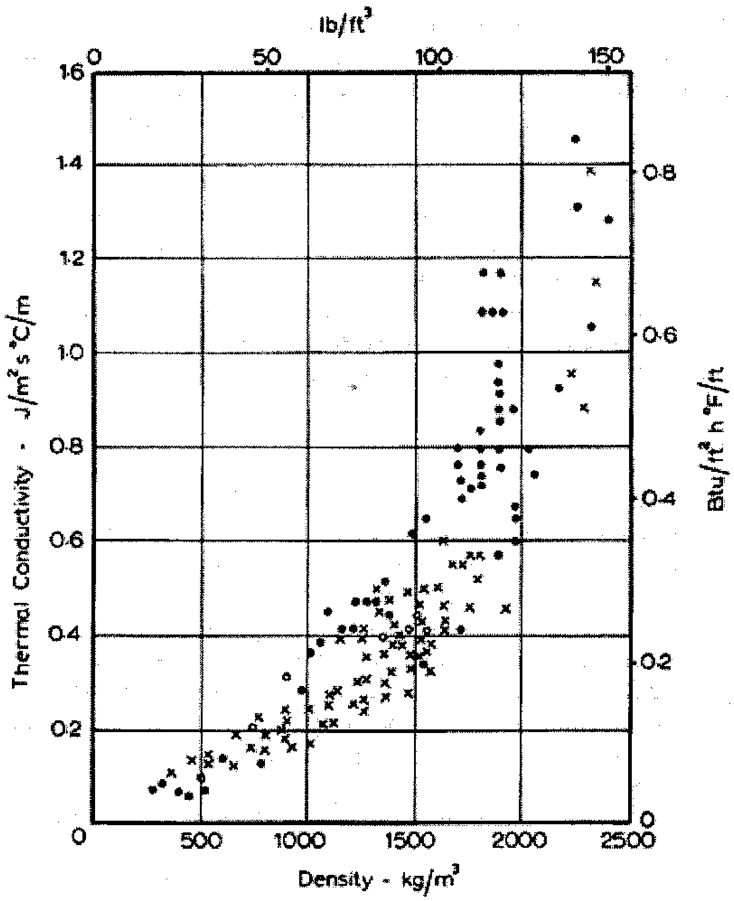


Figure 16. Thermal conductivity of lightweight aggregate concretes of various types (from Neville p.611)

The lower densities of refractory concrete ensure that there are sufficient pores to allow the steam pressure build up in the concrete to be released without causing explosive spalling. Unfortunately, concrete with low densities (lightweight aggregate and high porosity) possess little strength. Figure 17 show the relationship between the cold compressive strength of ceramsite refractory concrete, its density, and preheat temperature. According to Petzold, the maximum compressive strengths reached with vermiculite concretes are 710 psi for a density of 56 pcf (900 kg/m^3), 1420 psi for a density of 75 pcf (1200 kg/m^3), and 3550 psi for a density of 87 pcf (1400 kg/m^3). These strengths are highly dependent on the temperature however, with strengths dropping significantly as the temperature increases. The reduction in strength found in Portland cement concretes is applicable to that found in calcium aluminate cement concretes and is further explored under the section on "Strength".

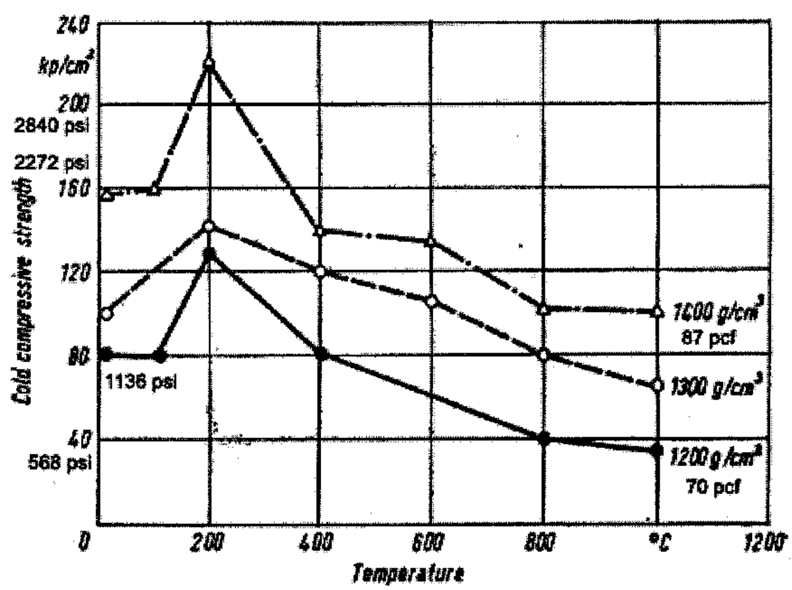


Figure 17. Relationship between the cold compressive strength of ceramsite refractory concrete and its density and temperature of preheat (Maslennikova) (from Petzold p.167)

Thermal Expansion/Shrinkage

Calcium aluminate cement experiences shrinkage as it is heated much in the same way Portland cement does. Figure 18 demonstrates the expansion/shrinkage behavior of an aluminous cement with two different contents of iron (less iron, the purer the calcium aluminate cement). Compared to the deformations experienced by Portland cement (see Figure 1), aluminous cement's shrinkage is less, which makes it advantageous for use in refractory concrete.

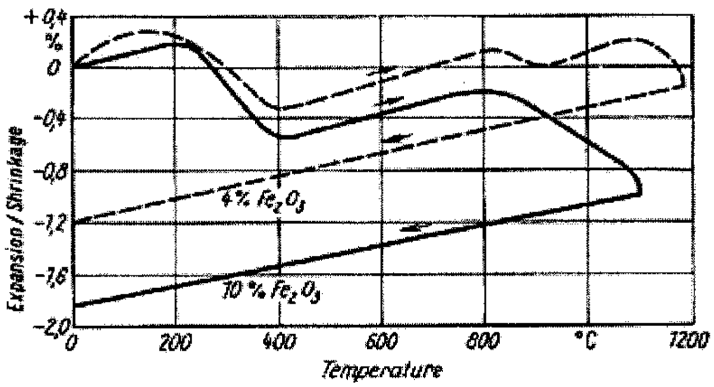


Figure 18. Expansion/Shrinkage behavior of aluminous cement having high and low contents of iron (from Petzold p.37)

The shrinkage in the calcium aluminate cement does not directly translate to the shrinkage in calcium aluminate concrete since other factors play a role as well, such as the water to cement ratio, aggregate content/type, specimen geometry, and drying conditions. However, the low cement to aggregate ratio in most concretes will assure that the total shrinkage of approximately 2% seen in Figure 18 will be considerably less in the concrete.

Shrinkage in the cement paste very much different from the shrinkage/expansion of the aggregate can lead to small but sufficient internal stresses to cause cracking in the concrete, unless fine aggregates and ceramic stabilizers are present in the mix. The primary purpose of the fine aggregate and ceramic stabilizer is to reduce the shrinkage of the cement matrix because they have low inherent shrinkage when heated. By selecting the grade and type of aggregate used, the expansion and shrinkage behavior can be controlled to a certain extent.

Initial heating of refractory concrete causes shrinkage, but at higher temperatures permanent expansion can occur. Most normal refractory concretes have less than 0.5% permanent linear shrinkage after firing at 2000°F (1090°C). The permanent change appears as cracks after the first firing, but these cracks close after being subjected to subsequent operating temperatures. Figure 19 shows the expansion and shrinkage behavior of a typical refractory concrete.

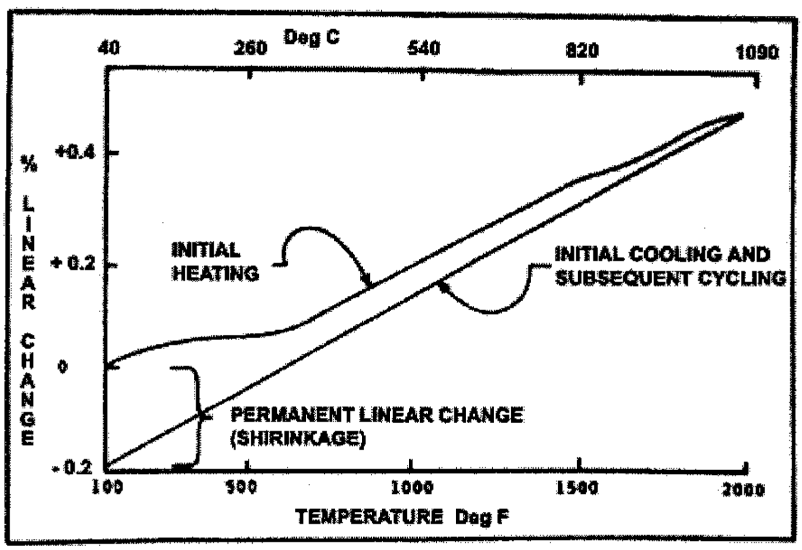


Figure 19. Net thermal expansion of a typical refractory concrete (ACI Committee 547)

The reversible thermal expansion of refractory concrete is approximately 3 x 10^{-6} in/in/°F (5 x 10^{-6} cm/cm/°C), but can be as high as 4 x 10^{-6} in/in/°F (7 x 10^{-6} cm/cm/°C) for high alumina cement concretes. The coefficient of thermal expansion of concrete increases as the water cement ratio increases and the cement content decreases.

Specific Heat and Capacity

For concrete heat capacity, the specific heat of the aggregate becomes the determining factor. Specific heat is a measure of the heat capacity per unit mass of a material, essentially the material's ability to absorb heat from its surroundings, and it represents the amount of energy required to produce a unit temperature rise. In general, the aggregate's specific heat should be about 0.20 cal/g·°C for low temperatures and increase to about 0.28-0.30 cal/g·°C for temperatures around 1400°C.

Although the aggregate's individual thermal capacity plays a significant role in the concrete's specific heat, special attention must be given to the formation of certain partly smelted compounds in the heated concrete, which could increase its thermal capacity. Other factors that affect specific heat are porosity, water content, and temperature.

Table 8 gives some specific heat values for calcium aluminate cement concrete using different types of aggregate. Vermiculite which is frequently used in fireproofing provides a low specific heat, a thermal property consistent with its low density, weight, and thermal conductivity. This means that vermiculite concrete will easily heat up, but because of its low thermal conductivity, it can effectively protect the structural steel underneath it. ACI Committee 547 provides the following values of specific heat for normal refractory concretes: 0.20 Btu/lb/°F (837 J/kg°C) at 100°F (40°C) to about 0.29 Btu/lb/°F (1210 J/kg°C) at 2500°F (1370°C). These values can vary plus or minus 0.025 units depending on the aggregate. Lightweight refractory concretes have specific heats similar to those of normal refractory concretes.

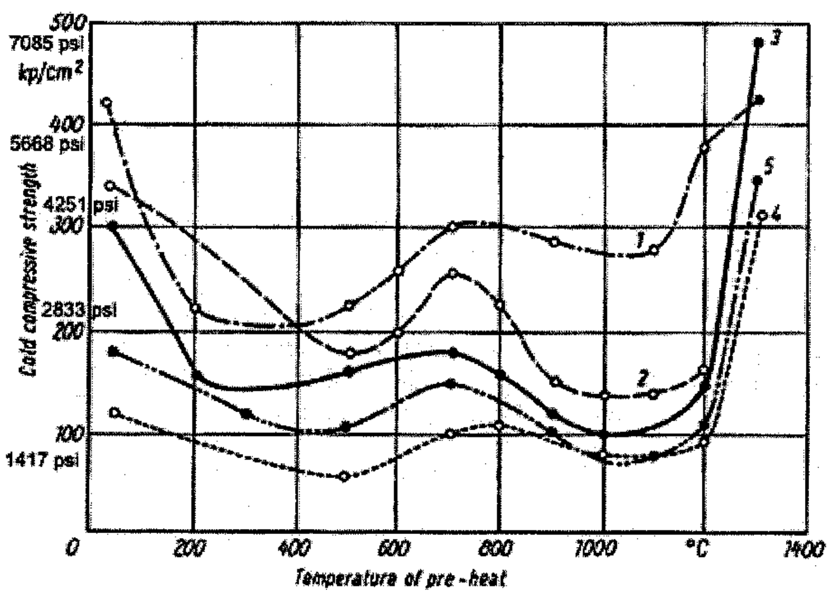
Table 8. The specific heats of various high-temperature concretes (Hammond) (from Petzold p.158). Ratio of aluminous cement:aggregate ≈ 1:3 to 1:4

Aggregate	Specific heat ($cal/cm^3 \cdot °C$)
Vermiculite	0.15
Diatomite	0.25
Expanded clay	0.35
Sillimanite	0.6
Chrome ore / Magnesia	0.6
Silicon carbide	0.7
Fused corundum	0.9
Fused magnesia	0.9

Strength

The strength of refractory concrete is highly variable and is dependent upon factors such as: type of cement, cement/aggregate ratio, water/cement ratio, type and grading of aggregate, reactivity between cement and fine aggregate, time between testing, and the curing process. Because of the logistics involved in testing at temperatures exceeding 1000°C, most tests are conducted to determine only the cold compressive strength. The cold compressive strength is simply the compressive strength of the concrete after it has been heated to a specified temperature and then allowed to cool. A drawback of this method is that it may not accurately measure the concrete's real compressive strength at service temperatures.

ACI Committee 547 gives crushing strengths of normal refractory concretes varying from 1000 to 8000 psi (6.9-55.2 MPa). Figure 20 shows how strength varies as the temperature increases in aluminous cement concretes with different aggregate types and contents. It can be seen that concretes with higher aggregate contents perform better both in terms of loss of strength and the ultimate cold compressive strength (see curves 1 and 5). The presence of very fine aggregates (up to 60% of aggregate) in the concrete lessens the reduction in strength because they react more readily with the cement and resist in the softening of the concrete by ensuring the proper development of ceramic bonds. Progressive strength increases after reaching 1000°C are indicative of the formation of these ceramic bonds.



1: Sillimanite 20% ; 2: Chrome ore 20% ; 3: Magnesia 20% ; 4: Chamotte 10% 5: Sillimanite 10%

Figure 20. Intermediate maxima of the cold compressive strength of pre-heated aluminous cement concretes (Mitusch) (from Petzold p.129)

The cement to aggregate ratios are usually in the range of 1:3 or 1:4 to satisfy typical applications, but in certain cases they have been found to be as low as 1:2 and as high as 1:6. High cement aggregate ratios are used in lightweight concretes while low ratios are more suitable for applications where higher strengths may be required. Up to a certain point, increasing cement content will provide higher strength development. An optimum cement content appears to be about 40% to 50%, but for higher contents the proportion of aggregates becomes too small for effective development of fire-resistance in the concrete.

Table 9 summarizes some typical mechanical properties of refractory concretes with various aluminate contents.

Table 9. Typical mechanical properties of refractory concretes containing aluminous cements (from Barnes p.433)

Cement type	40% Al_2O_3			50% Al_2O_3			70% Al_2O_3			80% Al_2O_3		
Aggregate	F	S	B	F	S	B	F	S	G	F	S	G
Compressive strength/flexural strength (MPa)												
6 hr. at 20°C	53/7	61/8	9/2	47/6	43/6	47/6	24/5	40/7	47/7	30/6	22/4	25/3
24 hr. at 20°C	85/11	110/12	99/12	98/10	112/13	97/10	42/8	59/9	72/11	47/6	51/7	110/13
Dried at 110°C	68/11	72/12	69/9	46/6	51/11	57/8	76/8	75/10	95/12	95/13	102/12	103/18
After firing at												
800°C	45/35	44/35	41/3	32/3	58/65	48/6	67/6	69/7	90/85	75/9	115/14	116/9
1100°C	27/3	33/4	30/3	23/3	39/6	31/3	38/5	38/55	45/5	62/75	89/11	75/7
RUL 0.5%	1200	1270	1200	1300	1355	1315	1310	1340	1300	1330	1400	1335
(°C) 5.0%	1340	1370	1450	1400	1410	1495	1420	1460	1430	1435	1500	1480
w/c ratio	0.42	0.48	0.41	0.41	0.48	0.41	0.46	0.46	0.50	0.36	0.38	0.36

Aggregate grading 0-5mm : Cement content 500 kg/m^3.
F=42-44% Al_2O_3 chamotte; S=sillimanite; B=brown fused alumina; G=calcined low iron bauxite (gibbsite).
RUL = Refractoriness Under Load: temperatures for 0.5% and 5.0% subsidence under a load of 0.2 MPa
Water/cement ratio is based on standard (ball-in-hand) consistency

The reduction in the strength of the concrete is consistent across the board for all contents of aluminate, but it is evident that for applications requiring higher strengths, a high aluminate content can provide higher strength than those with less aluminate. Most refractory concretes lose between 60-75% of their initial strengths after being fired, but do regain their strength after the formation of ceramic bonds. This regaining of strength after firing has led to the pre-heating of some refractory concretes before placing them into service, for the purpose of minimizing strength loss and extending service life.

The data presented here is the cold compressive strength and does not correspond to the concrete's real strength under load and service temperatures. A more reliable measure of strength is the hot compressive strength, which is nothing more than the compressive strength of the concrete at a specified temperature. Figure 21 shows the hot compressive strength of 4 different aluminous cement concretes.

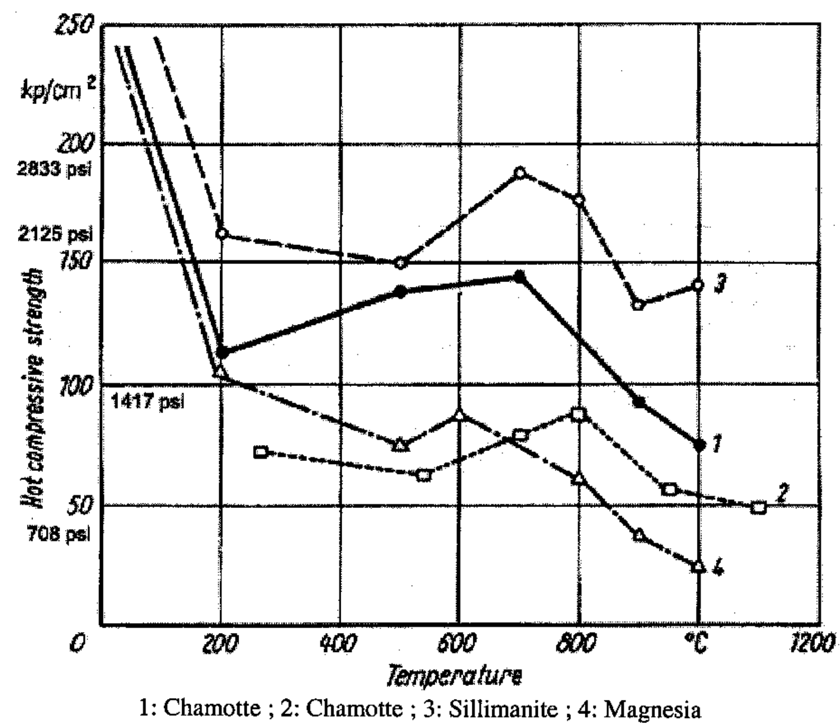


Figure 21. Hot compressive strength of aluminous cement concretes (Mitusch, Hansen and Livovich) (from Petzold p.132)

Comparison of Figures 20 and 21 show that cold compressive strength is about one third higher than the hot compressive strength. The hot compressive strength experiences similar reductions as the cold compressive strength up to temperatures of approximately 1000°C, after which there is no experimental data to show a strength gain from the formation of ceramic bonds. The effect of the ceramic bonding on strength may differ when the specimen is exposed to service load and temperature concurrently, as opposed to just a loading following the firing and subsequent formation of a ceramic bond. However, it can be expected that the strength will decrease further because the binding strength usually falls with increasing temperatures.

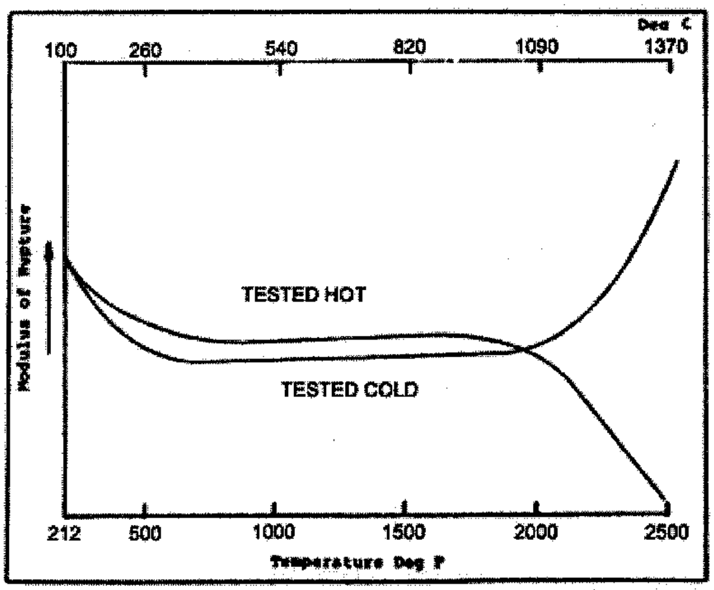


Figure 22. Effect of temperature on modulus of rupture. (from ACI Committee 547)

Flexural strengths were given in Table 9, all of which were significantly lower than the compressive strength. The modulus of rupture is an effective way of measuring tensile strength, and Figure 22 shows the relationship between modulus of rupture strength and temperature. Flexure tests as specified by ASTM C268 conducted on refractory concretes have yielded modulus of rupture values ranging from 300 to 1500 psi (2.07-10.4 MPa). Lightweight refractory concrete have significantly lower tensile strengths, with values ranging from 50 to 400 psi (0.3-2.8 MPa). Table 10, reproduced from ACI Committee 547 gives the hot and cold modulus of rupture of a 2800°F (1538°C) lightweight refractory concrete containing expanded fireclay as aggregate.

The complete divergence of the hot and cold modulus of rupture at 1090°C demonstrates the danger of relying on only the cold modulus of rupture or compressive strength. The extremely low tensile strengths at high temperatures can result in cracking caused by cement-aggregate interaction and any resultant tensile forces in the structure. It is important therefore to limit all refractory concrete to applications with only reasonable compressive loads and minimal or no tension.

Table 10. Hot and cold modulus of rupture of a 2800°F (1538°C) lightweight refractory concrete containing expanded fireclay aggregate (from ACI Committee 547)

	Modulus of rupture, psi (MPa)	
	Hot tested at temperature	Cold tested after firing and cooling
230°F (110°C)	350 (2.4)	350 (2.4)
1000°F (538°C)	300 (2.1)	Not determined
1500°F (816°C)	250 (1.7)	250 (1.7)
2000°F (1093°C)	210 (1.4)	225 (1.6)
2500°F (1371°C)	240 (1.7)	470 (3.2)
2700°F (1482°C)	90 (0.6)	800 (5.5)

This is especially true for lightweight refractory concretes, where tensile strength can be as little as 10% of that found in normal refractory concretes. The cold compressive strength of lightweight refractory concrete varies from 200-500 psi (1.4-3.5 MPa) with densities up to 50 pcf (800 kg/m^3). Higher density lightweight concretes with densities ranging from 75-100 pcf (1200-1600 kg/m^3) have cold crushing strengths from 1000-2500 psi (6.9-17.3 MPa).

Mixing, Curing, and Firing

The mixing, curing, and firing of fresh refractory concrete is as important as the selection of suitable cement and aggregate for the achievement of maximum service temperature. Poorly prepared refractory concrete may not perform at desired levels, much in the same way poor mixes and curing affects the strength of structural Portland cement concrete.

The mixing and curing of refractory concrete is affected by temperature as shown in the hydration reactions covered earlier. To get the maximum refractory properties of calcium aluminate cement, the formation of the stable compound C_3AH_6 is desirable, especially during the initial curing period. Recent work done by ACI Committee 547 shows the significant impact of temperatures on strength properties. It was found that the strength developed after mixing and curing at 85°F (30°C) and drying at 230°F (110°C) is nearly twice that of the concrete mixed and cured at 60°F (15°C) and dried at 230°F. Furthermore, high purity cement concretes experienced explosive spalling when the casting and curing temperatures were below 70°F (21°C). This spalling phenomenon is less likely to occur with low or intermediate purity cements.

Another concern with the curing of refractory concretes is the release of excessive heat during the calcium aluminate cement hydration. The high curing temperatures may cause the cement on the exposed surfaces to dry out before they can be properly hydrated, and thus should be kept under 210°F (99°C). If the temperature reaches a high level during hardening, the thermal stresses produced during cooling may also be sufficient to cause cracking in the concrete.

After being properly cured for at least 24 hours, refractory concrete should be dried at 220°F (105°C) to allow for the free water in the concrete to evaporate. Without the extra drying period, the water in the concrete can create steam pressure and cause explosive spalling during the subsequent firing process.

Tables 11 and 12 on the following pages have been reproduced from ACI Committee 547, and are intended to serve as a quick reference for the values associated with the physical and mechanical properties of different types of refractory concrete.

Table 11

Characteristics of normal weight refractory concretes

PRODUCT DESCRIPTION		TABULAR Al_2O_3 HIGH PURITY BINDER HIGH STRENGTH	3000E	GENERAL PURPOSE 2800F	HIGH STRENGTH 2800 F GUN	EROSION/ ABRASION RESISTANT	2800 F STEEL MILL	STANDARD	HIGH STRENGTH	COARSE HIGH STRENGTH 2350 F	COARSE HIGH STRENGTH 2600 F	LOW IRON HIGH STRENGTH
Recommended Service Temperature max., Deg. F		3400	3000	2800	2800	2400	2800	2600	2500	2350	2600	2600
ASTM Class (C-401)		G	F	-	-	B	D	C	C	B	C	C
Water Required for Mixing, Percent by Weight		8-11	8-12	10-12	(3)	10-12.5	10-13	15-21	14.0-15.5	11-14	3.5-11	14-16
Material Required (1) lbs. per cu. ft., lbs. per bag		160-165	140-145	129-133	129-133	125-130	125-131	108-114	120-124	126-130	137-142	118-120
Method of Application (2)		C-T-S	C-T-S-E	C-C	S	C-T-S	C-E	C-T-E	C-T-S-E	C	C	C-T-S-E
Bulk Density, Heated to temperature of: then cooled pcf	220 F	165 178	139 147	131 138	130 136	135 143	134 136	112 121	126 133	131 133	144 146	124 131
	1000 F	159 169	138 146	128 134	127 133	129 134	132 134	108 117	120 125	126 129	-	122 124
	1500 F	161 174	138 146	128 132	126 133	129 134	130 133	108 114	120 122	124 129	138 140	121 122
	2000 F	161 174	137 146	130 135	127 133	127 135	130 133	108 115	120 123	124 128	140 141	120 121
	2550 F	163 176	134 [illegible]	121 128	127 130	-	124 132	111 114	-	-	133 138	121 123
	2732 F	160 169	138 146	123 127	128 135	-	128 138	-	-	-	-	-
	3000 F	165 167	136 149	-	-		-	-	-	-	-	-
Total Linear Change % Heated to temp. of: then cooled (Note: Linear change figures are "TOTAL" in all cases and include percent of drying shrinkage occurring in transition from wet "as cast" to "as dried" state)	220 F	0.0 to -0.5	-0.1 to -0.6	-0.1 to -0.4	-0.2 to -0.6	-0.2 to -0.7	-0.3 to -0.4	-0.1 to -0.5	-0.1 to -0.5	-0.1 to -0.5	0.0 to -0.3	-0.2 to -0.4
	1000 F	-0.1 to -0.5	-0.1 to -0.6	-0.2 to -0.3	-0.2 to -0.5	-0.2 to -0.6	-0.3 to -0.4	-0.1 to -0.6	-0.2 to -0.5	-0.1 to -0.6	-	-0.4 to -0.5
	1500 F	-0.1 to -0.5	-0.2 to -0.6	-0.1 to -0.5	-0.1 to -0.5	-0.2 to -0.6	-0.2 to -0.4	-0.2 to -0.5	-0.1 to -0.7	-0.4 to -0.6	0.0 to -0.3	-0.4 to -0.5
	2000 F	-0.1 to -0.3	-0.2 to -0.7	-0.3 to -0.7	-0.1 to -0.9	-0.1 to -0.6	-0.2 to -0.5	-0.4 to -0.8	-0.1 to -0.9	-0.3 to -0.5	-0.1 to -0.5	-0.5 to -0.7
	2550 F	-0.4 to -1.3	-0.5 to -1.1	-0.8 to +1.3	-0.5 to +0.2	-	+1.7 to +2.2	-1.2 to +0.3	-	-	-0.1 to +1.7	-0.1 to +0.5
	2732 F	-0.7 to -1.4	-0.2 to +0.1	-0.5 to +1.0	-0.8 to +0.8	-	+1.3 to +2.4	-	-	-	-	-
	3000 F	-0.6 to -1.1	+0.1 to +0.7	-	-	-	-	-	-	-	-	-
Modulus of Rupture, psi Heated to temperature of: then cooled	220 F	1600 - 2590	450 - 840	360 - [illegible]	450 - [illegible]	1240 - 2000	445 - 745	310 - 520	820 - 1130	975 - 1030	810 - 1015	1020 - 1250
	1000 F	1820 - 2120	350 - 570	370 - 650	320 - 680	945 - 1240	175 - 310	200 - 270	300 - 590	535 - 710	-	395 - 440
	1500 F	1450 - 2120	290 - 580	230 - 680	530 - 840	1020 - 1865	145 - 295	150 - 200	300 - 560	400 - 560	300 - 415	370 - 570
	2000 F	930 - 1400	340 - 590	390 - 780	500 - 970	1000 - 1385	145 - 270	130 - 240	300 - 460	405 - 465	310 - 395	385 - 605
	2550 F	1280 - 2615	820 - 2050	1000 - 2450	1300 - 3030	-	1245 - 2605	820 - 1780	-	-	520 - 910	1370 - 2390
	2732 F	1290 - 2707	1260 - 2400	1110 - 2260	2290 - 3740	-	2095 - 2930	-	-	-	-	-
	3000 F	750 - 1280	1685 - 4620	-	-	-	-	-	-	-	-	-
Cold Crushing Strength, psi Heated to temperature of: then cooled	220 F	5180 - 10230	1030 - 2160	1420 - 3780	1190 - 2620	4510 - 7910	1280 - 3145	990 - 1570	2410 - 3800	3450 - 3870	2150 - 3580	3075 - 5470
	1000 F	8170 - 9160	1070 - 2250	1490 - 2950	1400 - 3000	3810 - 6490	645 - 1400	685 - 1030	1470 - 2210	1800 - 2290	-	2955 - 3795
	1500 F	7280 - [illegible]	950 - 2250	1110 - 2770	1690 - 3340	4410 - 7110	540 - 1260	630 - 840	1530 - 2090	1775 - 2325	1450 - 1590	1425 - 2845
	2000 F	3916 - 10000	980 - 2050	1330 - 2920	[illegible] - 3105	3620 - 5375	560 - 915	640 - 850	1450 - 2070	1400 - 2225	2050 - 1340	1500 - 2105
	2550 F	6180 - 11000	3280 - 4640	3200 - 7930	4250 - 11390	-	1021 - 1765	3200 - 5490	-	-	2470 - 2280	3735 - 6970
	2732 F	4330 - 10115	4280 - 5620	5280 - 12100	7140 - 13175	-	-	-	-	-	-	-
	3000 F	3320 - 5325	5870 - 10000	-	-	-	-	-	-	-	-	-
Thermal Conductivity Btu/in/hr-sq.ft.-Deg F at Mean Temperature of:	500 F	9.87	6.47	5.35	4.60	5.24	4.78	4.00	4.10	4.48	7.25	4.60
	1000 F	9.46	6.15	5.35	5.00	5.10	5.12	4.33	4.48	4.85	7.40	5.00
	1500 F	9.36	5.80	5.40	5.40	5.10	5.50	4.68	4.85	5.30	7.65	5.40
	2000 F	9.57	5.72	5.65	5.80	5.18	5.88	5.02	5.19	5.71	7.85	5.80
Chemical Analysis percent SiO_2		0.03	29.73	47.58	47.31	32.06	43.19	43.71	44.35	34.64	4.18	46.08
Al_2O_3, TiO_2		93.65	65.16	48.31	46.73	59.23	46.70	40.03	38.68	57.69	55.66	31.86
Fe_2O_3, FeO		0.27	1.15	1.47	1.37	0.91	3.05	4.22	4.78	1.30	1.19	2.57
CaO, MgO		5.52	2.48	1.47	3.25	6.89	6.09	9.03	11.31	5.63	2.96	17.00
Alkalies		0.11	0.39	0.82	0.84	0.59	0.69	1.22	0.74	0.42	0.45	1.14
Ignition Loss		0.30	0.66	0.15	0.47	-	Trace	1.14	0.11	0.27	0.11	0.67

Note: All measurements except thermal conductivity taken at room temperature.

SI conversion factors
Deg F = 1.8 C + 32
1 pcf = 16.02 kg/m³
1 lb = 0.4536 kg
1 psi = 0.006895 MPa
1 Btu-in./hr-sq ft — deg F

Table 12

Characteristics of lightweight insulating refractory concretes

COMMERCIAL PRODUCT DESCRIPTION	HIGH ALUMINA LOW IRON	GENERAL PURPOSE	LIGHT-WEIGHT 2250 F	LIGHT-WEIGHT 1800 F	VERMICULITE BASE VERY LIGHT-WEIGHT
Recommended Service Temp. max., Deg. F	3000	2500	2250	**1800	1600
ASTM Class (C 401)	Q	Q	P&O	N	Special
Water Required for Mixing, Percent by Weight	24-27.5	38-47	40-47	46-55	176
Materials Required, lbs. per cu. ft.	87-92	80-85	48-50	46-48	24
Method of Application*	C-S-E	C-T-S-E	C-T-S-E	C-S-E	C-T-E
Bulk Density, lbs. per cu. ft., Heated to Temp. of: then cooled 220 F	92-96	86-90	51-53	48-54	21-25
1500 F	90-91	80-83	47-48	47-54	20-25
2000 F	89-92	80-84	48-49	46-52	-
2250 F	90-91	80-82	47-49	-	-
2550 F	86-92	-	-	-	-
2910 F	88-93	-	-	-	-
Total Linear Change, Percent, Heated to Temp. of: then cooled 220 F	-0.2 to -0.3	-0.2 to -0.6	-0.3 to -0.4	-0.1 to -0.4	-0.2 to -0.4
1500 F	-0.4 to -0.7	-0.4 to -0.8	-0.3 to -0.9	-1.7 to -2.0	-0.9 to -2.0
2000 F	-0.6 to -0.8	-0.3 to -0.8	-0.3 to -1.1	-0.8 to -1.3	-
2250 F	-0.4 to -0.6	-0.2 to -1.4	-0.4 to -1.4	-	-
2550 F	-0.6 to +0.8	-	-	-	-
2910 F	-0.2 to +0.2	-	-	-	-
Modulus of Rupture, psi Heated to Temp. of: then cooled 220 F	265-360	190-350	100-150	200-420	15-55
1500 F	205-225	140-230	70-90	105-140	15-50
2000 F	280-315	120-250	75-115	100-205	-
2250 F	625-640	155-315	160-170	-	-
2550 F	950-955	-	-	-	-
2910 F	1755-1835	-	-	-	-
Cold Crushing Strength, psi Heated to Temp. of: then cooled 220 F	615-685	560-1040	290-450	390-750	30-70
1500 F	550-610	830-710	160-290	295-405	20-80
2000 F	450-545	460-800	130-220	200-285	-
2250 F	800-880	500-810	270-330	-	-
2550 F	1265-1415	-	-	-	-
2910 F	3530-4100	-	-	-	-
Chemical Analysis, percent					
SiO_2	36.92	40.08	37.38	43.17	-
Al_2O_3, TiO_2	54.63	38.13	34.79	17.68	-
Fe_2O_3, FeO	1.38	5.31	6.63	3.11	-
CaO, MgO	4.56	13.53	17.68	31.34	-
Alkalies	1.11	1.66	1.88	2.05	-
Ignition Loss	1.90	1.20	1.45	2.40	-
SO_3	-	-	-	-	-
Thermal Conductivity (k), Btu/Hr./Sq. Ft./F./In, At Mean Temp. of: 500 F	2.88	2.58	1.66	1.40	0.87
1000 F	3.19	2.86	1.98	1.71	1.15
1500 F	3.50	3.14	2.31	2.01	1.43
2000 F	3.82	3.42	2.63	-	-

*C-Casting; T-Troweling; S-Shotcreting; E-Extruding. All measurements except thermal conductivity taken at room temperature.

**2000 F (For back-up material)

SI conversion factors
Deg F = 1.8 C + 32
1 pcf = 16.02 kg/m³
1 lb = 0.4536 kg
1 psi = 0.006895 MPa
1 Btu-in./hr-sq ft — deg F

Refractory concrete applications

The ability of refractory concrete to resist high temperatures makes it an indispensable construction material for the petrochemical, steel, non-ferrous, ceramic, aerospace, power generation, and pottery industries. Before the introduction of castable refractory concrete, refractory brick was the material of choice when heat containment and control were necessary. Some of the disadvantages associated with refractory brick are the multiple joints, complicated anchoring, high placement and manufacturing costs, difficult repair procedures, and inflexibility in structural design. With refractory concrete, many of these problems are eliminated, and continuous improvements leave it open for various new special applications.

Other suitable uses for refractory concretes are in structures where there is cyclic firing at temperatures around 1000°C. Portland cement based concretes can be engineered to resist such temperatures, but the repeated dehydration and rehydration of the $Ca(OH)_2$ and CaO will eventually affect the structural integrity of the concrete. For such cases, the use of calcium aluminate cement concrete will increase the service life of the structure.

Precast elements such as tunnel linings are also ideal for refractory concrete because they require very little strength, they can be cured and fired with relative ease, and they can protect the actual tunnel from fires ignited by car crashes or other accidents. This leads into an extremely important application of lightweight refractory concrete – steel fireproofing.

Fireproofing

Fireproofing of structural steel can be done in several ways. Before the advent of spray-on fireproofing, most of the steel elements in a building were faced with brick, concrete, or tiles. One major drawback of this approach is the thickness of the protective facing. Hollow clay tile used to cover beams needs to be at least 4 inches thick, while concrete requires at least 2.5 inches to be effective. Spray-on fireproofing on the other hand needs to be only about an inch thick and can be easily applied to any steel assemblies.

Until the early 1970's, most of this spray-on fireproofing was a mixture of asbestos fibers and a cementitious binding agent. This cement asbestos mixture was sprayed onto the structural steel to create a thermally insulating protective layer whose primary function was to insulate the steel from excessively high temperatures that could significantly decrease the load-bearing capacity of the steel member and cause buckling.

Asbestos use in fireproofing and fire-retarding applications was widespread until it was discovered that breathing in asbestos fibers was hazardous to one's health. By the time the danger of asbestos was realized, it had already been used in the manufacture of various products such as heat-resistant clothing, automotive brake and clutch linings, ceiling tiles, asbestos-cement pipe and sheet, and fire-resistant drywall. The potential of these products to release breathable fibers depends largely upon its degree of friability, or its ability to crumble under hand pressure.

The friability of asbestos cement fireproofing is not very high because of its light weight and the fluffiness of the sprayed-on mixture. After the use of asbestos fiber in fireproofing was banned, materials such as mineral aggregates and other various fibers were considered as alternatives to asbestos. Today much of the asbestos in fireproofing has been replaced with lightweight mineral aggregates such as perlite and vermiculite.

Steel is a good building material because it is ductile, strong, and easy to assemble into structures, but its one disadvantage is its low fire resistance. At temperatures exceeding 200°F (93°C) the stress-strain relationship for steel becomes nonlinear, with reductions in strength and stiffness at increasing temperatures. Steels with relatively high percentages of carbon may undergo strain aging in the temperature range of 300-700°F (150 to 370°C), resulting in decreased ductility. The modulus of elasticity, yield strength, and tensile strength reach a maximum rate of decrease at temperatures in the range of 800°F (430°C) and 1000 °F (540°C). Creep deformation begins to appear at temperatures above about 500-600°F (260-320°C). Further increases to temperatures above 1000°F (510°C) result in a rapid decrease of the modulus of elasticity, which translates directly into excessive deformations of the structure. The reductions in strength and stiffness are dangerous because they could lead to catastrophic failure, whereas concrete exposed to comparable temperatures will only experience some spalling and cracking, but no catastrophic failure.

Current fireproofing products (e.g. Southwest Fireproofing) containing vermiculite aggregate can provide up to 4 hours of fire-resistance on steel girder work. The replacement of asbestos with mineral aggregates like perlite and vermiculite can be justified by their extremely favorable physical and non-hazardous qualities.

Vermiculite is a mica-like natural mineral that expands by up to 30 times its original volume upon rapid heating. Expanded vermiculite is then combined with either gypsum or Portland cement to be used as spray-on fireproofing or as insulating concrete.

Table 13 gives some physical properties of vermiculite insulating concrete produced by the Schundler Company while Table 14 contains data for spray-on fireproofing developed by Southwest Fireproofing.

Table 13. Properties of vermiculite insulating concrete (from The Schundler Company)

Cement:Aggregate:Sand	Density (pcf)	Compressive Strength (psi) 28 days	K (Btu-in/hr-ft^2-°F)
1:8	21-22	70-100	.64-.61
1:6	26-27	125-140	.70-.73
1:4	34-35	275-325	.79-.81
1:3:2	75-80	600-620	2.5-2.75

The relationship between concrete's density, thermal conductivity and compressive strength is clearly illustrated in both tables. Vermiculite, like many other lightweight aggregates possess extremely low strengths but excellent thermal properties. The Schundler Company claims that one inch of vermiculite concrete is equal in insulating value to 20 inches of regular concrete.

Table 14. Properties of spray-on fireproofing with vermiculite (from Southwest Fireproofing)

Fireproofing type	Type 5	Type 5-MD	Type 7-GP	Type 1-XR
Density (pcf)	15-17	22-27	22-27	38-48
Compressive strength (psi)	16	118	94	368
Binding agent	Gypsum	Gypsum	Portland cement	Portland cement

Type 5: Used primarily in locations not directly exposed to weather.
Type 5-MD: For use where a tough, durable, and damage resistant interior fireproofing is desired.
Type 7-GP: General purpose use where high humidity or moisture may preclude use of gypsum
Type 1-XR: For exterior use on petrochemical, chemical, and other industrial structures. Excellent weather resistance with superior durability and strength

Perlite is a naturally occurring siliceous rock that is also frequently used as a lightweight aggregate in concrete for fireproofing and insulating purposes. It expands from 4 to 20 times its original volume when heated and can weigh as little as 2 pcf while having melting point ranging from 1200-1300°C. Perlite insulating concrete produced by The Schundler Company provides compressive strengths from125-200 psi, densities varying from 24-30 pcf, and thermal conductivities ranging from 0.58 to 0.66 Btu-in/hr-ft^2-°F (0.085 to 0.095 W/m-K).

Fireproofing concretes from Southwest Fireproofing and The Schundler Company are just examples of what Portland cement and gypsum based fireproofing can do. Refractory concretes made with calcium aluminate cement will most certainly provide better fire-resistance and insulation at significantly higher temperatures. Table 12 in the previous section shows data for spray-on lightweight refractory concretes having recommended service temperatures in excess of 2500°F (1371°C). Whether the additional costs incurred from using such high performance fireproofing is justified or not is an issue best left to the building's owner, architect, and engineer.

Problems with using refractory concrete

Imagine having a structure that can withstand temperatures exceeding 1300°C. Its fire-resistance (as defined for most buildings today) would not be an issue because most fires will not even reach such intensities. Even the most serious and unexpected fires will not cause a catastrophic failure from the weakening of the structural members, and even if failure were to occur, the structure would allow ample time for its occupants to safely evacuate before collapse. Such structures are undoubtedly decades away from realization, but if reinforced Portland cement-based concrete can somehow be replaced with reinforced refractory concrete, such concepts may not entirely be out of the question. Despite advances made with refractory concrete, its primary physical limitation is its structural strength.

The previous section's coverage of refractory concrete's properties highlights the design dilemma stemming from the desire to attain maximum service temperatures and at the same time achieving high strength and durability. These qualities, unfortunately, cannot be improved without sacrificing the other. Other factors that need to be looked at are the concrete's cost, resistance to corrosion, thermal shock, weathering, chemical attack, cracking/spalling, and tension.

While some of the compressive strengths presented in Table 9 are high enough to qualify as structural concrete (4000 psi or 27.6 MPa), it must be remembered that these are cold compressive strengths, not hot compressive strengths. From Figure 21 it is evident that the highest strength at 1000°C is only about 2000 psi, or just half the strength of regular structural concrete. It must be assumed that the compressive strength decreases further as the service temperature increases.

Concrete's low tensile strength is accentuated at high temperatures and is a major problem for refractory concretes. In regular structural applications, this weak tensile strength is compensated for by using steel reinforcement bars, as discussed under the previous section on the tensile strength of Portland cement. For refractory concrete, this can be problematic due to the extremely high service temperatures. In general, the differential expansion between the steel rebars/fibers and the concrete will cause cracking.

Refractory concrete's resistance to weathering, chemical attack, thermal shock, and corrosion are heavily influenced by the concrete's density, porosity, modulus of rupture, compressive strength, cement purity, and aggregate hardness. For abrasion and weathering resistance, hard aggregates that provide high compressive and tensile strengths are necessary. Corrosive effects can be minimized by using dense concretes that can prevent harmful chemicals from penetrating into the pores of the refractory concrete and cause detrimental reactions. These reactions could produce products that cool, solidify, and expand, causing layers of exposed concrete to peel or shear away. Thermal shock is the deleterious effect of exposure to a rapid change in temperature, and is usually controlled by minimizing the thermal expansions and giving the concrete a high porosity to allow for thermal deformations.

There are essentially three variables that govern concrete's structural strength, durability, and fire-resistance – its aggregate, cement, and reinforcement. From a design standpoint, the weakest link among these three components is the reinforcement, or specifically the lack of it. Cement and aggregate can be selected to strike a balance of durability, service temperature, and compressive strength, but concrete's intrinsically low tensile strength and the restrictions on the use of rebar at high temperatures makes reinforcement the weakest link in refractory concrete. Even if the concrete were able to adequately shield the steel from destructive temperature gradients, the compressive strength will most likely be sacrificed to achieve the low thermal conductivity and high specific heat needed in such a situation.

However, because many refractory concrete applications take this property into consideration, (and it is not necessarily the failure of the concrete that is problematic, rather the failure of the steel reinforcement inside the concrete) it is somewhat improper to contend that reinforcement is the weakest link in the use of refractory concrete. Perhaps a better way to define this so-called weakest link is to describe it as the more influential variable in the determination of the concrete's mechanical and thermal properties. With this new definition, the improvement of refractory concrete hinges upon the selection of aggregates that can produce a durable and strong concrete, yet one that is sufficiently resistant to extreme temperatures.

The composition of the calcium aluminate cement is also important, but the development of new cements that contain increasing amounts of alumina is limited by the lime (CaO) content. Lime is needed for the completion of the hydration process and the subsequent binding action with the aggregate. At 90% alumina contents, the cement paste itself may withstand high temperatures, but the overall performance, especially the mechanical properties of the concrete will depend more heavily on the aggregate than the alumina content. Pure calcium aluminate cement is a necessary but not a sufficient condition in producing refractory concretes with high service temperatures and good mechanical properties.

The competitiveness of refractory concrete is influenced by factors such as its cement composition, aggregate type, use of admixtures, intended service life, type of concrete placement (precast or cast in-place), and application. A comparison by Petzold (using German prices from the 70's), found that commercial aluminous cement was approximately ten times as expensive as Portland cement. In addition to the higher cost of alumina cement, the labor and operating costs associated with the mixing, curing, and firing of refractory concrete make it more expensive than the placement of regular Portland cement concrete. Until the price of refractory concrete is significantly reduced, its use will be limited to applications where resistance to high-temperatures is an absolute necessity.

Improving refractory concrete performance

The improvement of refractory concrete performance can be considered in a number of ways. Strength, durability, and service temperature are the three most important performance criteria for refractory concrete. By now it is obvious that there is no silver bullet that can magically improve these three properties without adversely affecting the other. Because there is a limit on service temperature (having service temperatures in excess of 2000°C is unreasonable for most applications), this section will only propose measures that will increase refractory concrete's durability and strength.

One of the ways to increase the durability and strength in regular concrete is to reinforce it with metallic, synthetic, or mineral fibers. The tensile strengths of these fibers give the concrete additional resistance to tension and cracking. As mentioned earlier however, the only problem with using such fibers is their low fire-resistance. Therefore, the use of refractory fibers with tensile strengths comparable to those of steel fibers but with a higher softening temperature is ideal. Depending on their alumina content, ceramic fibers such as those made with aluminosilicate have been found to have service temperatures between 1300 and 1500°C. It remains to be seen whether these types of fibers can afford the concrete the same degree of durability and strength as steel fiber.

For compressive strength, the density of concrete and the selection of aggregate are the two main considerations. Table 11 shows several refractory concretes with high service temperatures and compressive strengths rivaling even that of regular structural concrete. All these refractory concretes have one thing in common – high thermal conductivity. Some of these concretes have thermal conductivities 4 to 10 times those of lightweight refractory concretes used for insulation and fireproofing. If high strength refractory concretes can be developed with lower thermal conductivities, it may be possible to embed steel reinforcement and make reinforced refractory concrete.

High performance concrete, which is essentially an extremely dense concrete, performs poorly under high temperatures because of the tendency for explosive spalling caused by the build up of steam pressure inside the concrete. To prevent this explosive spalling, polypropylene fibers have been incorporated in the concrete to ensure that as they melt (at around 200°C), they create a capillary structure that will allow the steam pressure to escape. This same concept can be used for refractory concretes, except that the fibers selected should melt at far higher temperatures.

As these high strength refractory concretes reach temperatures exceeding 1000°C (or whatever temperature deemed appropriate), the melting of the fibers and the subsequent formation of a pore structure will slowly decrease its thermal conductivity. Of course the effect on the compressive strength would need to be looked at as these fibers melt, but the better insulation of the concrete may provide sufficient time for the protection of the steel reinforcement to allow for the evacuation of any occupants.

Conclusion

The behavior of structures at high temperatures is extremely important, and the development of increasingly fire-resistant building materials will most certainly continue. Concrete has always been considered as a fire-resistant material with satisfactory performance under most fire conditions. Today's refractory concrete is the result of decades of research and development by numerous researches intent on raising the service temperature of concrete for new fields of application.

Improvements must be made in the construction industry to ensure that all structures perform adequately under intense fire conditions, deliberate or accidental. Additional research on concrete must be undertaken so that in the future there will be no such distinction between refractory concrete and regular structural concrete.

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